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Indoor Air Quality in Low Carbon Buildings in the United Kingdom

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Abstract:

There is always a demand for energy and the building sector demands a lot of energy. Consequently, due to the increasing amount of energy used in buildings, it is contributing to the increase of Greenhouse gas emission, and it is also contributing to the depletion of natural resources. The answer to this problem was to develop new kind buildings that will ensure that they would consume as little energy as possible. The term low carbon building was used to identify this type of building. However, since low-carbon building is aimed to conserve as much energy as possible it does not guarantee the indoor air condition inside these buildings. Thus, this thesis has studied indoor air quality in two renowned low-carbon buildings that were built using the latest technologies and building standards. The aim of this research was to study whether the implantation of new energy efficient technologies and low-carbon building standards has affected the indoor air quality inside the space. The result of the study has shown that the implantation of new energy efficient technologies did not compromise the indoor air quality inside the space. In fact, the use of new technologies like MVHR has insured the air quality inside the space and allowed for the pollutant inside the space to reach an acceptable level. However, there some issues that were discovered when analysing the data and performing the simulation for the three selected indoor space for this study. The first of these problems is that in the chemistry building, for example, not all areas inside the building have the same indoor air condition. The data from the Open Space Office (OSO) has much better indoor air quality compared to the First Floor Office (FFO). This could show that when designing a low-carbon building all areas inside the space are important and no certain region should be neglected. The second problem was found in the Eco-House Space (EHS) in which the natural ventilation did not provide an adequate indoor air quality condition. The third problem is overheating. the issue of overheating was present in all three indoor spaces which showed that in cold regions like the United Kingdom, there should a well-developed solution that will ensure that indoor air condition in low-carbon building is well kept in all seasons.

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Acknowledgement

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1. Chapter one: Introduction

1.1 Research background

There is always a demand for energy and the building sector demands a lot of energy. Consequently, due to the increasing amount of energy used in buildings, it is contributing to the increase of Greenhouse gas emission, and it is also contributing to the depletion of natural resources. A report by the Department for Business, energy and industrial strategy [1] shows that in 2017, the highest sector with the most energy consumption in the United Kingdom was the transportation sector which accounted for 40 %, followed by the domestic sector at 29 %, the industrial sector at 17 %, and the service sector at 14 %. Architects and engineers are aiming to improve the performance of buildings so that they would consume the least amount of energy possible. Thus, they are developing buildings that are termed energy efficient or (low-carbon) buildings. The significance of low carbon buildings stems from the fact that they are designed to reduce energy consumption and consequently reduce the emission of carbon dioxide (CO_2). In 2008, the United Kingdom produced the Climate Change Act. This Act will serve as a catalyst for reducing CO_2 emission by (80%) by 2050 [2], and it will also ensure that the country's energy consumption is monitored every year and to act upon the changes in the building code that will facilitate the mitigation of energy consumption. In addition, the building code, which is issued by the Ministry of Housing, is devoting large parts to regulate the energy consumption of buildings.

However, focusing on low energy design and disregarding other aspects of the building could be detrimental to the occupants of the building. The indoor air quality of the building is vital to its occupants because people spend most of their time indoors. According to a study done by Taylor et al [3], United Kingdom (UK) citizens spend 95% of their time inside buildings and 66% in their own residence. Spending a prolonged period of time in buildings that have inadequate indoor air quality will reflect on the health of the occupiers. There are several sources of indoor air pollution emitted from building material, furniture, heating systems, and anthropogenic products. Some of these pollutants are inevitable like the emission of CO_2 from the building occupant's perspiration. However, high levels of CO_2 could lead to many health issues like respiratory dysfunction, excitation followed by depression of the central nervous system, and it might also lead to oxygen displacement in the air [4]. There are other pollutants that might be present inside buildings like Volatile Organic Compound (VOC), Particulate matter (PM), and gaseous pollutants. All these pollutants might exist together or separately and in different concentrations depending on the level of ventilation inside the building. Therefore, monitoring their presence and concentration inside the building is crucial for the health and wellbeing of the occupants.

Indoor air pollutants could be generated from a variety of sources. These sources are generated either inside the building or transported from outside of the building. Some of the sources that are generated outside of the building like automobile emissions, PM and Volatile Organic Compound (VOC) in the atmosphere (from anthropogenic and/or biogenic sources), and in some cases, nearby factory or chemical plant. These pollutants could enter the building through windows, doors, or even through the infiltration of air from other unknown openings and crevices. For instance, in a study by Brauer et al [5], they have reported that there is an association between the concentration of indoor (NO_2) and outdoors sources of (NO_2). In that study, the authors had theorized that the strong correlation between indoor (NO_2) and outdoor (NO_2) could be explained by two reasons. The first is urbanization and the second is high volume traffic near the building. These sources of (NO_2) will find their way into the indoor environment either through infiltration or through natural ventilation.

On the other hand, some of the pollutants are generated inside the building and they come from different sources. In some cases, using energy efficient strategies might be responsible for some of the pollutant generated inside of the building. For example, reducing the air exchange rate could adversely reduce the quality of the air inside the building and accumulate a significant amount of pollutants inside the space and, on some occasions, could hiders the transport of pollutants outside of the building. Making the building airtight reduces the amount of energy needed to ventilate the occupied space, however, it could also mean that the pollutant inside the occupied space has nowhere else to go. A study done by Colton et al [6] reported that inadequate ventilation could cause the indoor air to have a high concentration of NO_2, VOCs, and PM as well as health problems associated with an airtight building like sick building syndrome. In fact, one study by Samuel et al, have concluded that poor indoor air quality is attributed to the reduction of fresh air entering the building and the construction of an airtight building. They have also found that high levels of CO_2 have shown to be found in an airtight building and that poor ventilation could lead to respiratory illness among infants by 50%, illness among students by 41%, short time absence from workers by 35% and a decreased productivity by 9% [7].

Another source of pollution is related to the technologies that were implemented inside the buildings that were initially utilized to improve the energy performance of these building, however, they have resulted in the deterioration of the indoor air quality. Technologies such as biomass boiler, earth tubes, mechanical ventilation and heat recovery systems (MVHR) are some of these technologies. For instance, using solid fuels could worsen the air quality condition as stated in a study by Moshammer et al [8] which stated that if people would switch from using oil and gas to wood-fired fuel for their heating systems, there will be an increase in the annual average PM_{10} concentration from 3 µg/m^3 to 5 µg/m^3 that could lead to 170 additional premature death annually. Another example could be found in a paper published by Sherman and Levin [9] which suggest that using renewable source of energy such as solar and wind energy generators might be a potential source for indoor air pollution. These technologies use batteries to store energy and they contain chemicals that are toxic to noxious. The authors suggest that these batteries should be stored in an isolated place away from the occupants of the building to avoid electrolytes and gaseous emissions.

building materials are some of the most common sources of indoor air pollutants. In many cases, these materials are categories as green or low energy-intensive because they need less energy to produce or in many cases are either recycled or come from a renewable source. Nevertheless, some of them have proven to produce a number of VOCs inside the occupied space. According to Kim [10], VOCs are present in many wood-based products. Some of these VOCs are chemicals that occur naturally in wood products, and some of them are added during processing. In new energy-efficient buildings with low air exchange rates, harmful levels of these VOCs could be present that might affect human health [10]. It is important to not only ensure that a healthy amount of fresh air is introduced inside the building but also ensure that there are no sources of indoor air pollutant are introduced into the occupied space.

The focus of this research will, therefore, be on low carbon buildings in the United Kingdom, and it will analyze the condition of indoor air quality by studying the concentration of common indoor air pollutants and their emission sources. The findings from this study will give a good indication of the condition that the occupants experienced inside and how to optimise the design of new buildings to ensure the best indoor air quality.

1.2 Aim and Objectives

The main aim of this study was to investigate the indoor air quality in low-carbon buildings. To this end the specific objectives shall be to;

1. Carry out comprehensive literature reviews in order to establish the technological and environmental factors affecting indoor air quality in low-carbon buildings. This would cover the thermal and environmental behaviour of various building materials and the effects of energy technologies on indoor air quality in low carbon buildings.
2. Carry out modelling and simulation of indoor air quality in selected low carbon buildings in the UK
3. Conduct a survey to assess occupants' satisfaction of indoor air quality in the selected low carbon buildings.
4. Undertake a practical thermal and environmental assessment of the selected low carbon buildings and use the data to validate the theoretical model.

1.3 Structure of thesis:

Chapter one:

This chapter contains the introduction of the thesis topic along with the main aim and objectives of this research.

Chapter two:

This chapter contains the literature review of several topics including indoor air quality, indoor air quality in low carbon building, important technologies used in low carbon buildings and their impact on indoor air quality, indoor air pollutants, and how to improve the indoor air conditions inside the building.

Chapter three:

Discusses the research methodology which includes the case study analysis, the qualitative method, and the description of the two buildings chosen for this thesis.

Chapter four:

This chapter lists the main mathematical models that are used to analytically analyze the data collected from the buildings and the software simulation.

Chapter five:

This chapter contains all the simulation result of the case study analysis of the two buildings

Chapter six:

In this chapter, all the data collected from the two building are illustrated along with data analysis

Chapter seven:

This chapter shows the result of the survey questionnaire result gathered from the participants who were occupying the two buildings.

Chapter eight:

The final chapter contains the concluding remarks for the entire thesis. In addition, the chapter also contains the discussion for the result from the simulation, the data collection and the survey.

2. Chapter two: Literature review

2.0 General

The topic of indoor air quality may not be seen as a close affiliation with the topic of low carbon building. nevertheless, there is a connection between these two subjects. When considering the topic of low carbon building, it is a practice that focuses on the efficient use of energy inside the building and to make sure that new buildings are built with the highest standard. These buildings are equipped with the latest technologies, materials and designs that will allow them to conserve as much energy as possible. However, when considering the topic of indoor air quality, it is thought that the field of indoor air quality has limited influence on the design of low carbon buildings. This perception is generally prevalent because when designing new low carbon buildings, the subject of indoor air quality is not given sufficient attention by architects and engineers. Therefore, more attention should be given to the evaluation of indoor air quality in low carbon and not to make it a secondary issue that is dealt with after the fact. The next following sections of the literature review will touch upon these topics and further explore all aspects that are related to indoor air quality and its association with low carbon and how can new technologies developed in low carbon buildings sometimes aid the status of indoor air quality and how can they sometimes harm the indoor air condition by producing new contaminates inside the space with the introduction of new materials and technologies.

2.1 Low carbon buildings

There is no doubt that buildings are very important for humans. They house the essential everyday needs for security, shelter, and privacy. Nonetheless, these buildings consume a large amount of energy. They contribute towards the increase of global warming and a considerable amount of natural resources are devoted to their construction. Therefore, they have a tremendous impact on the planet's ecology and natural resources. In fact, According to the Royal Institute of British Architects (RIBA) in the pre-industrial era, the atmosphere had 280 parts per million of carbon dioxide by volume compared to 380 parts per million in 2007, and it is expected to increase to up to 500 parts per million [11]. According to some studies, the UK's Green House Gas (GHG) emission in 2018 was around 451.5 million tons of Dioxide equivalent [12]. Nevertheless, it is worth noting that almost half of the total CO_2 emissions is attributed to building consumption. According to the Department of Energy and Climate Change in the United Kingdom, in the year 2009 (58 %) of the energy used by households is due to space heating, (24 %) to hot water, and the remainder (19 %) is directed toward cooking, appliances, and lighting [11]. since then, the country was obligated to reduce the amount of CO2 emission from 566.5 million tonnes carbon dioxide equivalent (MtCO2e) in 2013, to 462.1 (MtCO2e) in 2018 [13]. The increase in energy consumption was mainly driven by the rapid development of modern cities and at the beginning of the twentieth century, buildings were not designed to be energy efficient. However, it has become apparent that buildings are consuming a significant amount of energy.

In response to these challenges, architects and engineers have developed a new type of building design that is optimized to use considerably less energy than their predecessor. Low carbon building is a term that is used to describe these new types of buildings that have been designed by engineers to reduce the energy consumption of conventional buildings. The Department of Energy and Climate Change (DECC) defines carbon-neutral buildings "as through a transparent process of calculating emissions, reducing those emissions, and offsetting residual emission-net carbon emission equal zero" [14]. Even though low carbon buildings tend to have higher initial costs than conventional buildings, they still give several benefits over conventional buildings. The first benefit is energy savings. Using energy efficient strategies can affect the amount of energy that is used in the building. For example, in a study done by the Committee on Climate Change [15], implementing ultra-high energy efficiency standards within a wide scope of other energy-saving strategies could yield a reduction in energy consumption by 4 TWh and it could also reduce the peak demand associated with heat pumps in new homes (estimated to be up to 15-16 GW). In addition, using an ultra-high energy efficiency scheme could reduce the carbon emission by 27 tonnes of CO_2 over the lifetime of the building. Looking at figure (2.1) shows the reduction in energy consumption of an average home when implementing very tight energy efficiency strategies going from around 17,000 KWh annually to around 5000 kWh annually. In another study by Kats and Greg [16] where they have reviewed 60 different LEED buildings. Their study showed that energy efficient buildings are between 25 – 30 % more energy efficient than regular buildings. This will also lead to more reduction in operational costs. The second benefit is the reduction in emissions due to fossil fuel burning. Using fossil fuel to generate electricity would result in the emission of many harmful gases like CO_2, NO_2, PM, and SO_2. Reducing these gases will also decrease the mortality rate according to the EPA [16]. The third benefit of low carbon building is the reduction in waste materials and reducing the embodied energy within the building materials. In a study by Giesekam et al [17] the building sector consumes a great portion of building materials. According to Giesekam et al, throughout the life cycle of the building, a large portion of the energy used to construct buildings are from embodied energy in building materials which can be estimated between 2 – 80 % of the entire life carbon emission depending on many factors like location, building use, service life of the building, future energy supply, and material palette. The benefit of using low carbon strategies for future buildings is to decrease the amount of embodied energy in building materials by, reduce the dependence on carbon-intensive materials, extending the life span of the material, and/or constructing buildings that are easy to deconstruct. Another benefit of implementing low carbon strategies is to allow for materials to be reused by using materials from natural resources, using recycled materials, using repurposed materials, and construction products that have been optimized through novel production techniques [17].

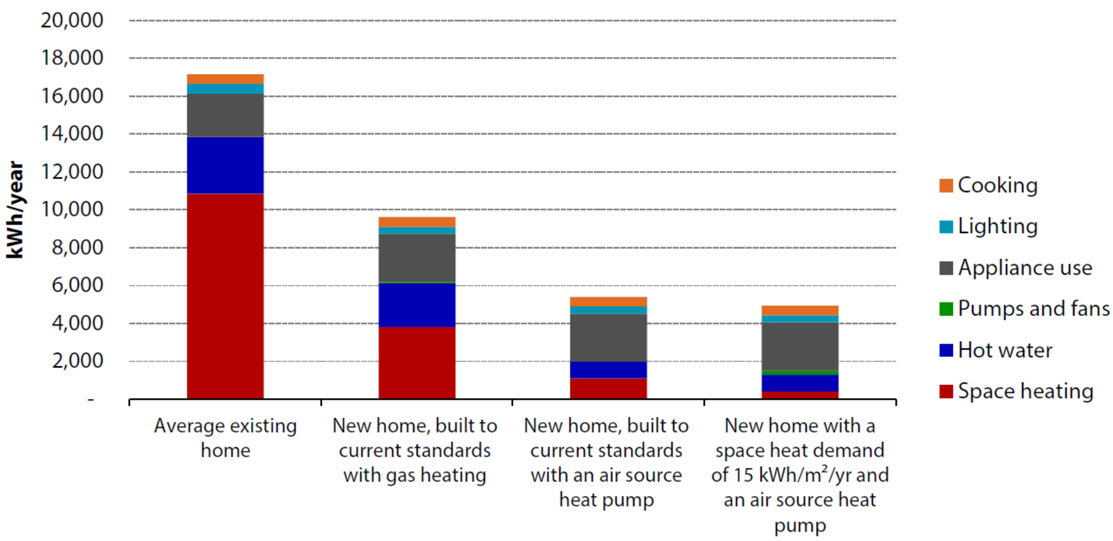


Figure 2-1 Breakdown of energy consumption in existing and new homes [15]

The United Kingdom has many attempts to reduce the overall nation's carbon emission by enacting new laws, producing new government incentives, and improving building regulation. In November 2008, the United Kingdom enacted a new law that is called the Climate Change Act. This law obligates the United Kingdom to reduce carbon dioxide emissions by 80% by the year 2050 compared to the benchmark of 1990 [18]. Other attempts have been made to reduce the country's carbon emissions. The new building regulation has been amended to reach the goals that are set out by the Climate Change Act. In addition, the 2013 building regulation has added a 9 % aggregate CO_2 emission reduction on top of the previous 2010 building regulation [18]. These measures are necessary to meet the Target Emission Rate (TER) by 2050. And lastly, a new government program was introduced to encourage the use of renewable energy. The Domestic Renewable Heat Incentive was introduced by the British Government to promote the use of renewable heat sources. Switching to heating systems that use eligible energy sources can help the UK reduce its carbon emissions and meet its renewable energy targets [19].

The key principle for minimizing the energy consumption in buildings is to follow the essential steps for developing low carbon buildings [20]. The first step is to maximize the benefits of passive design which will lead to a less frequent reliance on active systems (i.e. mechanical ventilation and HVAC system). The second step is to be lean. Meaning that the designer should design the building in a way to reduce energy consumption as much as possible. The third step is to be clean, meaning that all technologies that are used inside the building should be certified to be energy efficient and contain the highest standard in energy efficiency. The fourth step is to be green. Meaning that the building should be supplied with energy from renewable sources as much as possible and be less reliant on the electric grid system.

Despite all these benefits. Energy efficient or (low carbon buildings) are not without their flaws. Many low carbon buildings have poorer indoor air quality compared to conventional buildings. the reason is that some of the technologies that have been implemented in these low carbon buildings might have an adverse effect on the Indoor air quality of the occupied space. Many of these technologies use synthetic materials and chemical products that will eventually facilitate the accumulation of indoor air pollutants such as VOCs and sand particulates [21]. Some scientists claimed that building materials are a major source of formaldehyde and volatile organic compounds (VOCs) in the indoor air. Some of the VOCs detected inside the occupied space are volatile aromatic hydrocarbons (VAHs), semi-volatile organic compounds (SVOCs), and volatile aldehydes and formaldehyde (HCHO) [22]. Another study by Bluyssen et al [23] showed that when examining the result from the (European IAQ-Audit project) which included 56 audited European office buildings. The result of the study suggests that the quality of the indoor air is considered very poor as evaluated by the sensory panels with substantial dissatisfaction among the occupants. The study revealed that the occupants are a less dominant source of pollution and that sources of pollution in the audited European office buildings comprised mostly of building materials and components of ventilation systems. Long term exposure to indoor air pollutants might cause diseases and even death. Some of these diseases that might occur are respiratory infections such as pneumonia and chronic obstructive pulmonary disease [24]. Indoor air quality is essential for the well-being of the building occupants. Therefore, it is important to identify the factors that will affect the indoor air condition [25].

2.2 Indoor air quality in Low Carbon Buildings:

When designing a low-carbon building, the focus is usually on the energy efficiency of the building and less effort is spent on ensuring that the building has adequate indoor air quality. As stated before, because people spend a lot of time inside buildings, it is very important to ensure that the indoor air quality inside the space is adequate enough for human consumption. One strategy for ensuring the quality of the air inside the space is to study the sources of indoor air pollution to minimize their presence inside the space. These sources are generated either inside the building or transported from outside of the building. Some of the sources that are generated outside of the building like automobile emissions, PM and Volatile Organic Compound (VOC) in the atmosphere (from anthropogenic and/or biogenic sources), and in some cases, nearby factories or chemical plants. These pollutants could enter the building through windows, doors, or even through the infiltration of air from other unknown openings and crevices. This is very important for low carbon building because outdoor air ventilation is around 20 % of the air used to ventilate the air inside the building while 80 % of the air ventilation use recirculated air from inside the building [26]. Removing any pollutant from outdoor sources can reduce this rate of ventilation and save energy. In a study by Sidheswaran et al [26] they have used an Activated Carbon Fibre filter (ACF) to remove VOCs from the outdoor air. They have found that using the (ACF) filters along with a reduction of 50%

in the energy used to ventilate the space regularly, they have achieved a reduction of VOCs by 60 – 80 % and a reduction in formaldehyde by 12 – 40 %.

Other sources of indoor air pollution could be generated from inside the building. Sources like biomass boilers, building materials, Heating Ventilation and Air Condition (HVAC) systems, humans and human activities, and chemical products. Some of these pollutants occur naturally like CO_2 emission from human exhales, human dander, and other forms of human activities like cooking and washing. Others are more serious and detrimental like biomass boilers, chemical products, and excessive humidity. The building materials that are used inside the building emits several types of Volatile Organic Compound (VOC) into the indoor atmosphere. For example, in one study by Tang et al [27], they have found that some Wood-based panels bonded with urea-formaldehyde resin have the potential to emit hazardous formaldehyde fumes. Even human care products that that are used for cleaning might affect the health of the occupiers. In a research study by Missia et al [28], it was discovered that consumer products, for instance (personal care products, air fresheners, and cleaning products) could affect humans by inhaling the emitted volatile organic compounds (VOCs) or semi-VOCs, PM and secondary pollutants formed by the interaction with ozone particles in the air. It is vital that these pollutants that are either generated from humans, building materials, or building services be extracted from the indoor environment and replaced by outdoor fresh air.

Most modern building regulations and building codes are advocating for more airtight buildings to reduce infiltration inside the building. While it is true that having an airtight building would reduce the amount of energy needed to ventilate the air, it may also cause other problems for the indoor air quality inside the occupied space. As mentioned earlier, inside the building there are several pollutants that need to be removed from the building by ventilation, and having an extremely airtight building would jeopardize the health of the building's occupants. A study done by Colton et al [6] reported that inadequate ventilation could cause the indoor air to have high concentrations of NO_2, VOCs, and PM as well as health problems associated with an airtight building like sick building syndrome. In addition, energy efficient housing development in Chicago, United States, was reported to have higher 24-hour CO_2 (839 and 777 ppm vs.

635 ppm in control building sample), CO concentration of 0.43 and 0.44 ppm vs. 0.31 ppm in control building sample, and Total Volatile Organic Compound (TVOC) of 93 and 64 ppb vs. 47 ppb in control building sample [29].

Because most modern buildings use mechanical ventilation systems like the Heating Ventilation and Air Condition (HVAC) systems or Mechanical Ventilation and Heat Recovery (MVHR) systems, it is important to know that in some cases they could negatively affect the indoor air quality. The European Commission Collaborative Action [30] have reported that there could be risks resulting from using mechanical ventilators including; 1) The component of the HVAC systems could get dirty when installed or even after installation and therefore might release pollutants with odours; 2) Poor indoor temperature control due to the absence of cooling; 3) Low humidity in the winter; 4) Loud noises could be generated during operation; 5) Forces could cause droughts; 6) Microbe growth on cooling coils; 7) Re-circulation of indoor air could result in the contamination of HVAC components like supply air ducts. In addition, energy efficient buildings rely almost entirely on the HVAC system for ventilation, therefore in the event of malfunction or power outage, the concentration of indoor pollutants would increase dramatically. In a review study done by Aganovic et al [31], they concluded that many surveyed buildings had high levels of indoor air pollution that exceeded the minimum threshold limits of pollution (CO2 higher than1350 ppm, and TVOC higher than 3000 µg/m^3) recommended by the European standards. This was due to the extremely low ventilation rates, especially in energy efficient buildings. With low ventilation rate, indoor air pollutants would increase considerably. In addition, they also stated that poor maintenance was also a contributing factor to the high levels of indoor air pollution.

However, it is worth noting that mechanical ventilation does reduce the number of pollutants inside the building considerably if they are maintained properly and are running continuously. Even though natural ventilation may seem like a decent solution for removing indoor pollutants and reducing energy consumption, it cannot guarantee consistent removal of indoor pollutants due to the fact that natural ventilation is very dependent on weather conditions like temperature and, humidity and wind direction. Studies in central London show that naturally ventilated office spaces have the same outdoor concentration of PM2.5 and generally have a 20-30% lower indoor/outdoor ratio difference than mechanical ventilation systems [32]. Another study shows that natural ventilation has an 80% concentration of outdoor pollutant concentration [33]. In a study by Colton et al [6] where they observed 57%, 65%, and 93% lower concentrations of $PM_{2.5}$, NO_2, and nicotine (respectively) in green homes compared to control homes ($p = 0.032$, $p < 0.001$, $p = 0.003$, respectively).

2.3 Health complication associated with Indoor air pollution

According to the Environmental Protection Agency of the United States, [34] Indoor air pollution is recognized as one of the top five most urgent environmental risks to public health. In order to understand the effect of indoor air pollutants, it is important to identify them and identify their sources and examine their influence on human health. The Scientific Community on Health and Environmental Risks (SCHER) reported that more than 900 different compounds have been detected in indoor air [35]. Most indoor air pollutants are derived from human activities.

Indoor air pollution is influenced by the infiltration of outdoor air, specific indoor air pollutant sources, the interaction between building systems, construction techniques, and occupants. Some pollutants may have 2-5 times more indoor concentration than outside concentration. Many buildings like schools, and day nursery centres where they have higher levels of common indoor air pollutants because of poor building construction and maintenance, poor cleaning, and poor ventilation. Indoor air quality is very important especially for children whose immune system is still developing and inhale a higher volume of air per body weight than adults [36].

Lack of ventilation can contribute to the accumulation of indoor air pollution either by not bringing outdoor air to replace the indoor air or by not extracting the indoor air pollutants from the inside. Elevated temperatures and humidity could also contribute to the increase in indoor air pollution [37]. The air could enter the building via infiltration, natural ventilation, and mechanical ventilation. In the case of infiltration, the temperature difference between inside and outside will increase the rate of infiltration along with the wind which could also contribute to the rate of infiltration. People will develop various symptoms when exposed to indoor air pollutants such as the irritation of the eyes, nose and throat, headache, dizziness and fatigue [37] (see figure 2.2)

Some experts say that these could be more prominent when the person is inside of the building and as soon as he or she leaves the building, the symptoms will fade away eventually. This phenomenon is also known as Sick building syndrome which emerged in the 1970s and it was defined as a situation in which reported symptoms among a population of building occupants can be temporally associated with their presence in that building [38]. It occurred when the building occupants have reported similar symptoms such as nasopharyngeal irritation, rhinitis or nasal congestion, inability to concentrate, and general malaise-complaints [38].

The health problems occur depending on the type of pollutant that each individual might encounter. For example, according to Perez-Padilla et al [39], Indoor sources of air pollution can be categorized by type of source and by pollutant group. They also stated that Sources of pollution may be the cause of combustion processes for cooking and heating; from human activities, such as smoking, presence of biological agents, and use of chemical substances; and from emissions of construction materials and furniture. Indoor concentrations of pollutants depend on the number of emissions, the volume of the polluted space, and the rate of exchange between indoor and outdoor air. Each of these pollutants could affect the occupant's health in a particular way as illustrated in table (2-1) and (figure 2.2)

Table 2-1 Sources and characteristics of varied indoor air pollutants and associated health effects [39]

Pollutant	Sources and characteristics	Associated health effects
Biological pollutants	Dust mites, moulds, fungus, bacteria, products from men and pets, pests (cockroaches, mice, rats) enhanced by damp indoors. Also, microbial products such as endotoxins, microbial fragments, peptidoglycans and varied allergens.	A major concern is allergic reactions, which range from rhinitis or conjunctivitis to severe asthma. Indoor allergens are important causes and triggers of asthma: dust mite, cats, cockroaches, dogs, and indoor moulds and fungus. Also, possible infections, hypersensitivity pneumonitis, and toxic reactions.
Volatile organic compounds (VOCs)	VOCs (toxic gases or vapours emitted at room temperature from certain solids or liquids) include formaldehyde, benzene, and perchloroethylene, among many others. The semi-VOCs category includes compounds such as phthalates.	Adverse effects are varied, including eye and upper and lower respiratory irritation. Formaldehyde has been classified as a probable human carcinogen by the Environmental Protection Agency (EPA), but can cause rhinitis, nasal congestion, rash, pruritus, headache, nausea, vomiting, dyspnea, and epistaxis. Symptoms after exposure to pesticides may include headache, dizziness, muscular weakness, and nausea. In addition, some active ingredients and inert components of pesticides are considered possible human carcinogens.
Radon	A naturally occurring underground radioactive gas resulting from the decay of radium, itself a decay product of uranium. Decay products, either free or attached to airborne particles are inhaled.	Known human carcinogen. Radon is the estimated second leading cause of lung cancer, following smoking. While the risk to underground miners has long been known, the potential danger of residential radon pollution has been widely recognized only since the late 1970s, with the documentation of high indoor levels.
Particulate Matter	Variety of particulates, different size and composition Respirable size, mean aerodynamic diameter <10 μm (PM10) Fine particles <2.5 μm (PM2.5) can be deposited in the lower respiratory tract Organic and inorganic (metals, for example) pollutants can be carried by particulate matter in some cases, carcinogenic pollutants are attached to the particle, for example, higher molecular weight (5-ring and more) polycyclic aromatic hydrocarbons (PAHs) such as benzo(a)pyrene	Cause irritation and oxidative stress (additive to other compounds) producing lung and airway inflammation, hyperresponsiveness, and in long-term exposures airway remodelling and emphysema Reduced mucociliary clearance and macrophage response Carcinogenic
Gaseous	Carbon monoxide (CO)	Binds to haemoglobin interfering with the transport of oxygen Headache, nausea, dizziness Low birth weight, increase in perinatal deaths. Feto-toxicant has been associated with poor fetal growth
	Nitrogen oxides (NOx)	Irritant, affecting the mucosa of eyes, nose, throat, and respiratory tract Increased bronchial reactivity, longer-term exposure increases susceptibility to infections
	Sulfur dioxide (SO2), mainly from coal	Irritant, affecting the mucosa of eyes, nose, throat, and respiratory tract Increased bronchial reactivity, bronchoconstriction
	Hundreds of different hydrocarbons Aldehydes and ketones Lower molecular weight (2–4 ring) PAHs Some of these are classified as carcinogenic: 1,3 butadiene; benzene; styrene, and formaldehyde	Adverse effects are varied, including eye and upper and lower respiratory irritation, systemic effects Carcinogenic

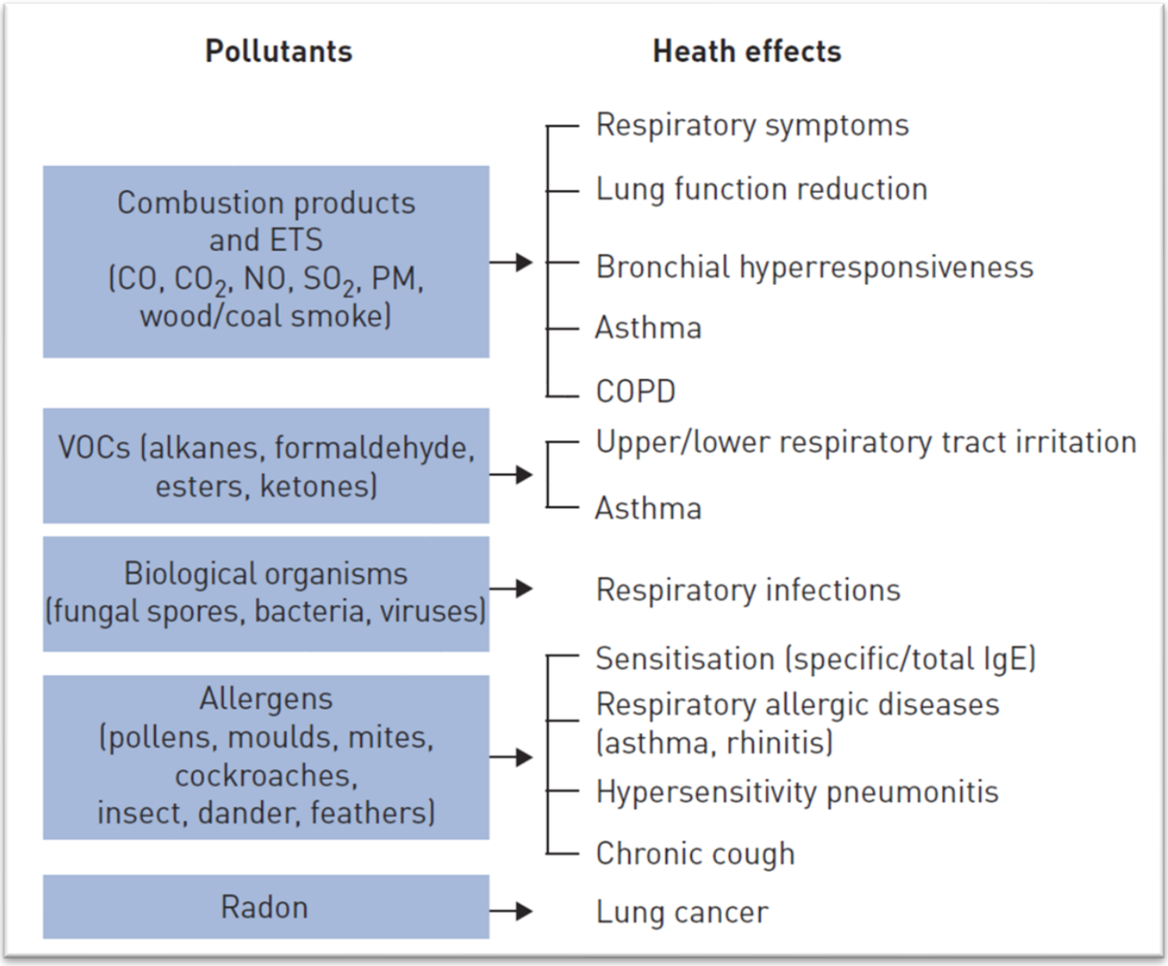


Figure 2-2 the main respiratory health effects of common indoor pollutants [37].

2.7 Types of indoor air pollutants

The buildings that people live in originate copious amounts of pollutants daily and they are present in almost every product manufactured. Most pollutants are originated from similar sources. Combustion pollutants are originated from using gas oil, kerosene, coal, wood, and tobacco. Building materials can emit several types of pollutants like volatile organic compounds. Some pollutants could be emitted from house products like cleaners and hobby products. Others could be emitted from outside of the building and afterwards find their way inside the building through infiltration, window, or door openings. Table (2-2) list indoor air pollutants that are found inside the building. Also, their association with health symptoms and figure (2-3) give a simple diagram explaining the types of pollution and its subsequent health effects [37]. The following subsections will detail some of the common pollutants found in the indoor environment.

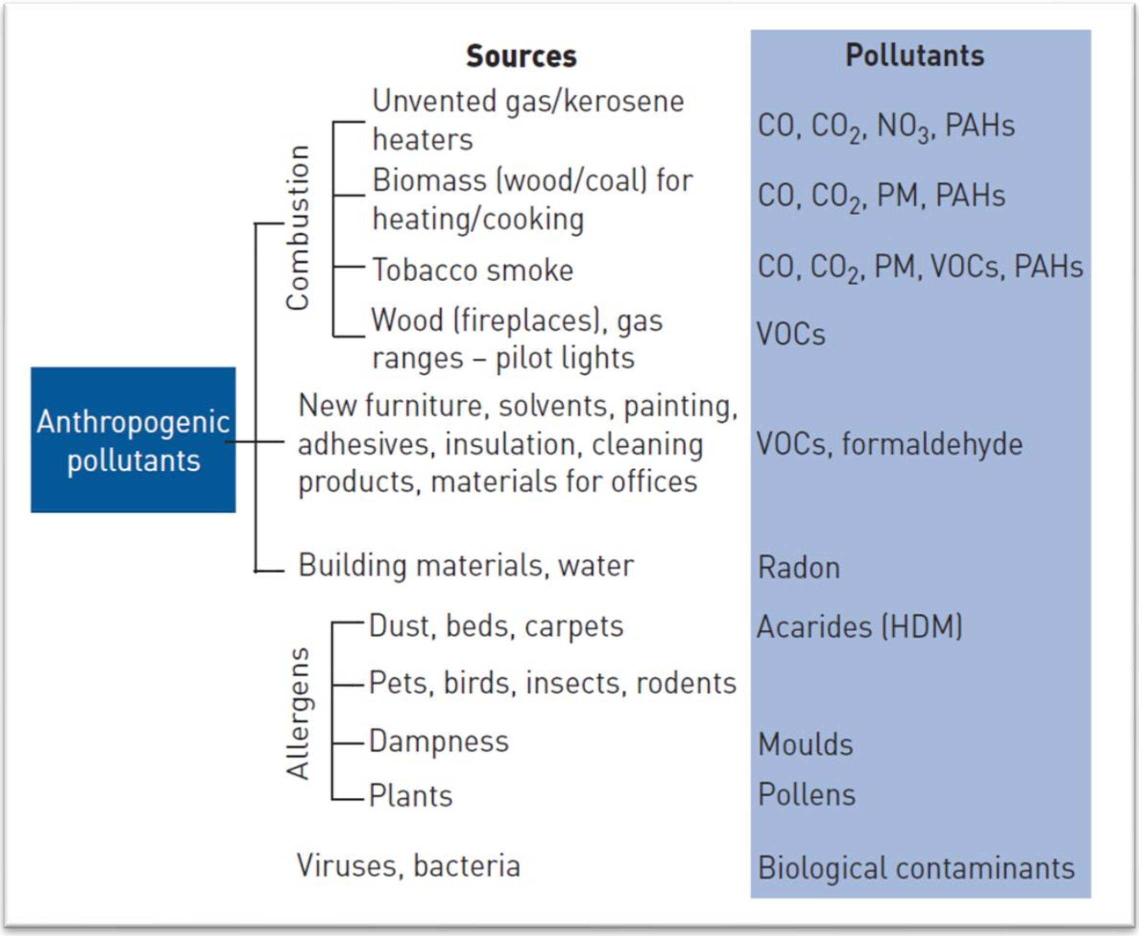


Figure 2-3 the main indoor pollutants and their sources [37].

Table 2-2 a quick reference to famous pollutant and their health effect [37].

2.12 Types of indoor air pollutants:						
Sings and symptoms	Environmental tobacco smoke	Other combustion products	Biological pollutants	Volatile organics	Heavy metals	Sick building syndrome
Rhinitis, nasal congestion	■	■	■	■		■
Epistaxis				■		
Pharyngitis, cough	■	■	■	■		■
Wheezing worsening asthma	■	■		■		■
Dyspnea	■		■			■
Severe lung disease						■
Other						
Conjunctival irritation	■	■	■	■		■
Headache or dizziness	■	■	■	■	■	■
Lethargy, fatigue, malaise		■	■	■	■	■
Nausea, vomiting, anorexia		■	■	■	■	
Cognitive impairment, personality changes		■		■	■	■
Rashes			■	■	■	
Fever, chilis			■		■	
Tachycardia		■			■	
Retinal haemorrhage		■				
Mylagiya				■		■
Hearing loss				■		

2.7.1 Sensory pollution:

A typical mixture of indoor air may contain about 6000 compounds of which 500 are air pollutants emitted by building materials and equipment and there are also an additional 5000 compounds that are derived from tobacco sources. These compounds can affect the occupants by stimulating the Olfactory sense, that is situated in a small area of the nasal cavity which is sensitive to about 500,000 odours, and the general chemical sense, situated all over the mucus membrane of the nose and it is sensitive to more than 100,000 irritants [40].

The strength of the perceived pollution could be quantified by the olfactory measurement which is the unit of one Olf. A unit of Olf is the sensory pollution strength from a standard person defined as an average adult working in the office or similar work in a sedentary condition and having hygiene of a standard 0.7 bath per day. The strength of the most pollutants sources could be measured by knowing how many Olf units can cause the same dissatisfaction effect of a 1 standard Olf [40].

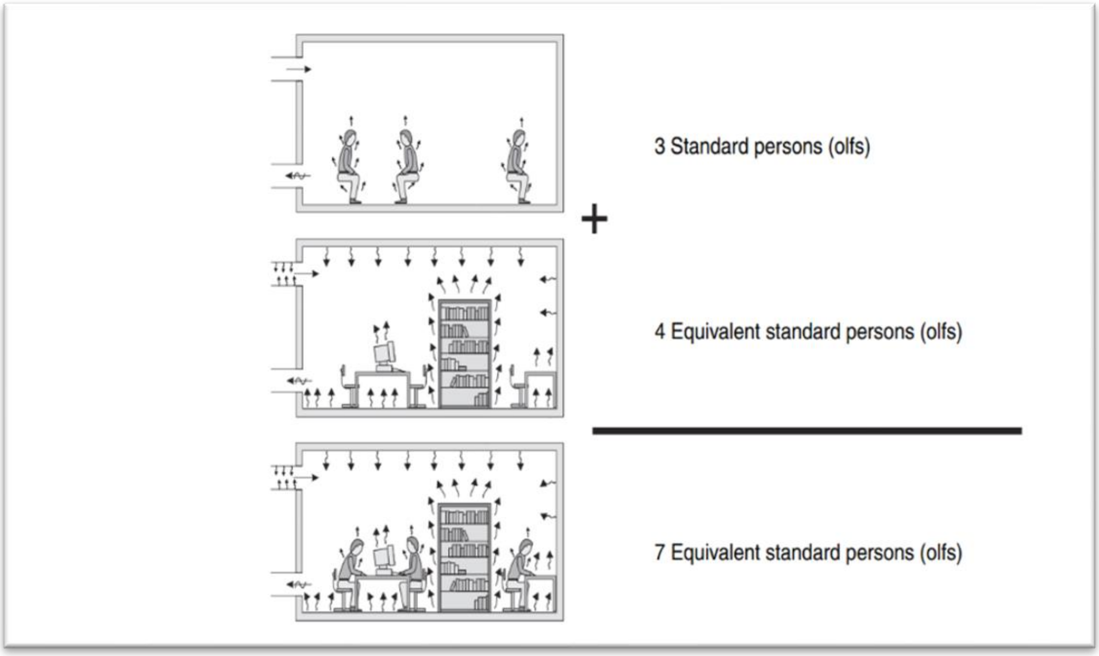


Figure 2-4 an example illustrating the sensory pollution loads in an office expressed as equivalent standard persons [40].

Table 2-3 sensory pollution loads from human [40].

Source	Sensory pollution load olf/occupant
Adult sedentary (1-1.2 met)	1
Low level of physical exercise (3 met)	4
Medium level of physical exercise (6 met)	10
High level of physical exercise (10 met)	20
Children kindergarten, 3-6 years, (2.7 met)	1.2
School, 14-16 years, (1-1.2 met)	1.3
(met) = metabolic rate. / olf/occupant = olfactory per occupant	

In table (2.3) an example of calculating the olfactory by accounting an empty room a 4 Olf. If there are three people occupying the room, the total olfactory will be 7 Olf [40]. The aforementioned table contains a summarization of the sensory pollution load from different sources. It shows that the sensory pollution load increases as the activity of the people inside the space increases. Like, for example, if the person is sedentary the Olf unit per occupant is 1. Likewise, an increase in activity level, (i.e. medium level of physical activity) would increase the Olf units per occupant by 10 Olf. The reason why the Olf unit is higher during higher activity levels is that the body produces more sweet and higher rates of respiration. Another research by Fanger [41] quantifies how the strength of pollution sources indoors influence indoor air quality as it is perceived by humans, a Pol unit has been developed. One Pol unit is the perceived air quality in a space with a sensory load of 1 Olf ventilated by 1 L/S. The Pol unit could be considered as the concentration of air pollution that can be sensed by humans and is defined as the concentration of human bio effluents that could cause the same dissatisfaction as the actual pollution [41]. The sensory strength of pollution cannot be directly measured with an instrument, neither can it be predicted from an analysis of hundreds of chemicals typically occurring in indoor air. The only way of knowing is to consult a panel of human subjects who will be judging the sensory strength of pollution [40]. The equation for the sensory pollution load is:

$$G = 0.1 * Q * (Ci - Co)$$

Whereas

G= sensory pollution load, Olf

Q= measured outdoor air supply rate L/S.

Ci=perceived air quality indoor (decipol)

Co=perceived air quality outdoors (decipol)

The HVAC system could be responsible for various sources of indoor pollution. If the component of the HVAC system is not being kept properly, cleaned, and maintained there is a chance that contaminants that are supposed to be extracted by the HVAC are been compiled by the HVAC system itself. Some of the components that can potentially deposit pollutants on their surface are the air humidifier, the rotary heat exchanger. In addition, some pollutants like dust can be accumulated by the filter [40]. An assessment has been done on eight ventilation systems and eighteen office buildings which showed that sensory pollution load from the ventilation system can on average be as high as 40-50 Olf. In that study, it was apparent that the most important sensory pollution within the ventilation system is a used particle filter. If the particle filter is not being changed periodically, the sensory pollution from it alone could be about 40-55 Olf/m^2. Besides, the sensory pollution from the ducts could amount to 0.2 Olf/m^2. The rotary heat exchanger could accumulate a considerable amount of pollution. In one case, a rotary heat exchanger was exposed to a chamber that emitted typical building materials pollutants and it gathered a sensory pollution load of 50-125 Olf [40].

2.7.2 Volatile organic compound

According to Salthammer [42], volatile organic compounds (VOC) means any compound of carbon excluding carbon monoxide (CO), carbon dioxide (CO_2), carbonic acid, metallic carbides, and carbonates and ammonium carbonate. There are also defined by the United States EPA as organic compounds whose composition makes it possible for them to evaporate under normal indoor atmospheric conditions of temperature and pressure [42]. According to the World Health Organization (WHO) [43], volatile organic chemical compounds have a boiling point ranging from 50 ℃ to 250 ℃. VOCs are emitted as gases at room temperature into the indoor air from solid or liquid materials that contain VOC. Table (2-3) lists some of the common VOCs and their boiling point. Some of the examples of VOCs are (e.g. formaldehyde, benzene, perchloroethylene) the concentration of VOCs is higher inside the building than outside. In a study by the EPA, they surveyed six communities in six regions in the United States and found a higher indoor concentration of VOCs than Outdoor concentration by ten times even in areas where there is a major source of outdoor VOCs like petrochemical plant [44].

Table 2-4 classification of organic indoor pollutant [45]

Description	abbreviation	Boiling point temperature	
		From (°C)	to (°C)
Very volatile organic compound	VVOCs	<0	50-100
Volatile organic compound	VOCs	50-10	240-260
Semi volatile organic compound	SVOCs	240-260	380-400
Organic compound associated with particulate matter	POM	>380	---------

Voltaic organic compounds can be detrimental to human health. Some of the symptoms that are originated from volatile organic compounds can be mild like irritation of the nose or throat. Other researchers have found that VOCs have been linked to an increase in the prevalence of allergies across industrial countries [44]. A national survey was done in France to assess the effect of VOCs and found out that a high concentration of VOCs in homes was associated with an increased prevalence of asthma and rhinitis in adults. A high concentration of VOCs can cause serious illnesses, for example, elevated exposure to formaldehyde might lead to chronic bronchitis; also, the increased level of exposure to aromatic and aliphatic chemicals could lead to specific immunoglobulin; prolonged exposure to painting might lead to respiratory infections [45]. the most common types of VOCs found inside homes are listed in table (2-4). According to the EPA [38], the main symptoms of related high levels of VOCs are headaches, conjunctival irritation, nose or throat discomfort, allergic skin reaction, dyspnea, nausea or emesis, declines in serum cholinesterase levels, dizziness, fatigue, and epistaxis (mainly from formaldehyde). The health effect of exposure to VOC in a non-industrial building environment can range from sensory irritation at a low or medium concentration to toxic effects at high levels of concentration. Most occupants will experience these symptoms inside the building and once they are outside the building, these problems become less severe [46]. VOCs can cause neurotoxic, organ toxic, and carcinogenic effects. The parts of the body that would respond to VOC are; the mucus membrane of the eye, nose, and throat, the skin on the face, neck, hands, and upper and lower airways [43].

Chemical structure	Frequently detected compounds
Alkanes	n-hexane, n-decane
Cycloalkanes and alkanes	Cyclohexene, methyl- Cyclohexene
Aromatic hydrocarbons	Benzene, toluene, xylene, 1,2,4-trimethylbenzene
Halogenated hydrocarbons	Dichloromethane;1,1,1-trichloroethane,trichloroethane, tetrachloroethene, 1,4-dichlorobenzene
Terpenes	Limonene, alpha-pinene, 3-carene
Aldehydes	Formaldehyde, acetaldehyde, hexanal
Ketones	Acetone, methylethylketone
Alcohols, alkoxyalcohol	Isobutanol, ethoxyethanol
Esters	Ethylacetate, butylacetate, ethoxyethylacetate

Table 2-5 chemical structure of common VOCs [44]

The emission of VOCs could be from various materials and household products. These materials could be paints, ink, plastic parts, lacquers, adhesives, cleaning products, personal products (such as scents and hair sprays), and solvents. VOCs could also be found in wood adhesives and wood coating, plastic part coating, fabric coating, cabinet, countertop lamination, furniture, Building materials and home furnishings, motor vehicles, and repair shops [44] table (2-5) lists some of the common VOCs along with their emission in indoor air. It is important to investigate the effect of VOC because of several reasons. The first Is that there are many individual compounds that might be complicated when they get mixed with other VOCs inside the indoor space. Second, the concentration of VOC indoors exceeds the concentration outside. Third, some VOCs could be toxic for the occupants. VOC detected indoor air is mostly belong to nine groups of compounds. Most of the VOCs are originated from solvents, formaldehyde, and acetaldehyde [47].

Table 2-6 examples of sources of VOCs, their emission characteristics and emitted VOCs [47]

Sources	Duration of emission and characteristics				Some examples of emitted VOCs
		days – weeks	hours – days	minutes – hours	
Building related materials					
Carpets	**R**				**Solvents, 4-phenyl cyclohexane**
Wood products	**R**				**Terpenes, aldehydes, wood preservatives**
Vinyl floor	**R**				**Solvents; 2,4,4-trimethyl; 1,3pentanediol diisobutyrate; ethyl hexanol**
Human related sources activity					
Smoking			**I**	**I**	**Aldehydes, benzene, nicotine**
Cleaning			**I**	**I**	**Solvents, limonene**
Painting		**I**	**I**	**I**	**Solvents, aldehyde**
Appliances				**I**	**Solvents, aldehyde**
Equipment sealing and glueing		**I**	**I**	**I**	**solvents**
Outdoor sources					
Traffic	**R, I**	**R, I**	**R, I**	**R, I**	**Aromatic hydrocarbons**

R= regular emission I= irregular emission

2.7.3 Pollutants originating from combustion

The pollutants that are originated from the process of combustion is significant to the health of the occupants. Aside from the pollutants that are originated from tobacco smoking, they could come from various sources such as wood stoves, unvented kerosene, and gas space heaters, fireplace, and gas stoves [38]. In addition, outside sources are also significant such as motor vehicles [47]. Some of the pollutants that could originate from the combustion process are PM and gaseous pollutants. Gaseous pollutants include: carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) [47]. Particulates, on the other hand, are emitted into the air when the fuel in the combustion is not burned completely or (incomplete combustion) [38].

2.7.4 Carbon monoxide (CO)

According to McCann et al [48], Carbon monoxide is a colourless, odourless, and tasteless gas that is the result of the incomplete combustion of carbon fuels. In England and Wales, between 2006 and 2011 around 40 people have died from the exposure of CO, and over 200 are admitted to hospital each year from accidental CO poisoning, in addition to that, 4000 are said to be infected each year but are not admitted to the hospital. McCann et al [48] have reported that these figures might underestimate the real number of people infected with CO exposure due to the fact that many people are thought to be exposed to CO and suffer from CO poisoning but remain undiagnosed, and in some occasions, they have symptoms that are non-specific. This gas may cause a variety of symptoms that are derived from the combination of CO with haemoglobin that forms carboxyhemoglobin (COHb). COHb can hinder the flow of oxygen transport to the cells. Its effect is prominent in tissues that have high oxygen needs like the brain, muscles, and myocardium. According to Pollard et al [49], CO can result in tissue hypoxia due to its higher affinity to haemoglobin as compared to oxygen., Exposure to high levels of CO can lead to neuropsychiatric damage which can be lethal in some cases. Furthermore, carbon monoxide can affect the body in both low concentrations and high concentrations. At low concentration, it could cause headaches, dizziness, weakness, nausea, confusion, and disorientation. The portion of the demographic who are affected the most by CO are the elderly, children, and people with chronic anaemia of heart disease [38].

2.7.5 Nitrogen Dioxide (NO_2)

Nitrogen dioxide is a colourless, odourless gas that irritates the mucous membranes in the eye, nose, and throat and causes shortness of breath after exposure to high concentrations. Several studies show nitrogen dioxide at prolonged exposure at low concentrations could lead to respiratory infection. Moreover, studies of animal subjects reveal that repeated exposure to elevated levels of NO_2 can cause lung diseases such as emphysema. Children and people with asthma are affected the most [38]. Some studies of asthmatic patients have shown that there is a positive connection between NO_2 concentration and respiratory symptoms including wheezing, breathing difficulty, shortness of breath and cough, and chest tightness. NO_2 is generally generated from the combustion of gas fuel for cooking and heating appliances. Some sources for NO2 are Kerosene heaters, and unvented gas stoves [37].

2.7.6 Radon

The United Kingdom of Health and Safety Executive defines radon as "a naturally occurring radioactive gas that can seep out of the ground and build up in houses and indoor workplaces" [50]. Radon is sometimes concentrated in higher amounts in homes that are built on top of soils that are rich in radon [38]. The gas could seep through small open cracks of the building like construction joints, gaps in foundations around pipes, pumps, or wires [51]. Many studies have shown that exposure to radon at any level could cause lung cancer. In fact, radon has proven to be the second cause of lung cancer subsequent to tobacco smoking [37]. According to the Health and Safety Executive [50] usually, breathed radon gas is immediately exhaled and present little radiological risk, but occasionally the outcome of the decay from radon inside the body behave more like solid materials than gas and these solid particles are themselves radioactive. According to the EPA [52], Exposure to radon accounts for about 21,000 deaths from lung cancer each year. Similarly, in the United Kingdom, approximately 1100 death occur each year due to lung cancer of which 85% of these deaths are at an indoor concentration of less than 100Bq/m3. Although, most of these deaths are a combination of cigarette smoking and radon exposure and only 7 of these deaths have confirmed to be caused by radon exposure alone, with six of them out of seven are attributed to smoking along with radon exposure [53].

2.7.7 Animal dander, dust mites, and other biological contaminants

A biological air pollutant is in almost every house, school, and workplace. Sources of biological contaminants include outdoor air, humans, pets, and indoor surfaces, and water reservoir where it is possible for fungi and bacteria to grow [38]. Relative humidity plays an important role in increasing the population of biological contaminants [38]. When the room has high levels of humidity, it insinuates the growth of mould and other biological contaminants. Another contributor to the increase of biological contaminants is the HVAC system. The HVAC system could serve as an incubator for biological contaminants. This could happen when the HVAC system is situated near areas where there is significant exposure to biological contaminants such as standing water, organic debris, or bird dropping. The HVAC system itself could house biological contaminants in some parts like the humidifier, cooling coils, or the condensate drain pans. Likewise, dust and debris may also be captured in the duct system or mixing boxes of the air handler [38]. Contaminants from biological agents could cause three types of human diseases. in some cases, they could cause infection where pathogens invade human tissue. In another case, it could cause hypersensitivity diseases where specific activation of the immune system would cause diseases. toxicities, where biologically produced chemical toxins cause direct toxic effects.

2.7.8 Pesticide

According to the Environmental Protection Agency, surveys have shown that 75% of households in the United States use at least one product of pesticide indoors. The most often products used are insecticide and disinfectants. Other studies have shown that 80% of people's exposure to pesticides occurs indoors and that measurable levels of up to a dozen pesticides have been found in the air inside their homes [54]. Other possible sources include contaminated soil or dust that floats or is tracked in from outside, stored pesticide containers, and household surfaces that collect and then release the pesticides [54]. Both active and inert ingredient in the product of pesticide contains organic compound and they could add to the amount of organic contaminant in the space. Exposure to high levels of cycloidian pesticides commonly associated with misapplication has produced various symptoms, including headaches, dizziness, muscle twitching, weakness, tingling sensations, and nausea. In addition, the EPA is concerned that cycloidians might cause long-term damage to the liver and the central nervous system, as well as an increased risk of cancer [54].

2.7.9 Biomass fuel

Many people around the world rely on heating devices to heat the house in the winter. Burning fuel is one of the ways that many people use to heat the house and some of these instruments use fuel like oil, biomass, and natural gas. However, biomass emits a considerable amount of PM and CO. In China, for example, indoor air pollution from biomass fuels is responsible for approximately 1,000,000 premature deaths annually, compared with the estimated 1,200,000 deaths to be caused in the country each year by outdoor PM pollution [37]. Strong evidence suggests that there is an increased risk of acute lower respiratory infections in childhood (at least 2 million deaths annually in children under the age of 5). Moreover, there is also evidence of an associated risk of developing Chronic Obstructive Pulmonary Disease (COPD), mostly for women, and with the risk of tuberculosis and asthma. According to The International Agency for Research on Cancer, they have classified the emissions from the indoor combustion of coal as a Group 1 carcinogen [37].

2.7.10 Mould and dampness

Humidity occurs naturally in every home from human activities. For example, cooking, showering, and washing are all sources of humidity inside the house. However, the percentage of relative humidity ratio must be kept at a certain level so that mould and fungi might not grow. Besides adequate ventilation, other actions, such as cleaning and gravitational settling, are also causing the microbe concentration to decrease. In addition, bacteria and fungi do not significantly grow under normal conditions. According to the European lung foundation [37], many energy efficient buildings contain mould which is indicative of the airtightness that leads to increased levels of humidity. Many researchers argue that building materials themselves contain nutrients necessary for microbial growth. Not all building materials have the same nutrients for fungal growth [37]. Moulds are a source of allergens, mVOCs, and mycotoxins. According to Mendell et al [55], Some meta-analyses studies have shown that there is a strong correlation between dampness/mould and increases of approximately 30–50% in respiratory and asthma-related health outcomes, including current asthma, ever-diagnosed asthma, upper respiratory tract symptoms. The authors also concluded that there is an association between indoor dampness-related conditions and some common respiratory or allergic health symptoms, including dyspnoea, wheeze, cough, respiratory infections, bronchitis, allergic rhinitis, eczema, and upper respiratory tract symptoms.

2.7.11 Particulate Matter

According to the EPA [56], the term PM is referred to a mixture of solid particles and liquid droplets that exist in the air. Some particles, like dust, soot, dirt, or smoke, are large enough to be visible by the naked eye, and others are so small they can only be detected by an electron microscope. Some researchers like Grau-Bove and Strlic [57]define particulate matter “as all the particles that can be found in the atmosphere, in other words, those that can be suspended in air and transported by it before they deposit”. The aforementioned definition includes particles composed only of several molecules, with diameters around 0.01 µm, all the way to coarse dust with diameters around 100 µm [57]. The effect of PM is dependent on their size.

In general, indoor airborne particles have two main sources which are indoor generated particle source, and outdoor particles transported from the outside [58]. Other sources of PMs are cleaning, ventilation, cooking, dust coming from outside of the building like furniture material, consumer product, occupants' activities, and automobile [59], [60], & [61]. Sousa et al. [62] have reviewed several studies in regards to PM_{10} and $PM_{2.5}$ concentration in nurseries and primary schools from 2008 until 2012 and discovered that; 1) the average PM concertation worldwide is higher than the recommended level by the national legislation and World Health Organization (WHO); 2) indoor/outdoor ratios were several times higher than 1, and 3) PM concentrations were reported as mainly due to constant re-suspension of particles.

The significance of studying PMs for indoor air quality is due to their effect on human health and their ubiquity. According to Nadali et al [58] Inhalation of these particles, containing-allergen is related to adverse impacts on human health. Many studies have shown a link between daily exposure to ambient fine and ultra-fine particles with an increase in cardiovascular mortality and hospitalization. In other studies, it shows an increase in mean systolic and diastolic blood pressure in both young and elderly adults due to long-term exposure to PM2.5 [58]. Years of research have concluded that all combustion-derived PM are inflammatory to some extent in the lungs. Wu et al [63] postulated that these findings would explain the strong association between PM and cardiopulmonary disease. PMs derived from biomass combustion poses a serious health concern in developing countries in which About 3 billion people in the world rely on burning biomass fuels for energy such as wood, charcoal, dung, or crop residues, in open stoves for cooking, heating, and lighting, etc [63]. Biomass fuel produces incomplete combustion containing PM which in turn produces many chemical substances like benzene, benzopyrene, and carbon monoxide. These substances could cause millions of annual premature deaths caused by lung cancer, ischemic heart disease, acute lower respiratory tract infections (ALRIs), COPD, asthma, and stroke [64]. A study addressing the health effects of exposure to indoor PM in the general population was conducted in Northern Italy, which concluded that indoor $PM_{2.5}$ was associated with the presence of acute respiratory symptoms and mild lung function impairment, especially among non-smokers [65].

To protect people from PM indoor air pollution exposure, national and international authorities have set up standards and guidelines. The PM concentration limit suggested by the World Health Organisation (WHO) and the European Commission for $PM_{2.5}$ is 25 µg/m^3 and the US Environmental Protection Agency has suggested a value of 13 µg /m^3 [66]. another example of PM guidelines is set by the Institute of Environmental Epidemiology, Ministry of the Environment of Singapore. which recommended the maximum concentration of 150 mg/m3 for PM10 as the limit for acceptable indoor air quality [67]. Of course, some standards will recommend guidelines for PM exposure over a period of time throughout the day. the first example is given by the Indoor Air Quality Management Group from Hong Kong. They recommend that the exposure limit for PM_{10} to be between 20 µg/m^3 for excellent condition and 100 µg/m^3 for a good condition over 8-h average in offices and public spaces, [68]. The second example is given by the World Health Organization that recommends PM guidelines for ambient air which are 25 and 50 mg/m^3 for PM2.5 and PM10, respectively over a 24-hour period [69].

2.8 Indoor air pollution generated from energy efficient technologies

Paraschiv Spiru et al, (2017) [70] have reviewed the literature on indoor air quality in energy efficient buildings and have found that indoor air pollution is emitted regularly from heating, and cooking. They argue that $PM_{2.5}$, SO_2, NO_x, NH_3, PAH, and VOCs are among the most important pollutants to measure in indoor air. They also argue that when buildings become more energy efficient due to the implementation of new regulations, it will affect the quality of the indoor air. According to Paraschiv Spiru et al, [70] ineffective ventilation is the primary factor that results in poor indoor air quality. This will lead to a higher concentration of indoor air pollution and higher levels of humidity.

A study was done by Esfand Burman et al [71] investigated the performance of eight new-build and newly refurbished. The eight buildings were from different sectors like Office buildings, Schools, Hospitals, and Apartment blocks that comprise different important sectors in the United Kingdom building [71]. This study was similar to other studies that investigated the performance gap of several buildings such; the low carbon building performance (LCBP) research conducted by the carbon trust, the building performance evaluation programme. They reported several studies that measured the indoor air quality in new energy efficient buildings and reported that some of these buildings have higher levels of VOCs like (benzene, trichloroethylene, and formaldehyde). they also reported that PM levels are very important to be controlled in low energy buildings because of a lack of filtration in some HVAC that has a lower air exchange rate. Figure (2.5) shows very high levels of CO_2 and VOCs in one of the offices that were monitored. The result shows that the CO_2 concertation of the building on the third floor is repeatedly higher than 1500 ppm due to the malfunctioning sensor. Complaints about excess heating and draft have led to the disconnection of the CO_2 trigger for motorized natural ventilation which led to the increase of CO_2 levels. It is clear from these data that the energy requirements were not compatible with the indoor environmental conditions optimal for the users inside the building. this could be also illustrated in figure (2.5) where it is apparent that the percentage of time the occupied zones within the case study buildings did not meet the recommended thermal comfort conditions and CO_2 concentration levels in heating season and summer. It is not just the indoor pollutant; other aspects of the indoor environment are affected as well. In figure (2.6) where it could be seen that in the apartment buildings (both apartment 1 and 2) the relative humidity, temperature, and CO2 concentration was optimised for the users. Another example is given in school 1 and 2. Both have similar issues with the apartment building [71].

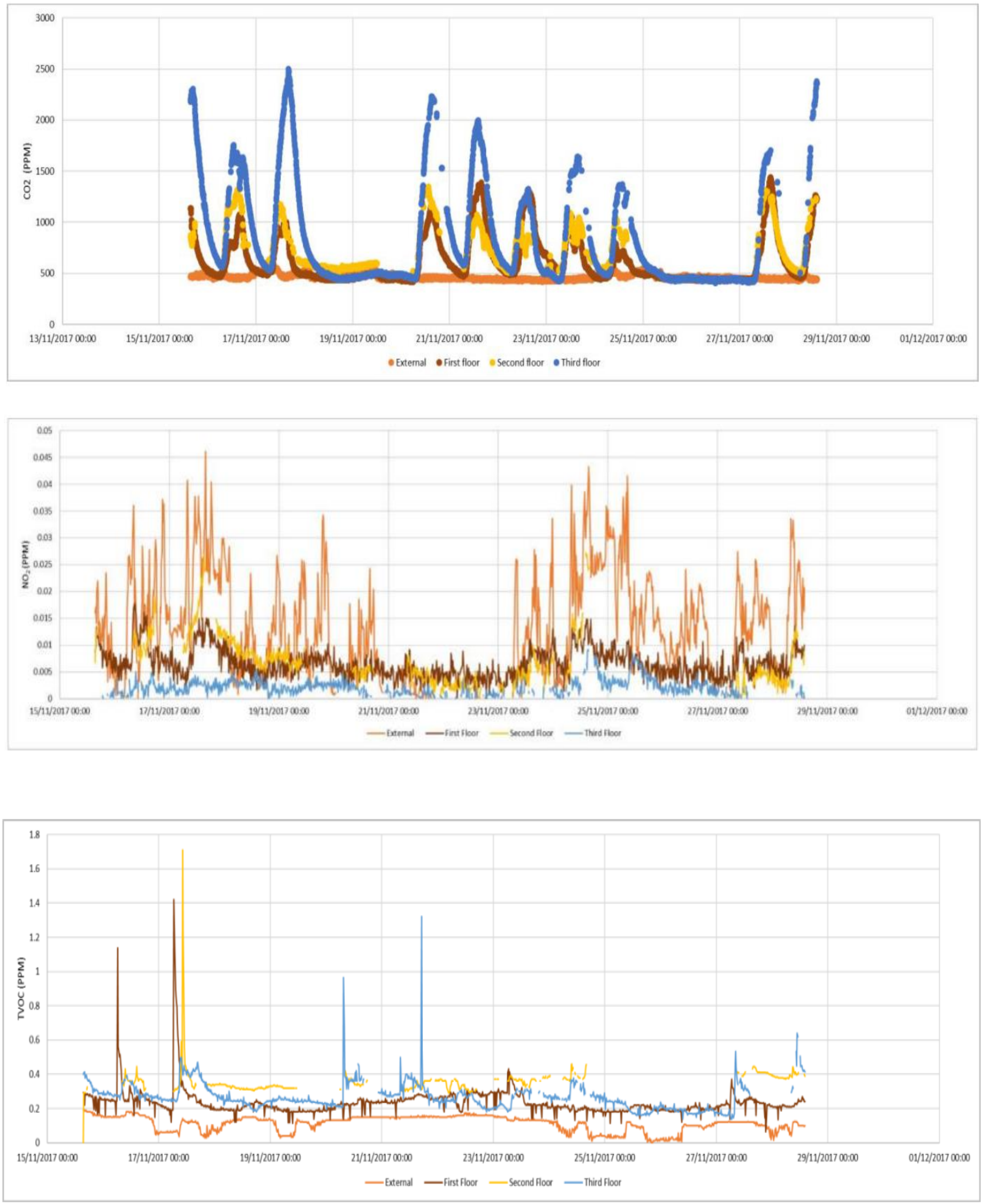


Figure 2-5 charts showing the levels of CO_2, NO_2, and VOCs inside the building [71]

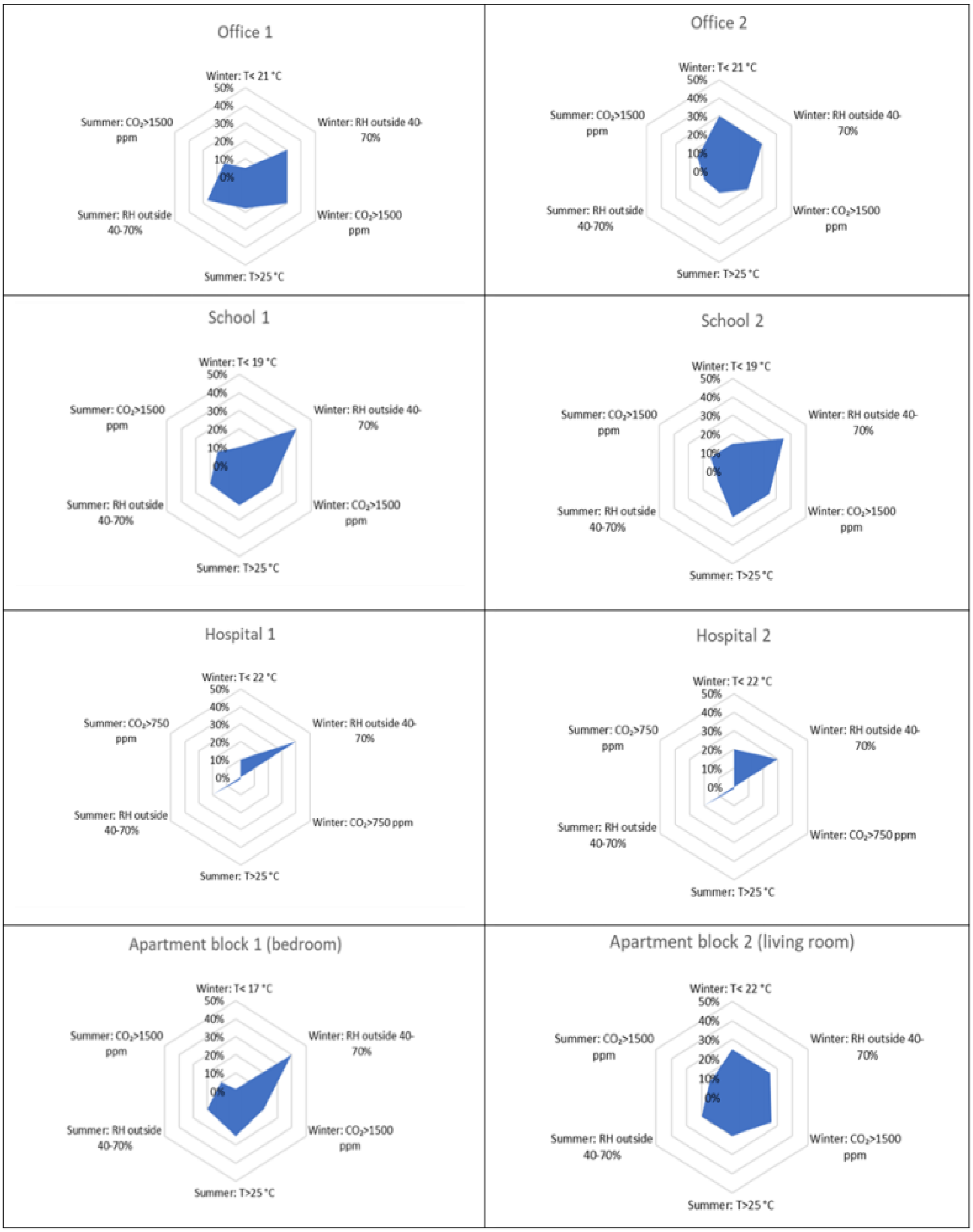


Figure 2-6 the percentage of time the occupied zones within the case study buildings did not meet the recommended thermal comfort conditions and CO_2 concentration levels in heating season and summer [71]

In a study by Liva et al [72] they assessed the indoor air quality of five educational institutional buildings table (2-6). All buildings are refurbished with major energy efficiency changes such as windows insulation, enhanced exterior envelope, and the installation of a new HAVC system. The result of the study has indicated that the measurement of indoor air quality inside the buildings showed high levels of CO_2 concentrations in energy efficient buildings as indicated in figure (2.8). The grey colours in the chart show the times when the CO2 concentration exceeded the adequate level during working hours. These measurements are especially prominent in two rooms: room E2, and room D1. In room E2 the level of CO_2 reached 2707 ppm. In room D1, the concentrations of CO_2 are repeatedly above 1000 ppm (95% of the working hour times) [72]. When tracer gas was used to detriment the rate of air exchange, the researchers found that the air exchange rate was kept too low between 0.33 and 0.57 to preserve energy. This could be seen in the tracer gas concentration. The researchers noticed that the SF6 gas concentration was increasing rapidly and decreasing which indicates that the complete air exchange happens only once every 3 hours in the room where the measurement was taken. Moreover, many buildings either had the HVAC system running inconsistently or not working at all.

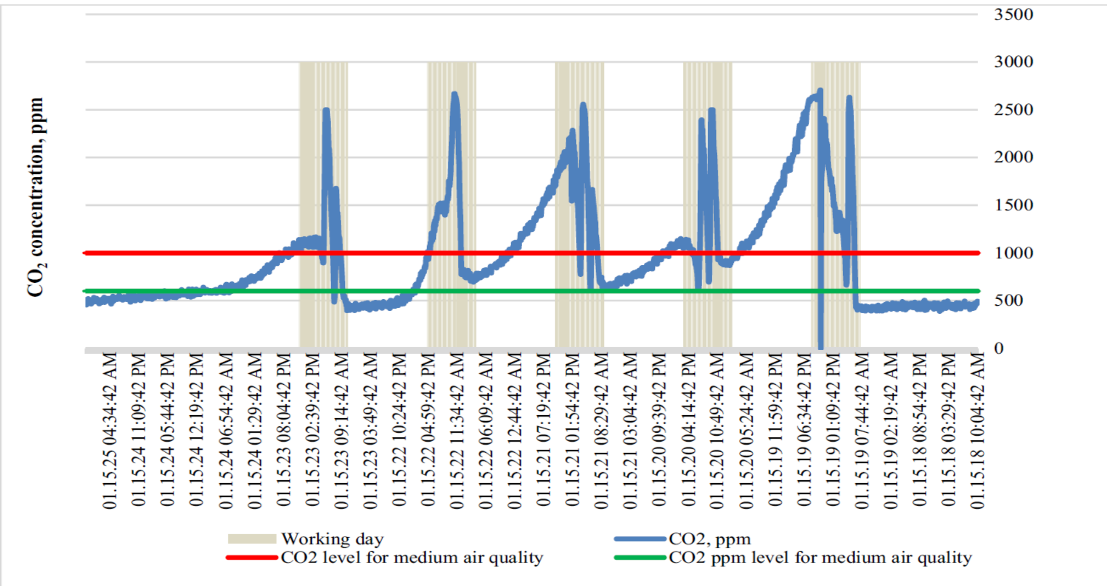


Figure 2-7 CO2 concentration [72]

Number of room	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	F1	G1	H1
CO_2 level exceeded time in working days 24h	7.7	8.6	3.6	10.9	3.7	2.6	21.8	2.5	2.25	11.9	4.7	1.1	0
CO_2 level exceeded time in working days 8:00-18:00	7.35	8.1	1.4	6.2	3.12	2.4	9.5	2.5	2.2	7.1	3.5	1	0
CO_2 max	2602	2690	1783	2674	2071	1515	2500	2128	2667	2708	1451	1507	891

Table 2-7 measurements taken from two rooms in each building. the data here shows the times when the CO2 exceeds 1000 ppm [72]

A recent study by Zohaib Shaikh et al [73] they investigated different kinds of air conditioning systems that could consume the least amount of energy while ensuring the best indoor air quality using the energy software simulation IES-VE's module ApacheSim ™. The systems that were simulated {hybrid cooling system, Variable Air Volume (VAV), Variable Refrigerant Flow (VRF). The building simulated was a mixed-used building made up of 59 stores with an area of 2731 m_2 and a height of 235 meters and. Figure (2.9) illustrates the comparison between the four systems in terms of energy consumption and CO_2 concentration. The first system they simulated was the Variable Speed Drive (VSD) which shows that the system reduces the amount of energy consumption by 8% and simultaneously improving the indoor air quality inside the building by producing acceptable CO_2 concentration and thermal comfort.

The second system was the Variable Air Volume (VAV) system that resulted in higher energy consumption, but it was the best system in terms of indoor air quality. The system had successfully improved the Predicted Mean Vote (PMV) at 0.66 and it also improved the CO_2 concentration from the baseline of 624.2 ppm to 559.5 ppm. The third system was the VRF which is a cooling solution that was proposed for reducing energy consumption by using varying refrigeration rates and recirculating the same air into the building. The system had achieved a 30% reduction in energy consumption. However, the CO_2 concentration resulting from this device was around the average of 3597.0 ppm. This is a very high level of CO_2 and it could prove detrimental to the health of the occupants. The last system was the mono-draught cool phase system which successfully reduced the energy consumption from the baseline by 22%. The system did manage to produce good indoor air quality by reducing the CO_2 concentration by 586 ppm. however, the (PMV) was 2.22 which is considered high compared to the other systems simulated figure (2.8) the reason is that the thermal battery could absorb heat greater than its capacity [73].

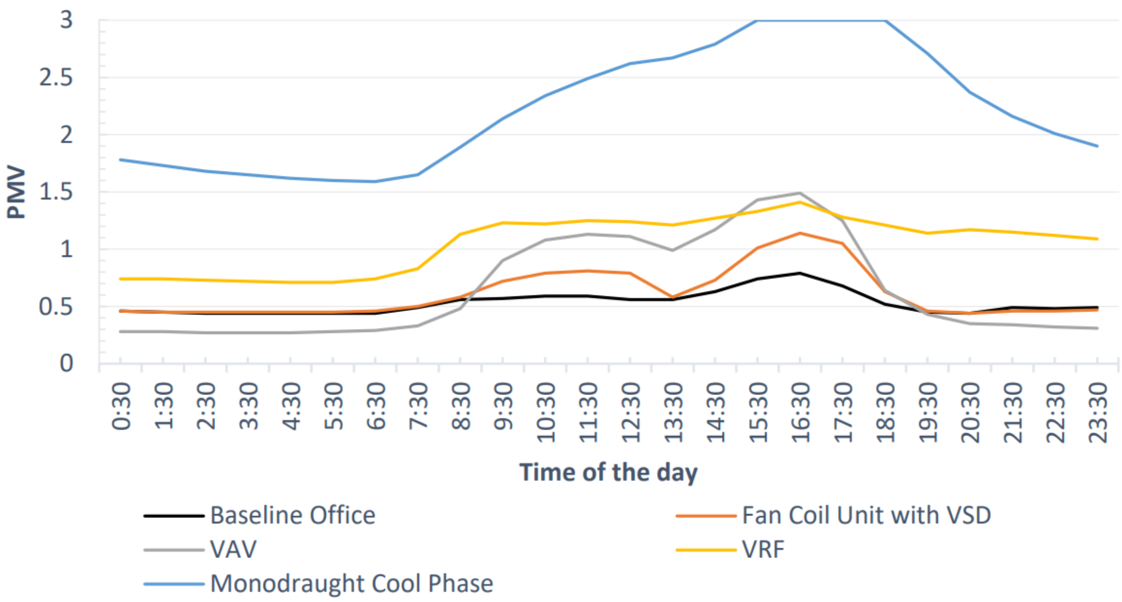


Figure 2-8 trend in PMV for different cooling systems [73]

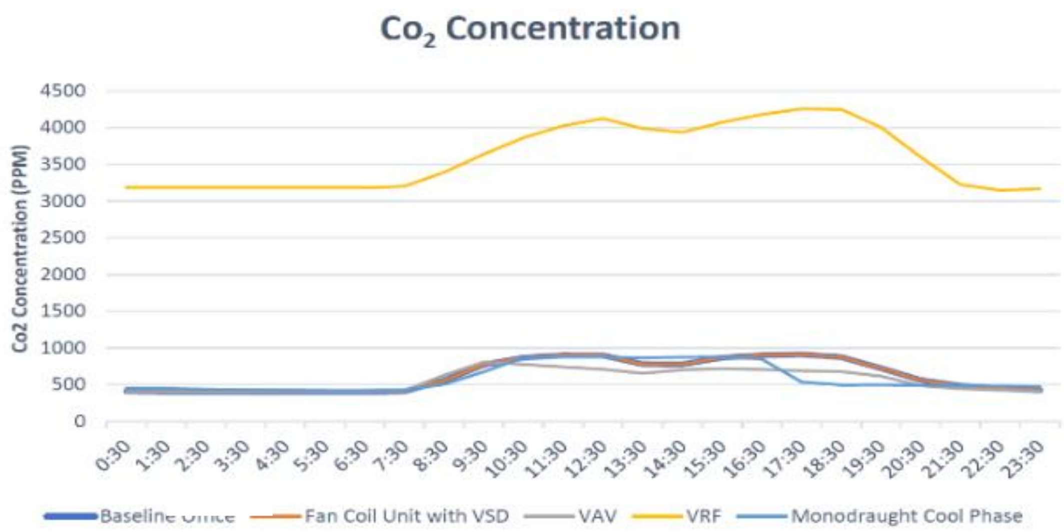


Table 15. Average CO_2 Concentration level for different cooling systems.

Model	Baseline FCU	Fan Coil Unit with VSD	VAV	VRF	Monodraught Cool Phase
CO_2 Concentration Levels (PPM) for Office Model	624.2	624.2	559.5	3597.0	586.0

Figure 2-9 comparing the co2 concentration in all systems [73]

A research study conducted by Derbez et al [74] evaluated the indoor air quality in seven energy efficient buildings in France. The survey was conducted during the pre-occupancy period and during the occupancy period. Forty-four VOCs and seven aldehyde compounds in ten families of VOCs were detected at least once. In the majority of cases, the number of these compounds varied between 20 and 35 per house. They have compared the pollutant concentration levels of several VOCs and found that three aromatic hydrocarbon compounds (ethylbenzene, m- and p-xylene, and 1,2,4 trimethyl benzene) aliphatic hydrocarbons, and n-decane were around 1.5 times higher in these new energy efficient buildings than other regular building across the nation. Hex-aldehyde and aldehyde have been also found in the newly built building and it is most likely related to the use of wood and particle board wood for the furniture [40], and [74]. $PM_{2.5}$ mass concentration never exceeded 30 µg/m^3 and the most consistent reading was between 6 – 28 µg/m^3. The researchers had confirmed that the concentration of $PM_{2.5}$ was higher in the winter compared to summer readings in houses A, B, C, and E but did not find the same pattern in house F. Radon was present as well in many houses like B, E, and D with D showing the lowest concentration. The range of radon concentrations was between 7 and 66 Bq/m^3.

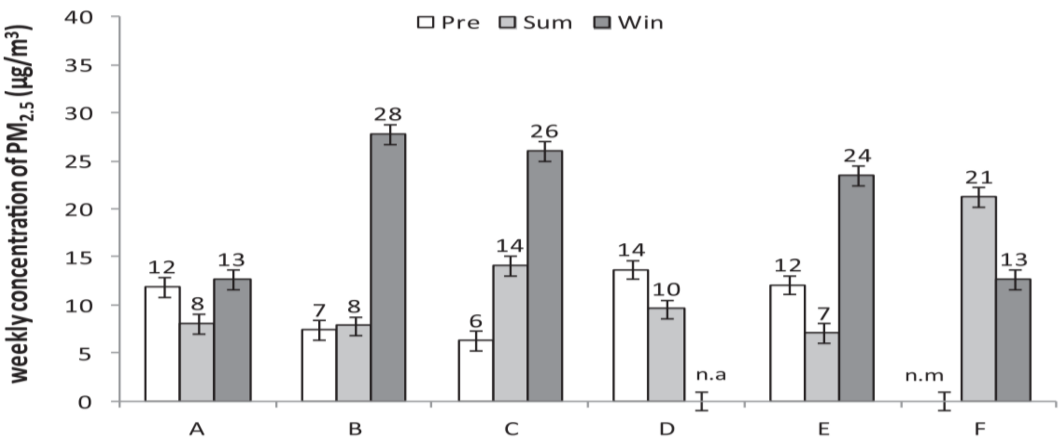


Figure 2-10 Weekly mass concentrations of PM2.5 (mg/m3) measured in the living room for six houses during the pre-occupancy stage (Pre) and during occupancy (summer: Sum; winter: Win). n.a.: not available; n.m.: not measured [74]

Table 2-8 Descriptive statistics of CO2 level (ppm), T (C) and RH (%) measured weekly in the main bedrooms of six occupied houses by season. (Sum: summer; Win: winter; P25: 25th [73]

House code		CO_2 (ppm)				T (°C)				RH (%)			
		Mean [min–max]	P25	Median	P75	Mean [min–max]	P25	Median	P75	Mean [min–max]	P25	Median	P75
A	Sum	695 [372–1840]	463	578	911	25.2 [23.2–27.1]	24.6	25.1	25.7	47.4 [39.2–57.9]	45.1	47.4	49.8
	Win	788 [378–1207]	684	811	883	20.5 [14.2–22.6]	20.0	20.5	21.0	30.8 [21.3–41.2]	28.4	30.0	33.0
B	Sum	381 [291–861]	314	351	413	24.2 [19.8–28.0]	23.1	24.2	25.4	46.3 [26.0–64.9]	42.7	46.2	51.4
	Win	722 [467–1257]	595	701	823	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
C	Sum	879 [366–1942]	501	656	1371	20.6 [19.3–25.0]	19.8	20.3	21.1	44.9 [33.2–53.4]	42.6	45.1	47.0
	Win	920 [415–1679]	586	778	1320	19.7 [16.8–26.7]	19.2	19.5	19.8	34.7 [24.1–41.2]	32.7	34.3	37.0
D	Sum	738 [331–1829]	367	449	1293	21.9 [18.7–25.1]	21.2	21.6	22.7	47.9 [38.2–59.4]	45.7	48.3	50.2
	Win	1013 [430–2030]	484	768	1654	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
E	Sum	451 [361–1229]	379	406	471	21.6 [17.9–23.2]	21.1	22.0	22.4	58.1 [34.4–75.9]	52.7	58.1	64.5
	Win	622 [360–1263]	475	573	701	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
F	Sum	504 [355–1032]	409	460	527	25.7 [24.6–27.2]	25.3	25.7	26.0	46.9 [36.6–62.1]	43.8	45.9	48.9
	Win	633 [415–1115]	521	642	705	21.8 [19.1–33.6]	21.1	21.6	22.2	30.5 [14.4–45.3]	27.9	29.3	33.2

The CO_2 levels are similar to VOC levels in which the highest concentrations were measured in the winter period and the lowest concentrations were measured in the summer period. The lowest concentrations of CO_2 were similar to the measured outdoor levels, and the highest levels were less than 2100 ppm Table (2-8) [74].

M. Derbez et al [75] did a study on indoor air quality in energy efficient buildings in 75 newly built and retrofitted buildings and compared them to available data from energy efficiency and European dwelling and the French housing stock. These buildings are built according to the national requirement of energy efficient buildings with 40-75 kWh/m2/year for the new buildings and 64-120 kWh/m2/year for refurbished buildings. The measurements were taken in both heating and non-heating season. They have found that the concentration of alpha-pinene was higher in the masonry-built buildings (median= 44 µg/m3) and lower in the brick buildings (median= 10 µg/m3). In addition, alpha-pinene is also very high in areas under the insulation used for the attic that uses natural fibre materials (wood fibres, and cellulose fibres) (median= 64 µg/m3) compared to other apartments that do not use this type of material (median= 15 µg/m3). Lastly, alpha-pinene is higher in wood furnished bedrooms (median= 26 µg/m3) than other bedrooms with different furniture material (median= 17 µg/m3).

Another study by Perret et al [76] measured the presence of VOCs in 169 energy-efficient dwellings in Switzerland they investigated the influence of different building characteristics on indoor VOCs. They identified 74 compounds like carbonyls and alkanes. The median formaldehyde concentration levels were (14 µg/m3), as for the TVOC, the median level was around 212 µg/m^3. The median levels of benzene were less than 0.1 µg/m^3. Finally, toluene's median level was around 22 µg/m^3. These concentrations were less than the upper exposure limits. When comparing retrofitted dwellings with newly built energy efficient dwellings, they found that 90% and 50% of dwellings have surpassed the chronic exposure limits for TVOC at 200 µg/m^3, and for formaldehyde at 9 µg/m^3, respectively. According to Perret et al [76], these findings strongly suggest that there was a strong possibility that these detected VOCs were likely to originate from common sources. The researchers suggested that Interior thermal retrofit solutions and the absence of a mechanical ventilation system were most likely the reason for the elevated levels of formaldehyde, aromatics, and alkanes. In general, energy-renovated dwellings had higher concentrations of certain VOCs compared with new energy efficient built homes. The results suggest that energy efficiency measures in dwellings must take into account the strategies to abate the sources of VOCs exposures in order to avoid adverse health outcomes.

Kauneliene et al [77] investigated The indoor environment in 11 newly built low energy residential buildings in Lithuania. The thermal comfort in some of the buildings was not ideal like for example in house numbers B6 and B11 where the indoor temperature exceeded 28 C for three to five hours over a period of one week. This clearly shows that the design of these energy efficient buildings does not provide the best thermal conditions inside the building and could not regulate the temperature inside the building during warm seasons, once the outdoor temperature exceeds 30 C. The researchers had attributed the indoor air quality problems to the less than efficient air exchange which was between 0.08 and 0.69 ACH. However, even though the ventilation rate was insufficient, this does not show in some other indoor pollutants reading like CO_2. The CO_2 levels were within recommended threshold values. The mean concentration of CO_2 among buildings ranged from 439 ppm (B5) to 1117 ppm (B2). The concentration does increase in some cases like in building B2 where the concentration of CO_2 exceeded 1000 ppm 35% of the measured time, and two times exceeded 2000 ppm. the researchers explained that the lower concentrations of CO_2 might be attributed to the large floor area of the building that ranged between 30-70 m^2/occupant. Lastly, the concentration of formaldehyde was higher than the countries acceptable standards. the levels of formaldehyde ranged from 3.3 µg/m^3 in building (B10) to 52.3 µg/m^3 in building (B7) with an overall measured median value of 30.8 µg/ m^3. Therefore, the concentration of formaldehyde exceeded the Lithuanian national standard limit daily value of 10 µg/m^3 in all buildings, except in the unoccupied building (B10). However, some would argue that these figures are not high when compared to other standards. According to Kauneliene et al [77], the Lithuanian standard limit daily value is very low. In comparison with the WHO guideline exposure threshold values which is 100 µg/m^3.

In a study done by Vasilyev et al [78]. They have measured the levels of radon concentration and the rate of ventilation in five apartments located in different multi-story dwellings between the period from 2010 to 2013 in Ekaterinburg. The buildings were constructed in the period between 2007 to 2012. Each of the buildings was built according to the suggested specification of the energy efficient buildings that were recommended by the Russian Building code. The results show that there is a considerable amount of concentration of radon in modern energy efficient buildings compared to other types of buildings. According to Vasilyev [78], the increasing demand for energy efficiency led to the reduction in the average ventilation rate in urban dwellings using modern technologies. Thus, explaining the high rise in radon concentration. Another study in Hungary [79] took Continuous measurement of indoor air quality in 10 locations in Budapest, focusing on temperature, humidity, radon, and CO_2 concentration. In this research, the results have shown that the level of radon in the living area of the energy efficient family home was significantly high, especially if there was no automated heat recovery ventilation (HRV) unit installed. The radon level was as high as 500 Bq/m^3, in comparison to the working HRV measurements of 110 Bq/m^3 [79].

In the UK a study was done by Yu and Kim [80] where they reviewed the background information pertaining to low carbon buildings in the United Kingdom. Four energy efficient houses were built. Two buildings were designed according to level 5 sustainable homes requirement by the UK government and the other two were Swedish style homes which have exceeded the level 5 requirement of sustainable homes. Keeping in mind that these buildings were not occupied for the majority of the time and the measurements were compared to the national average of 876 homes in the United Kingdom. The two Swedish homes have shown very high concentrations of VOCs in the first year that is near the 95 percentile of the mean values found in the survey done at the national level of English homes. The concentration was initially 9700 µg/m^3 during the first year and in the second year, it went down to 635 µg/m^3 and after 18 months it reached the acceptable levels of 200 µg/m^3. However, this value is very similar to regular occupied English homes. These levels were maintained for the following seven years which according to the authors shows the ineffectiveness of the HVAC systems to dilute some of these pollutants. The main pollutants found in these two buildings were (2,2,4-trimethyl-1,3pentanedoil mono-isobutyrate). The other two homes were similar to the Swedish homes in terms of TVOCs concentration in which it started very high in the first year and then gradually declined. It is worth noting the buildings contained low emission particle wood board which allowed the buildings to have a lower concentration of formaldehyde. Levels were very low in the autumn season around 50 µg/m3 but it did rise to 100 µg/m3 which is higher by 22 µg/m3 compared to the national survey of English homes [80].

Contrary to the previously mentioned studies, some other studies have argued that the indoor air quality in energy efficient buildings is better than conventional buildings. The first study was conducted by Yang et al [81] they investigated a large sampling of 650 random energy efficient homes in western Switzerland with and without Minergie certification. Among them, 33% (217 out of 650) from the Minergie labelled (a green-certification) buildings (M), while the rest of the 433 buildings were energy-renovated (R) homes which benefited from the national energy renovation project for buildings. the researchers did a survey questionnaire and field measurements of total volatile organic compounds (TVOC) radon, formaldehyde and fungi. The results indicated that 90% of (M) homes used renewable and low carbon energy sources for space and water heating. In comparison, only 40% of (R) homes Used low carbon technologies for space and water heating. The field measurement showed that the concentration of (M) homes was lower than the (R) in general. The radon concentration was 48 Bq/m^3 in the (M) homes compared to 91 Bq/m^3 in the (R) homes. Likewise, the TVOC in the (M) homes was 167 µg/m^3 compared to 259 µg/m^3. The formaldehyde was 12 µg/m^3 in the (M) homes compared to 15 µg/m^3 in the (R) homes and fungal in the (M) homes was 33 colony forming units (CFUs) compared to colony-forming units 48 CFUs in the (R). the researchers revealed that the (R) homes were relying on natural ventilation. On the other hand, the (M) homes were designed to utilise mechanical ventilation. The second study is by Langer et al [82] who conducted an indoor air quality investigation in 20 passive houses and 21 conventional newly built buildings in Sweden. This study has focused on three aspects 1) comparison of indoor climate and pollutant concentration between the two different buildings, 2) compare the results with other Swedish buildings, 3) study the seasonal variation in indoor air quality in five passive houses. The result of this study showed that the indoor air quality in passive houses is comparable and sometimes better than a newly built conventional building. The passive house has also significantly lower relative humidity and the formaldehyde was also significantly lower. Furthermore, the TVOCs in conventional buildings were higher than energy efficient buildings. The third study is by Peter Wallner et al [83] they compared energy-efficient buildings fitted with a controlled ventilation system (including heat recovery systems) to conventional houses that were not fitted with mechanical ventilation. The two buildings were built at the same time. The study demonstrated that the indoor air quality in energy-efficient new houses is better than conventional buildings. The fourth study was conducted by Junghans et al [84] where they have analysed the performance of sophisticated automated HVAC systems in an energy efficient building and found out that modern HVAC systems could provide human comfort and an adequate level of indoor air quality. Finally, the results show that the energy efficient buildings automation system for automated natural ventilation reduces the energy demand for heating and cooling significantly.

The transition to low carbon building has been in the making of the new building sector in the European Union. According to Kylili & Fokaides [85], twenty-five cities in the EU are set to be at the forefront of the transition into low carbon economy by 2020. In order to achieve that, the SET-Plan funds for Zero Energy Building (ZEB) is allocating large funds to support the inclusion of renewable energy sources into these buildings [85]. These initiatives are geared toward the use of renewable energy sources for domestic heating and cooling. It is estimated that half of all the heating and cooling demand will rely on renewable energy sources. The suggested technologies are biomass, geothermal heat pumps, solar thermal heating and cooling, and district and local heating. In particular, biomass which is considered to be the most popular renewable energy source to be used, and also contributes considerably to zero energy buildings [85].

In a review study by Noam Bergman & Nick Eyre [86], they suggested that in order to reduce emission, there are several approaches, the first one to consider is thermal insulation, followed by energy efficiency, then microgeneration as a renewable energy source. The use of the term microgeneration is most commonly used in the UK. It refers to the small-scale production of electricity and heat from the same apparatus with the use of a prime energy source. Microgeneration includes many technological elements such as micro wind power, photovoltaic cells, biomass and micro combined heat and power, ground source heat pumps, and solar thermal heating [86].

The importance of microgeneration was also illustrated in another review study by Caird & Roy [87]. According to the authors, installing microgeneration systems into as many newly built houses as possible and refurbished houses is a government strategy to increase the percentage of renewable energy sources (biomass stoves and boilers, heat pumps, solar thermal hot water systems, and micro-CHP technologies) in the UK from 6.5% by 2030 to 15% by the year 2050. In addition, in the same study, the authors have also reported that there are as many as 95,000 microgeneration installations that were made in the UK among them 90,000 solar hot water systems, around 2,000 installations of ground source heat pumps, and from 500 to 600 installations of biomass boilers [87].

Some studies have suggested that using some of these technologies might harm the occupant of the building. for example, According to Yang et al [88], biomass is described as an organic material with chemical energy content and it is made of a variety of agriculture, forestry resources, municipal solid urban wood, and industrial residue. The aforementioned study by Yang et al [88], was made to study the Emission Factor (EF) of particulate-bound PAHs exhausted from two types of industrial biomass boilers. Additionally, the researchers also studied the PAH (EF) from one industrial coal-fired boiler were for comparison. The study has shown that the total EFs of PAH emitted from the boilers ranged from 0.0064 to 0.0380 mg/kg with an average of 0.0225 mg/kg. In addition, benzo (a) pyrene (BaP) from the tested biomass fuels were 0.86 $\mu g/m^3$ from the first boiler that uses wood pellets, 0.38 $\mu g/m^3$ from the first boiler that uses straw pellets, and 1.24 $\mu g/m^3$ from the second boilers that used wood pellets. When compared to coal-fired boilers, the total PAH EFs for the tested coal-fired boiler was 1.8 times lower than the average value of biomass boiler. the researchers had concluded the difference in the values between PAH (EFs) for biomass and coal is attributed to the difference in the volatile contents of the fuels. For example, wood pellets have a volatile content of 75.8%.

Likewise, straw pellets have a volatile content of 57.0% while coal on the other hand has only 31.4%.

Another study was conducted by Li et al [89] where they studied the emissions from two different size biomass boilers with wood pellets as the main energy source. The first was the smaller-scale biomass boiler (SBB) that generates (210 KWh). The second was the medium-scale biomass boiler (MBB) that generates (1.4 MWh). Table (2-9) shows the nitrogen dioxide emission from the two boilers. From looking at table (2-9) it is inferred that the potential for biomass boilers to emit NO_2 can range from 284.57 mg/m^3 in the (SBB) to 338.12 mg/m^3 in the (MBB) depending on the amount of Oxygen supplied during the bringing process [89].

In the literature review done by Demirbas [90], the authors have mentioned that during incomplete combustions, biomass fuel could emit several types of pollutants like particulate matter, carbon monoxide, nitrogen oxides, sulfur oxides, Acid gases, polycyclic hydrocarbons, and volatile organic compound. In addition, some studies have shown that when researchers analyzed the some emitted from biomass combustion, they found that it contains 400 types of VOCs in the form of alcohols, carbonyl esters, lactones, phenols, PAH, acids, and other types of VOCs [90].

<table>
<tr><th>Operating condition</th><th>Primary air supply (m^3/h)</th><th>Secondary air supply (m^3/h)</th><th>Secondary to primary air flow ratio</th><th colspan="4">total Primary to total airflow ratio</th><th>Air excess</th><th>Nitrogen oxides emission</th></tr>
<tr><td>SBB-1</td><td>300.00</td><td>0.00</td><td>0.00</td><td colspan="4">1.00</td><td>1.17</td><td>284.57</td></tr>
<tr><td>SBB-2</td><td>300.00</td><td>120.00</td><td>0.40</td><td colspan="4">0.71</td><td>2.04</td><td>116.57</td></tr>
<tr><td>SBB-3</td><td>300.00</td><td>150.00</td><td>0.50</td><td colspan="4">0.67</td><td>2.26</td><td>187.89</td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="4"></td><td></td><td></td></tr>
<tr><td>MBB-1</td><td>2808.00</td><td>648.00</td><td>0.23</td><td colspan="4">0.81</td><td>2.75</td><td>253.10</td></tr>
<tr><td>MBB-2</td><td>2196.00</td><td>648.00</td><td>0.30</td><td colspan="4">0.77</td><td>2.09</td><td>222.74</td></tr>
<tr><td>MBB-3</td><td>1440.00</td><td>648.00</td><td>0.45</td><td colspan="4">0.69</td><td>1.27</td><td>205.36</td></tr>
<tr><td>MBB-4</td><td>1260.00</td><td>648.00</td><td>0.51</td><td colspan="4">0.66</td><td>1.07</td><td>338.12</td></tr>
<tr><td colspan="2">MBB-5</td><td colspan="2">1440.00</td><td>360.00</td><td>0.25</td><td>0.80</td><td>0.96</td><td>154.99</td><td></td></tr>
<tr><td colspan="2">MBB-6</td><td colspan="2">1440.00</td><td>180.00</td><td>0.13</td><td>0.89</td><td>0.76</td><td>148.14</td><td></td></tr>
</table>

Table 2-9 Nitrogen oxides emission from the two boilers

Some studies have investigated the effect of CHP generators. The first study was conducted by Ricardo Energy & Environment [91] they have gathered information about the effect of CHP in five boroughs in Lonon the United Kingdom (Camden, Enfield, Kensington, Chelsea, Southwark Westminster). They investigated 375 CHP cites and measured PM, Carbon Dioxide (CO_2), and Nitrogen Dioxide (NO_2). Table (2-10) shows the different pollutants emitted from these CHP generators. In their report, they have demonstrated that the application of CHP in the Great London Area (GLA) has proposed some problems to the local community in terms of air quality. The researchers suggested that the use of gas fire CHP should be reconsidered and that is because the effect of CHPs can affect not only the neighbouring air quality. But also, the indoor air quality inside the building close to these generators. A possible solution could be in the abatement method which requires that all CHPs be fitted with a filter that would filter out the pollutant air emitted. The manufacturers are installing catalytic systems for CHP generators that are below 100 mg/Nm^3. However, the researchers have discovered that the performance of an individual plant will depend on how it is designed, operated and maintained. The evidence from the measurements of systems in the field revealed that the actual real-world performance of plants can be varied and that the optimum performance may not be achieved in practice [91].

Table 2-10 estimations of the Emissions to air from the CHP plant identified [91]

Borough	Calculated emissions (Tonnes/year) of :		
	Oxides of nitrogen	Particulate matter	Carbon dioxide
London Borough of Camden	563	3.29	46,174
London Borough of Enfield	203	1.66	34,365
Royal Borough of Kensington and Chelsea	168	1.08	17,568
London Borough of Southwark	638	4.69	88,436
London Borough of Westminster	959	5.22	64,212
Total for five boroughs	2,532	15.95	250,755

Another study by the Cambridge Local Plan [92], stated that CHPs must be cautiously used due to their air quality impact. They have also stated that Biomass CHPs may not be supported under the Air Quality Management Area (AQMA). The researchers realized that the CHP's effect on the air quality is dependent on many factors such as flue design, emissions, size and type of plant, and dispersion, and the availability of abatement equipment installed. The report discussed two major types of prime movers for CHPs. The type of prime mover can be significant to the air quality of CHP. The most common gas-fired CHP available is either the internal combustion engine or the turbines engine. When comparing the two it appears that the gas turbines produce the lowest emissions and are the most electrically efficient of the two. Because gas turbine produces much less NO_x emission it is unlikely that they would require an abatement system. The combustion engine, on the other hand, has higher NO_x emissions and should be specified with lean burn technology [92].

Another study by Tong et al [93], investigated the effect of a biomass-fueled combined heat and power system equipped with an Electrostatic Precipitator (ESP) in Syracuse, New York. They installed two sampling stations at the top of two rooftops. The sampling stations were equipped with $PM_{2.5}$ and CO_2 analysers in which one could capture the plume while the other one served as the background for comparison depending on the wind direction. The result from this study suggested that with the absence of an ESP a near 7 times increase in near-source primary $PM_{2.5}$ concentrations with a maximum concentration above 100 µg/m^3 at the building rooftop. In addition, some above-ground "hotspots" can present potential health to the people residing around this area. The research also suggests that since particulate matter could penetrate inside buildings through infiltration and fresh intakes, it is important for CHPs to be equipped with emission control for biomass combustion in populated urban regions. the wind has played a role in spreading the emissions of CHP in the region and it was found that in the direction of the prevailing wind, the maximum ground-level concentration was around 35 µg/m^3, and at the rooftop-level concentration had exceeded 100 µg/m^3. These concentrations can cause health problems to building occupants by infiltration into the building either by windows or HVAC systems. In addition, higher wind speed allows the plume to travel closer to the ground and, therefore, increasing the near ground concentration. raising the stack temperature could create more air buoyance and causes the plume to travel higher from the ground, and vice versa [93].

A study was conducted by Petrov et al [94]. They evaluated the emissions of a microturbine-based CHP Integration Test System that is located at the Oak Ridge National Laboratory (ORNL). The (ORNL) had tested the emissions of the microturbine-based CHP test system (gas microturbine paired with heat recovery systems) to determine emissions output for both steady-state and transient operations of a microturbine-based CHP system. The steady-state tests measured the emissions at different microturbine power output levels and different air inlet temperatures. The transient tests measured the emission levels as the microturbine power output was varied during start-up and changed from one output level to another during power dispatching. Figure (2.11) demonstrates the level of emissions that correlates to the power output. When operating at full power the 30-kilowatt microturbine produces 30 $ppmV_{15}$ (41 mg/m3), V_{15} refers to combustion at 15% oxygen, of carbon monoxide, 0.6 $ppmV_{15}$ (1.5 mg/m3) of sulfur dioxide, and 4 $ppmV_{15}$ (8 mg/m3) of nitrogen oxides. The researchers of this study came up with several conclusions that describe the nature of CHPs emission in regards to their operational capacity. The CHP has been tested at different power settings starting from a third-load of the power output to full-load power output. The first conclusion shows that when operating at full power, the microturbine produces the lowest emissions of air pollutants like CO, SO_2, NO_x. the second conclusion is that even at the highest SO_2 concentration dewpoint is not reached. The third conclusion was that when reducing the power level of the microturbine, the cumulative emission reached a higher level than at full power of primary emissions like CO, SO_2, NO_x. The highest measured CO levels reached was between 440 – 500 ppm V_{15} at low power output levels between 16 – 20 Kilowatt.

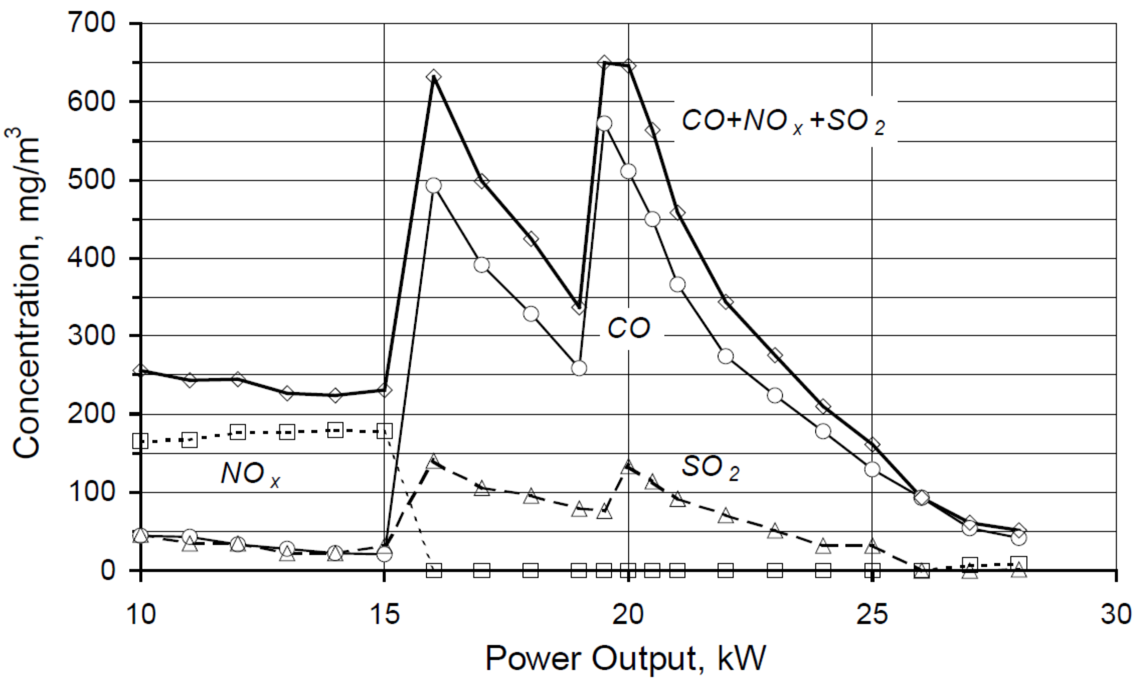


Figure 2-11 Concentration of CO, NOx, and SO2 (mg/m3) Versus Microturbine Power Output [109]

A study done by Dascalakia et al [95], evaluated an existing Hellenic school building stock in terms of energy performance and construction characteristics. All new building owned by the public sector were required to be nearly zero-energy buildings. The government was hoping to achieve this goal by implementing new technologies like on-site energy production using combined heat and power generation or district heating and cooling, to satisfy most of their demand. The result of the research shows that about 60% of the recorded ambient temperature and around one-third of the relative humidity readings was incompatible with international standards. The CO_2 concentration was also incompatible with the international standards around 17-35% of the time during measurements. Among the complaints received by the researchers regarding indoor environmental quality, a lack of ventilation was the most prominent complaint.

GSHP is used to provide domestic space and water heating, and, in some cases, cooling [96]. GSHP is better than a regular air source heat pump because of two reasons. First, the temperature underneath the ground is higher than the ambient air above the ground in the winter and lower than the ambient air temperature in the summer. The second reason is that the ground source heat pump relies on water as a refrigerant which has a high thermal capacity. It is also important to know that the performance of GSHP depends on the performance of the ground loop [96].

All GSHP would cause undesirable changes in the temperature of lakes, rivers, underground water, and soil. In both closed loop and open loop systems installed in-depth could result in the interconnection of different aquifers during drilling that might affect the flow or the quality of underground water. In a closed-loop system, a thermal transfer fluid is used as a refrigerant which is considered toxic. This refrigerant if leaked could damage the groundwater. The open-loop system might cause an increase of localized ground that might affect the structure of surrounding buildings [97].

Many consider GSHP to be one of the cleanest sources of renewable energy. Despite that, there are some studies that say throughout the life cycle of GSHP, they could affect the environment in many ways like; depletion of natural resources, greenhouse effect, acidification, and eutrophication. A study was done in Greece on the life cycle assessment of GSHP. They have tested the emission of certain refrigerants (chlorodifluoromethane $CHCF_2$) and it shows that 79% of CO_2 emissions are from the production of raw materials, while 14% are from the cement used for the ground pipes. Moreover, 81% of SO_2 emissions are from raw materials, and 19% from the operation of the system. Lastly, 45% of NO_x emissions are from the production of raw materials, and 45% are from drilling [97].

Other studies have shown that GSHP may contain chemical components that will make them very dangerous for the environment and the occupants of the building. for example, in one study by Heinonen et al [98] they stated that when using GSHP some important environmental aspect must be kept in mind which is the anti-freeze fluids required in closed-loop systems for freeze protection in many applications. The reason for using an antifreeze refrigerant is that in some locations the temperature is very cold and the liquid inside the pipes must remain in the liquid state, therefore, some chemicals are used to prevent it from freezing. Some of these chemicals are potentially toxic to humans and animals, others are potentially flammable so that their use could pose a risk of fire or explosion, especially during installation when the fluids may be present in concentrated form. GSHPs are intended to be used for prolong period of time, so corrosion of piping and equipment could also pose a problem [98].

In another study by Nou & Viljasoo [99] the aim of the study was to use different heating systems to improve the indoor air environment and to measure the indoor environmental quality. the researchers measured the indoor ambient temperature, relative humidity, air velocity, and dust concentration. The result of the study showed that in regards to dust (i.e., particulate matter) the lowest concentration of dust is associated with the district heat. In contrast, the highest dust concentrations were associated with the implantation of the ground source heat pump. The researchers had theorized that when the GSHP increases the floor's temperature, the air adjacent to the floor would move upward and stir up the dust particles from the floor. Moreover, the researchers have as also found that dust mite numbers also increase with GSHP. The result of the study had concluded that the most dangerous alternative heating system for human health was measured when using the heating of the ground source heat pump. This was evident since only 40% of the data met the standard for indoor climate conditions. As a result, the general dust content in the room air was very high [99].

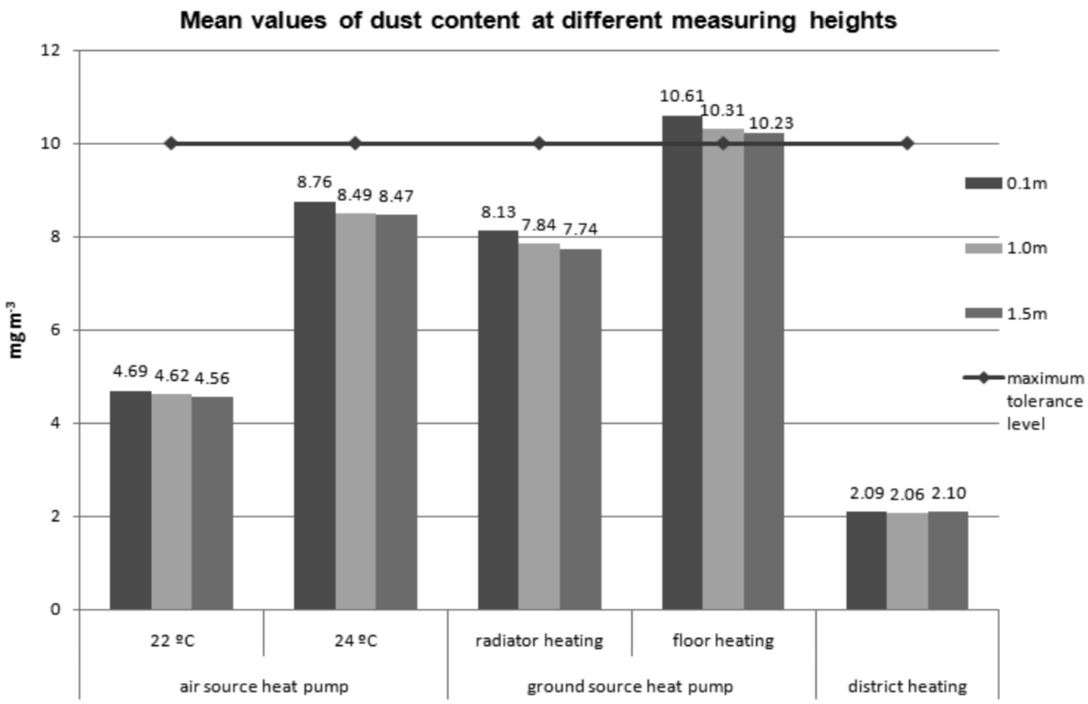


Figure 2-12 Mean values of dust content at different measuring heights (0.1 m, 1.0 m, and 1.5 m) [99]

2.10 Mechanical Ventilation and Heat Recovery (MVHR) system & Heating

2.10.1 Ventilation and Air Condition (HVAC)

Mechanical ventilation systems have been used for decades and people are very reliant on them. While they provide adequate conditioned air into the occupied space, they consume a noticeable amount of energy. According to Cociorva & Iftene [100] heating, ventilation and air conditioning is estimated to consume around one-third of the world's energy. In most modern buildings, the mechanical ventilation, is the sole provider of fresh air into the building and no background ventilation or infiltration should be allowed, and the reason for that is because modern buildings are developed to preserve as much energy as possible, thus many architects and engineers would rather equipped new energy efficient buildings with mechanical ventilation to ensure that the air supply inside the building is controlled in terms of airflow and temperature. [101]. Apart from being one of the most contributors to energy consumption in buildings, it is possible for them to house an environment for pollutants to be created. One of the issues that are related to indoor air quality and HVAC systems is the airtightness that is mostly recommended in many building codes and engineering practices. Highly insulated houses can be too airtight that will lead to a limited amount of outside air to enter the building.

The MVHR system consists of an exhaust and supply fan, air-to-air heat exchanger and duct system. The principle of the system is that it extracts warm moist air from the kitchen and the bathroom of the dwelling, pass it through the heat exchanger and then to the outside of the building. While the hot air passes through the heat exchanger it pre-heats the incoming air from the outside of the building [101].

According to Nash [102], mechanical ventilation systems are the prime suspect of insufficient ventilation rates within energy efficiency houses. The mechanical ventilation systems are tested in laboratories where they could achieve the minimum requirement. However, in a real application, these systems do not reach their full potential. The various element might cause a lack of potential functionality like; incorrect design, installation, and maintenance. The loud noise that is projected from the device causes the residence to lower the fan speed or even turn them off altogether. Like many other European countries, the Netherlands is adapting a net-zero approach for designing new houses. Therefore, the country is increasing the airtightness of new buildings. Highly insulated houses can be too airtight that will entail that only a limited amount of outside air is allowed to enter the building.

In a study done by Balvers et al [103] where they have examined the performance of MVHR in 150 houses across the Netherland that were built according to the latest energy efficacy standards legislated by the government. The researchers have found out that in 48% of the houses the air supply was inefficient, 85% of the houses have at least one room that was under-ventilated (0.7 L/S/m^2), 55% of homes did not meet the minimum extract rate. In addition, some of the prevailing shortcomings found in this research related to indoor air quality are that around 30% of the homes did not comply with the reference level recommended. Also, the ducts were contaminated with dust in almost 77% of all homes, even though they were only a few years old. The researchers also discovered that maintenance was not carried out regularly in 82% of all homes. Moreover, the air filters have appeared to be unclean or dirty enough to be replaced see figure (2-13) [103].

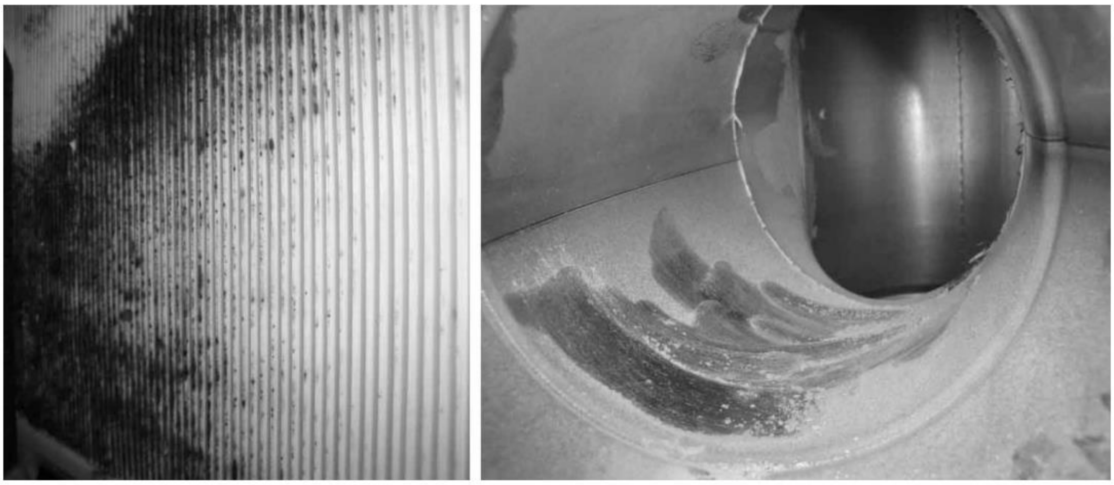


Figure 2-13 Left: example of a contaminated heat exchanger of a MVHR system. Right: example of dust accumulation in an air supply [103]

Another issue that relates to HVAC systems and indoor air quality is the contamination of the filters. The use of filters is crucial for the purification of the air. However, in many cases, these filters themselves could be the source of some contaminants inside the building [104] [105] also, contribute to the development of sick building syndrome and affect the performance of the occupants within. In a study by

Hyttinen et al. [106] and [107] they illustrated that terpenes, phthalates, carboxylic acids, aldehydes, alcohols, nitrogen-containing organic compounds and aromatic hydrocarbons were the main pollutant emission in the thermos desorption analyses of the filter dust. In addition, some of these organic compounds can react with the existing ozone contained in the air passing through the filters that result in ozone removal. However, ozone oxidation from this reaction may be desorbed to the airstream and degrade perceived air quality [108].

The Derwent project was a collaboration between the Leeds metropolitan university, the Environment and National Power and Building Research Energy Conservation Support Unit (BRECSU). The objective of the project was to explore the possibilities of incorporating a Mechanical Ventilation system with Heat Recovery (MVHR) systems in newly developed homes [101]. The study is concerned with the air quality inside the building and especially the concentration of CO_2 and relative humidity because they are good indicators of the air quality inside the control space and the test space, and it also predicts the effectiveness of removing pollutants from inside the space. The field trial was based on a comparison of an experimental group of houses fitted with the whole house balanced MVHR, and a control group in which natural ventilation was supplemented by extract fans in kitchens, and bathrooms [101]. The result of this research showed that the amount of CO_2 is higher in controlled buildings than in buildings equipped with MVHR. Also, the absolute humidity levels recorded in all of the rooms were lower in the MVHR dwellings, around 7 g/kg, compared to the control buildings.

Another study by McGilla et al [109] This paper they investigated the potential implications of the Passivhaus standard on indoor air quality. Three mid-terraced Passivhaus dwellings were selected for the investigation. The two-storey, 3-4 bedroom timber frame dwellings achieved level 4 in the Code for Sustainable Homes and were compliant with the Lifetime Homes standard. The result of this study shows that high levels of CO_2 above 1000 ppm were measured in all of their monitored households. This is because of several factors the first being that the MVHR is not cleaned properly and the occupants are unaware of the setting for boosting the fan speed so that more contaminates could be diluted. The high levels of CO_2 have been recorded in both summer and winter months which might suggest that the ventilation inside these dwellings was not adequate. The researchers have hinted that the reason for the high CO_2

concentration can be the result of inadequate performance, use and/or maintenance of the MVHR system. For example, in bedroom number 3 the level of CO_2 peaked as high as 2,598 ppm during the summer measurement period. The German Working Group on Indoor Guideline Values, based on health and hygiene considerations proposed that concentrations of indoor carbon dioxide below 1000 ppm are classified as harmless, while concentrations between 1000 and 2000 ppm are classified as elevated. However, concentration levels above 2000 ppm are classified as unacceptable. The researchers are encouraging more investigation into the performance of MVHR systems in practice and whether or not they provide adequate ventilation in low energy, Passivhaus dwellings.

2.12 Earth-to-Air heat exchanger (ETAHE)

Earth has proven to provide a great heat sink to either dissipate heat or extract heat. This heat can be utilized in three ways; A) by direct contact in which the building is in direct contact with the earth. B) Indirect where the interior of the building is conditioned by air through the earth, C) in an isolated system using GSHP. The temperature fluctuation inside the earth's soil is damped due to the high thermal inertia of the earth. This high thermal inertia causes the thermal lag inside the soil in which the air temperature outside the soil is different from the temperature inside of the soil [110]. However, in order to take advantage of the interchange of heat between the earth the heating system an earth tubes materials should meet certain criteria like cost, corrosion resistance, and durability. Some of the materials considered for ETAHE are; concrete, metal, and plastic, and other materials. In order to ensure the airflow inside the earth tube is appropriate, it is important to ensure that the depth as well the diameter of the tube is adequate for the building because increasing the tube's diameter will reduce the airspeed and increasing the tube's length will increase the pressure difference throughout the tube and it will also be harder for the fan to work. There are two main ways for ETAHE arrangement. The first is the open-loop system. This system receives air from the outdoor through an open tube outside of the building, then the air passes through the heat exchanger before it is delivered to the interior space. The Second is the closed-loop system. This system does not receive air from the outside. Instead, the interior air is then circulated through the pipes [110].

2.12.1 Environmental issues related to ETAHE

Many studies have confirmed that the ETAHE system has some environmental issues with humidity and mould growth. Condensation occurs when the temperature inside the tubes are below the dewpoint temperature. many have argued that dehumidification is difficult to achieve inside the tube [110]. In cold-warm, humid air, the ETAHE system will always increase the relative humidity of the air. When the air is cold, its capacity to hold water vapour reduces. In addition to condensation, mould growth is more likely to happen when the humidity level increases. The international energy annexe established a surface humidity criterion for design purposes; 1) the monthly average humidity at the surface should be below 80%, 2) The risk of mould growth above 80% RH is eminent, and 3) the pipes should be designed with a 1degree tilt so that the water will be drained away from the tube [110].

Researchers agree that using earth tubes is very beneficial for energy efficiency. However, using earth tubes has some drawbacks like many other building technology systems. Some researchers like Rodrigues & Gillott [111] and Ozgener [112] have summarized some of the related issues pertinent to earth tubes: (1) they might increase the level of humidity inside the building; (2) they might compromise the indoor air quality because of condensation and/ or water infiltration through the pipes, and in some cases, there is a possibility of having fatal microorganisms cultivating inside the damped tubes; (3) draught might be excessive in some cases that might also lead to occupants discomfort; (4) there is also the problem with noise coming from the fans through the pipes (5) in many cases, these systems could be very expensive to build.

Moisture is not the only issue that might be caused by earth tubes. Since earth tubes are built underground, precautions measures have to be taken with the level of radon that might present in the site. In a study by Ringer et al [113] they investigated and surveyed a couple of energy efficient buildings located in areas prone to have high levels of radon under the Radon Prevention and Remediation or (RADPAR). The researchers analyzed several aspects of the building that might have a direct effect on the levels of radon inside the building like Heating technology, construction, and ventilation technology. Additionally, the study included a survey of 28 passive houses, and in situ measurements taken from 9 passive houses. Some of these homes were equipped with Earth tubes used as a heating and ventilation system for the building. The researchers used two sets of tubes in this study (concrete tubes and plastic tubes) see figure (2.14). The result of the study indicated that using certain construction materials in the earth tube have resulted in different radon concentration. This was evident when researchers compared the concentration of radon air coming from two kinds of earth tubes. One earth tube is made of concrete and the other is made of plastic. The result showed that the air coming from the concrete tube has 1.5 higher radon than the air coming from the plastic tube. The result of the study showed that the ratio increase by 2.0 when using air filters at the air intake. The reason being is that the air pressure is increased when passing through the filter, thus increasing the amount of soil gas being permitted into the building. Another reason is because of the increase in the dust load on the filter which reduces the supply air rate and thus increases radon concentrations; once again this ratio is higher in the concrete tube rather than plastic tubes. Furthermore, Ringer [113] in his study suggested that all building that incorporates earth tubes must have an airtight system to seal the tube from the rest of the building along with an airtight building envelope to reduce the chances of radon penetration from the soil.

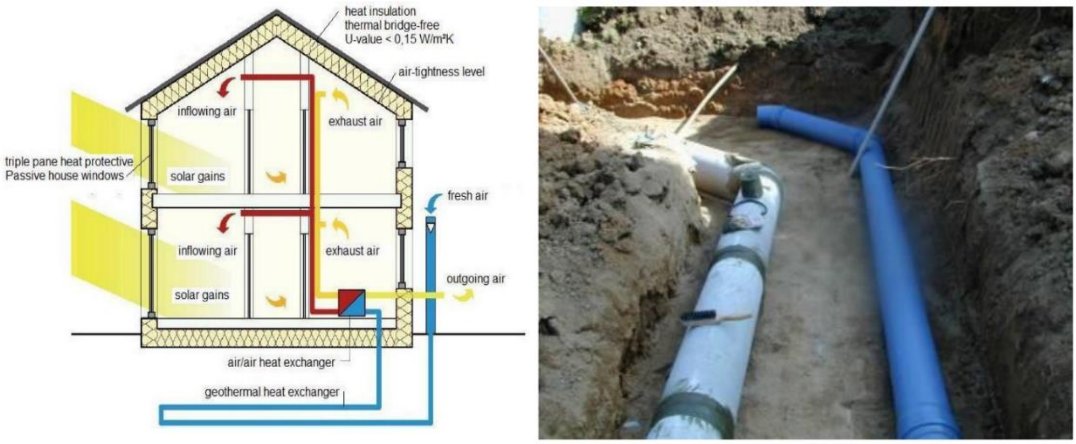


Figure 2-14 on the right a schematic drawing showing a typical Passive house included in the study. on the left the placement of two different types of tubes

Another issue that might disturb the indoor air quality inside buildings equipped with ETAHE is the presence of microbes and fungi. In a study conducted in Kimobetsu town of Hokkaido, Japan [114] the authors have completed a three-year evaluation of two near-zero energy houses in terms of indoors microbes contamination, CO_2, $PM_{2.5}$ and PM10.

The result of the study showed that in terms of CO_2 concentration, the average levels were lower than 1000 ppm, although in the summer the values did briefly increase higher than 1000 ppm for a very short period of time. In terms of microbial contamination, the result showed that in house A the average airborne bacteria was between 93 – 619 Forming Units per cubic meter or (CFU/m^3). Whereas in house B the concentration of bacterial in indoor air was between 331 – 1700 CFU/m^3. The concentration of bacteria in house A is considered low to moderate. While in house B, the concentration is considered moderate to high. On the other hand, the average concentration of fungi in house A was between 29 – 3200 CFU/m^3, and between 48 – 4027 CFU/m^3 in house B. These values are considered very low (during spring and winter) to high (during summer), while in house B they are considered low (during spring and winter) to high (during summer) respectively. The researchers of this study [114] have concluded that the concentration of airborne fungi was revealed to be very high during summer periods in household A and in household B. The researchers have suggested that in order to remove microbial contamination, the house must be either be naturally ventilated through the windows or the rate of ventilation must be increased in the summer to eliminate the increase in humidity necessary for mould growth. The authors of this research have also suggested that the earth tube must be improved by removing all possibilities for condensation inside the tube that will induce the growth of Fungai and bacterial. One way to improve the condition of the earth tubes is to use hydrogen peroxide or alcohol for sterilization inside the earth tube. Another way to improve the condition of the earth tubes is to use a highly efficient filter for fungal spores or an activated carbon filter for odour at the end of the earth tube [114].

Another study by Ahmed et al [115] published a case study review of the earth tube system incorporated in the sustainable precinct at Central Queensland University, Rockhampton, Australia. The result of the study indicated that the humidity levels are sometimes higher than in other buildings. Table (2-11) shows the difference between buildings with earth tube systems (HEPC) and regular buildings (VEPC) or standard rooms.

Modelled rooms	Indoor temperature (°C)			Outdoor temperature (°C)			Relative humidity (%)		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
HEPC	22.61	25.32	24.58	20.62	36.19	29.77	32.12	86.37	65.24
Standard room	23.27	25.72	24.90	–	–	–	36.72	81.95	63.14

Modelled rooms	Indoor temperature (°C)			Outdoor temperature (°C)			Relative humidity (%)		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
VEPC	23.48	26.39	24.61	25.87	37.46	31.10	55.19	83.46	67.95
Standard room	23.54	26.88	24.87	–	–	–	48.18	78.99	58.58

Table 2-11 air temperature and relative humidity of the earth tube houses compared to the regular houses [115]

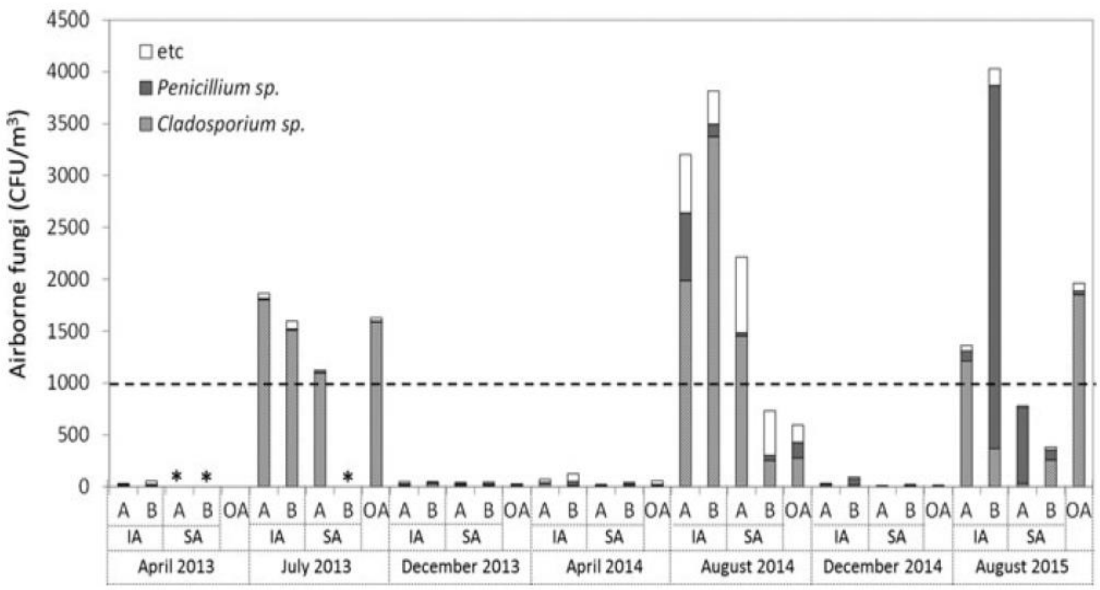


Figure 2-15 Seasonal differences and identification of airborne fungi in the indoor air, supply air, and outdoor air. A: household A, B: [114]

An additional study by Darkwa et al [116] shows a similar result in terms of increased relative humidity inside the room from earth tubes. The experiment studied the main source of fresh air supply to the research laboratory in the Centre for Sustainable Energy Technologies (CSET) at the University of Nottingham, Ningbo-China. In this research practical result along with theoretical result was used to evaluate the performance and the environmental impact of Earth-Tubes. The theoretical results were obtained by using the simulation software EnergyPlus®. The theoretical result has shown that relative humidity levels have improved from a mean value of 70% to 60% due to latent heat gains in the Earth-Tube. The particle data were collected from the system during a time period between March and July 2010. The result from the practical data collection has shown that the levels of humidity increased from 70 % to 85% because of the high levels of latent heat exchange with the air system. The air was further dehumidified with an air handling unit, however, the data collected still showed that the humidity levels were higher than the anticipated design value of 55%. The researchers have concluded that these findings might suggest that in some locations, like hot humid climates, the performance of an Earth-Tube system could be affected by unstable thermal conditions in the soil.

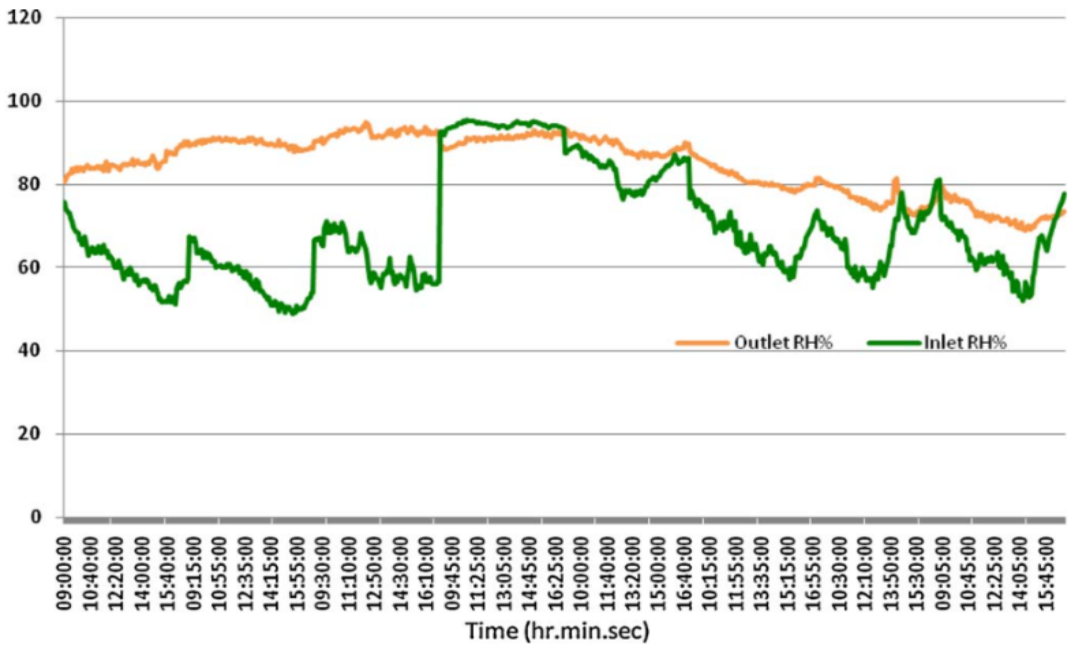


Fig. 16. Relative Humidity profiles: 21–30 July 2010 (cooling period).

Figure 2-16 Relative humidity profile (cooling period)

This study was done by Leo Samuel et al [7], where they have tested an alternative method to introduce conditioned air inside the building. they used the earth air tunnel system (EATS) because it is considered energy-efficient and eco-friendly. The researchers measured the cooling performance and indoor air quality. For the evaluation of the indoor air quality, they measured the fine particles ($PM_{2.5}$ and PM_{10}, CO, CO_2, temperature, and relative humidity. The average PM_{10}, $PM_{2.5}$ and PM_1 concentrations were 6.77, 6.11 and 3.17 mg/m3 respectively when the EATS was operated. Interestingly, the previously mentioned data were marginally higher when the EATS was operational compared to the data taken when EATS was not operational. As for the rest of the data taken, it shows that during the operation of the EATS the average indoor CO_2 level was 418 ppm, air temperature 26.5 C° and RH was 58%. These data were within the acceptable range. The researchers have discovered that by analysing the diurnal indoor CO_2, it correlates with the photosynthetic and anthropogenic activities inside the building.

2.13 Pollutants from building materials

Many occupants in modern buildings have been complaining about the indoor air quality inside the building especial from products that contain formaldehyde. The symptoms that are observed from the occupants are similar to the symptoms from the exposure of low concentration gases and solvent type organic compounds. In a study done by Molhave [117], they have studied seven newly built buildings and thirty-seven old buildings and compared the concentration of VOC in both types of buildings and they have found that the average concentration of VOC in all 42 buildings was 3.2 mg/m^3. The range of data taken starts with 0.01 mg/m^3 as the lowest readings and 1410 mg/m^3 as the highest readings. Organic solvents are widely applied to numerous materials. In fact, according to Molhave [117], most industrial materials have been in contact with solvents. There is a wide range of VOCs in building materials, but only some of them are detectable. The detectable VOCs are the non-polar of a slightly polar compound with a boiling point of 25-250 °C are detected. Table (2-12) shows some most important sources of VOC from building materials and the least important sources of VOCs from building materials.

Some of the sources of VOCs are; paints, varnishes, solvents, waxes, and carpets. In a study done by Katsoyiannis et al [118] where they have analyzed ten building materials in a lab to measure the Total Volatile Organic Compound (TVOC). The specimens were divided into two categories; lime base products and concrete based products. The results of the study show that after 24 hours the highest average of TVOC was recorded with lime-based materials at 4050 mg/m^3, and after 72 hours, the concrete base materials were the highest at 1700 mg/m^3. Also, in the study, they have found that lime base material loses more TVOC than concrete base materials. Researchers postulate that the low concentration of solvents in lime-based material might be the reason for low readings for TVOC after 72 hours. Neopentyl glycol (NPG) or (2, 2-dimethylpropane-1, 3-diol; CAS:126-30-7) was detected as the main emissions from cement samples. During the seventy-two hours of testing, the concentration of (NPG) from C3 and C4 were 480 to 1400 μg/m^3 respectively. Neopentyl glycol is present in many cement products because it is used as an important additive. However, not all cement products will exhibit the same emission of (NPG). In samples, C1 and C3 they showed a reduction in emission after 72 hours of testing. While in samples C2, C4, and C5 they have shown an increase in (NPG) emission. The ratio of NPG/TVOCs is increasing between 24 and 72 h showing longer persistence compared to other emitted chemicals. Figure (2.17 & 2.18) shows the ratio of neopentyl glycol (NPG) to total volatile organic compounds (NPG) /TVOC ratio after 24 hours and 72 hours of exposure to common materials [118].

Table 2-12 the 10 ten most important sources for organic gases and vapours of solvents type in the indoor environment [117]

Material number	Type	Concentration (mg/m^3)	
		Corrected	**uncorrected**
10 least important sources			
15	Synthetic fiber carpet	0.13	2.0
11	Wood fiber board	0.11	3.0
8	Mineral wool	0.068	0.38
24	Hessian wall covering	0.031	0.09
29	Glass fiber board	0.016	0.40
7	Putty	0.016	1.4
12	Neoprene fillet	0.0075	0.81
13	PCV fillet	0.0026	1.1
28	Neoprene fillet	0.0008	0.35
35	Laminated board	< 0.0004	< 0.01
10 most important sources			
20	Eva glue	1530	1410
22	PVA fillet	58	58
21	PVA glue	34	9.8
40	Floor textile	9.0	40
37	Polystyrene foam	7.9	41
32	Isocyanate varnish	707	30
39	PVC floor covering	3.8	55
5	Sealing agent	3.4	169
3	Acrylic Latex Paint	2.4	2.0
26	Rubber floor covering	2.3	28.4

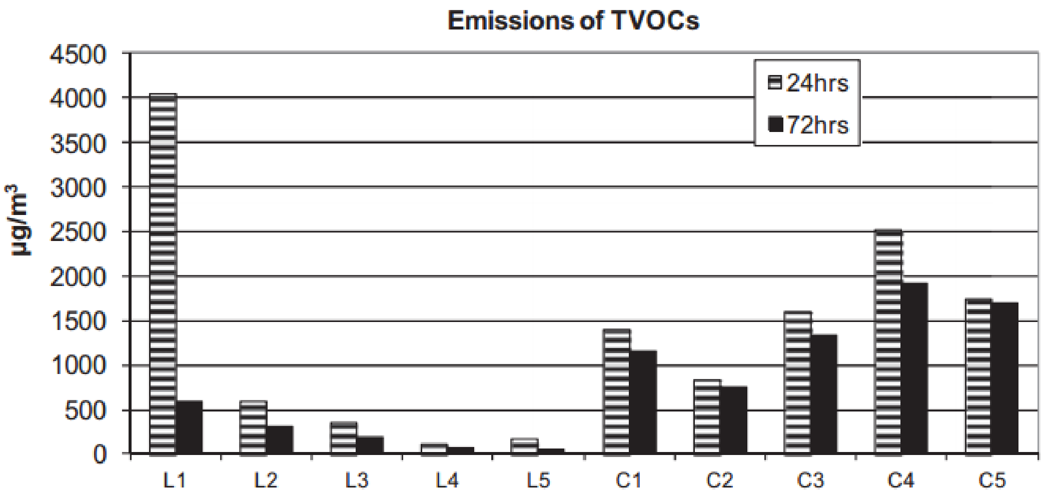


Figure 2-18 emission of TVOC from the tested materials, L1-L5 and C1-C5 (L= lime base materials, and c= concrete base materials [118]

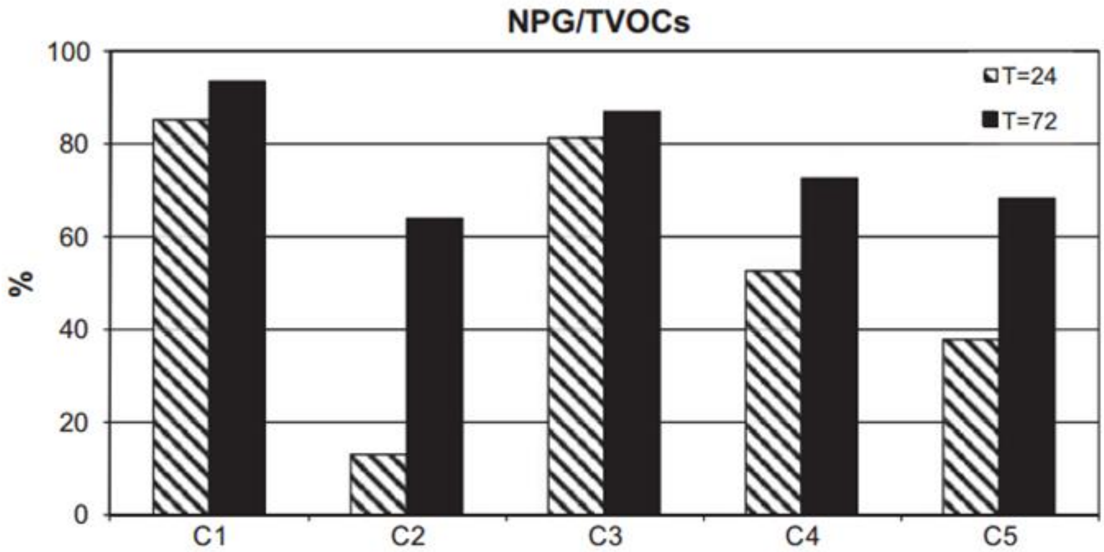


Figure 2-17 NPG/TVOC ratio after 24 hours and 72 hours of exposure test of coment materials [118]

A study by Wolkoff and Nielsen [119] had reviewed the literature on VOC emitted from building materials and focused on eye and airway irritation and unpleasant odours. The concentration of VOCs had seen to be generally below 50 µg/m^3 with most of them having a concentration below 5 µg/m^3. In both European and American studies have shown that the concentration of the majority of VOC is generally below 10 µg/m^3. Table (2-13) shows some of the major and most often reported indoor VOCs.

The definition of Total Volatile Organic Compound given by the European Collaborative Action as a sum of VOC concentrations (in µg/m^3) within the VOC chromatographic window. However, according to (ECA) there is no cause-effect relationship exists between the concentration of TVOC and adverse health effects like airway irritation. Figure (2.19) shows the categorization of TVOC among other air pollutant compounds defined by the (ECA). Some indoor emitted VOCs from building materials have odour thresholds sufficiently low to cause an impact on the perceived air quality, in some cases even malodorous events. The effects could last for long periods of time like in some cases for long periods like for example after renovation [119].

Australian review[a]	European audit[b]	US review[c]	BASE study[d]	Swedish housing stock[e]	German study[f] Selected (new) VOCs
Benzene	Acetone	*o*-Xylene	Acetone	Toluene	Group 1:
Tetrachloroethylene	Isoprene	Benzene	Hexane	Decane	Phenoxyethanol
p-Dichlorobenzene	2-Methylpentane	Tetrachloroethylene	Toluene	Dodecane	Butyldiglycol acetate
Ethylbenzene	Hexane	*m*-, *p*-Xylenes	1,1,1-Trichloroethane	Nonanal	Longifolene
m-, *p*-Xylenes	2-Methylhexane/benzene	Ethylbenzene	Methyl chloride	Undecane	Dimethyl phthalate
1,1,1-Trichloroethane	Heptane	Trichloroethylene	Benzene	Limonene	
o-Xylene	Toluene	Toluene	Ethanol	C_{11}-Alkane	Group 2:
Decane	*m*-, *p*-Xylenes	1,1,1-Trichloroethane	2-Propanol	C_{12}-Alkane	*α*-Pinene
Toluene	*o*-Xylene	Dichlorobenzenes	Dichlorofluoromethane	Xylenes	Camphene
1,2,4-Trimethylbenzene	Decane	Styrene	*m*-, *p*-Xylenes	C_{10}-Alkane	*β*-Pinene
Hexane	Trimethylbenzene	Undecane	2-Butanone	Trimethylbenzenes	3-Carene
Nonane	Limonene	Dodecane	Trichlorofluoromethane	Butoxyethoxyethanol	Group 3:
Limonene		Octane	*o*-Xylene	Butoxypropanol	Styrene
			Undecane	C_7-Alkane	*o*-Xylene
			Tetrachloroethylene		C_{12}-Alkanes
			Methylene chloride		
			1,2,4-Trimethylbenzene		Group 4:
			Decane		1,2,3-Trimethylbenzene
					1,2,4-Trimethylbenzene
					Methylcyclohexane

Table 2-13 ubiquitous VOCs in indoor air measured in European and North American field studies [119]

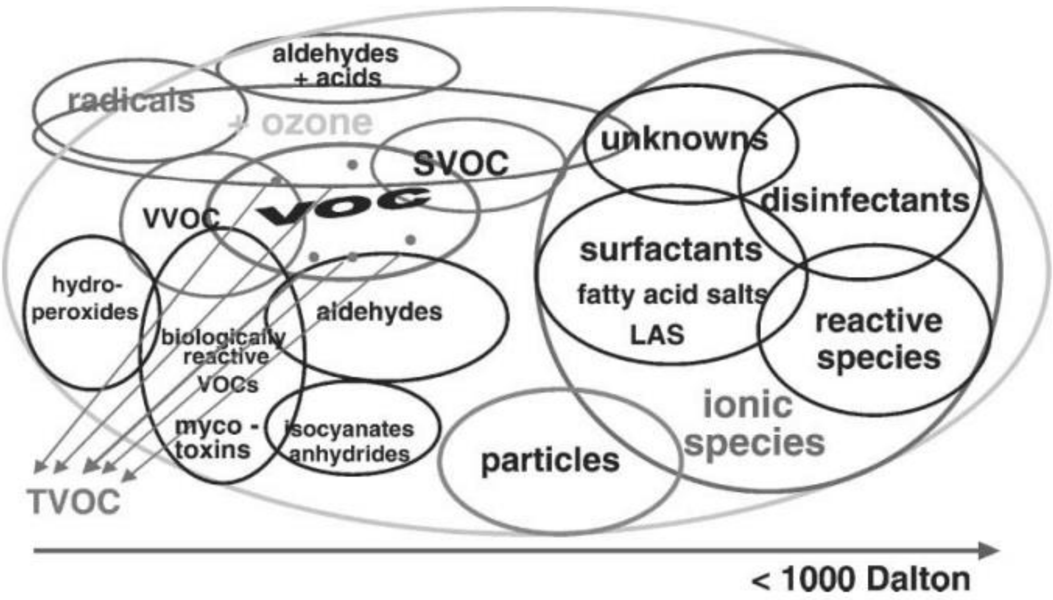


Figure 2-19 schematic and tentative presentation of the OCIA universe [119]

2.13.1 Overview of the problem associated with indoor air quality:

The causes for elevated indoor pollutants are because of two reasons the first is the advancement in modern technology, and the second is the use of new building materials and furnishing. New buildings contain many synthetic materials and furnishing from walls, carpet and air conditioning systems. The use of new materials has instigated the emission of a large number of new indoor pollutants in greater concentrations. Table (2-14 and 2-15) shows some of the common VOC components from wood stain [120]. Building engineers are making new buildings more airtight and they have allowed the supply of fresh air to be mainly from mechanical ventilation. Consequently, the pollutants inside the building have risen dramatically. According to the EPA [121], a study of human exposure to air pollutants indicated that indoor concentration of air pollutants is 25 times higher than outdoor air pollutants. In a non-industrial building, the most common pollutant that will cause the phenomenon of Sick Building Syndrome (SBS) is VOC. Indoor VOC comes from a variety of sources like building materials, ventilation systems, household, and consumer products, office equipment, and outdoor sources [122]. Building materials are one of the major sources for VOC. A review by Bellie et al [123] indicated that more than 60% of the VOC emitted in the air is generated from building materials. These materials include wood stain, latex paint, floor wax, carpet material, PVC flooring, gypsum boards, insulation materials, and HVAC systems [120].

Peak number	Peak name	retention time	Area (counts)	Concentration (mg/m^3)
1	Octane	12.23	334	31.7146
2	Nonane	16.751	26142	1495.602
3	Decane	22.826	35848	1977.007
4	Undecane	29.451	296	28.5036

Table 2-14 properties of major components from the wood stain at 23 C [120]

Compound	Formula	Molecular weight	Vapour pressure (mm Hg)	Boiling point (°C)
Octane	C_8H_{18}	114.2	12.07	125
Nonane	C_9H_{20}	128.3	3.93	151
Decane	$C_{10}H_{22}$	1.25	1.25	174
Undecane	$C_{11}H_{24}$	0.35	0.35	196

Table 2-15 list of identified compounds in the wood stain [120]

2.13.2 Measurements of VOC from wet and dry coating

Most wet materials contain petroleum-based solvents and therefore, emit VOCs. Previous studies have shown that the emission process from materials with wet coating goes through three phases. The first phase represents the period shortly after the material is manufactured and applied to the substrate of the base material. In this stage, the emissions are high, but they decay considerably. In the second phase, the coating dries out as the emission changes from the evaporative state to internal diffusion. In the third phase, the materials become almost completely dry. At this stage, the off-gassing of the material decreases and so does the decay rate [123]. Other studies have shown that the emission of wet material depends on the surrounding environment like (temperature, humidity, air velocity, turbulence, and VOC concentration in the air [120]. The wet material is usually applied on a substrate, a base on which the wet material is coated, and depending on the material emission rate. The lab testing done by Yang and Dong [120], showed that both the initial emission rate and emission decay rate on the glass substrate is higher than wood board substrate. However, when the oak board is used, the emission rate decreased to 60%. Other factors might increase the emission rate of wet materials. Temperature and air velocity that affects the emission rate of wet coating. It was observed higher air velocity and higher temperature increases the rate of emission [120].

Dry materials do not have wet coating, and they are important to address because most of them cover a large surface area. Some of these materials are wood flooring, carpet, vinyl, wall coverings (e.g. wallpaper, and fabric), and ceiling material (e.g. acoustic tile, rigid foam). Some dry materials have longer emission than wet materials. For example, carpets emission tends to last several years. The surrounding environment might also have a significant effect on the emission rate of carpets. According to Yang and Dong, high temperatures increase the emission rate of carpets. At 23 °C, it takes 68 months for the average TVOC concentration to drop to less than 1 $\mu g/m^3$. However, at 30 °C it takes 23 months to reach the same concentration, and at 40 °C, it took only 16 months to reach the same concentration [120].

2.13.3 Modern construction materials and indoor air pollutants in low carbon literature

2.13.3.1 Concrete

Many materials like concrete could emit radon due to the fact that concrete uses earth materials. Masonry materials like, brick, tile, and concrete are commonly known to emit radon [124]. The radon levels could vary significantly depending on the clay and rock that has been extracted from. A study in the United States has shown that radon is mainly emitted from concrete and gypsum materials even in high stories above the ground. They have measured levels of 218 Bq/m^3 and 481 Bq/m^3 which is much higher than the recommended level by the EU/UK safe limit [124]. This is because concrete is made of aggregate and it might contain uranium and radium. When radon gas decay it can produce polonium, lead, and bismuth that can remain in the lungs and cause cancer. Another example of materials that could emit radon are gypsum plasterboard or drywall. The materials can be contaminated by radioactive waste products which might also emit gamma radiation and radium. The concentration of radon in buildings is 40 % higher than outdoor concentration which shows that concrete materials are a significant source of radon other than radon coming from the site. The radon content inside the materials is dependent on the moisture content. The dryer the material the less radon exists. Other recycle materials can emit radon like fly ash masonry blocks material [124].

Concrete is one of the most famous construction materials used all over the world. In many cases, concrete manufacturers would alter the chemical composition of the material in order to cut cost or reduce energy consumption. for example, countries like Japan use some additives to the concrete that has been shown to emit some level of VOCs and ammonia by using amine additive, likewise in China where they use a urea-based mixture in the wintertime to accelerate the hydration rate and influence the freezing point of the water Lindgren [125].

A study by Torsten Lindgren [125] developed a standardized questionnaire which was distributed between May–June 2004 to the employees who were working in a Beijing city centre office building and developed a similar questionnaire that was distributed to the employees in another office building in a suburban area of Stockholm. Researchers have documented a clear presence of ammonia odour in the Beijing building, but there were no ammonia smells in the Stockholm building. Ammonia is mostly attributed to the increase of malodor and mucous membrane irritation in Beijing. In addition, the researcher has also cited different articles related to the increasing concern for the prevalence of ammonia in Chinese buildings according to Bai Z et al [126]. Exposure to household ammonia above 1 ppm might cause mucous symptoms. The Swedish legislation, suggest that the maximum level exposure allowed for work environments is 25 ppm (¼18 mg/m3) [125].

In some cases, concrete could be used to purify the air from indoor air contaminants. A process called photocatalysis is used to convert organic pollutants into water (H_2O) and carbon dioxide (CO_2) without requiring an additional process according to Yu Ql and Brouwers [127]. This method could be used to remove many pollutants like carbon monoxide, nitrogen oxides, sulfur dioxide, carbon dioxide, chlorinated hydrocarbons, hydrocarbons and VOCs Yang J et al [128] By integrating photocatalyst particles between a thin surface layer of concrete the photocatalytic compounds could be used as an air purifier. Moreover, due to the large surface of the wall that could be covered by the photocatalytic particle, it could cover a large area of the pollutant that airborne close to the surface of the wall Beeldens [129]. According to Guerrini GL et al [130] Photocatalytic cementitious materials is a new and innovative way to improve indoor air quality because photocatalysis can increase the rate at which the natural oxidation process takes place. Thus, allowing for faster decomposition of pollutants, and preventing them from accumulating, and favouring their decay.

Norbäck et al [131] tried to investigate the correlation between asthma symptoms and pollutants emitted by concrete flooring. this study took place in Four geriatric hospitals in Sweden. The doctors have carried out the investigation by asking the participants about social status, smoking habits, medications allergies and other diseases. the researchers have analyzed the responses and were able to establish a correlation between asthma symptoms in adults and dampness as a result of alkaline degradation of DEPH in PVC building material. This was presumably because of the presence of 2-ethyl-1-hexanol in indoor air. The researchers have concluded that the increased level of humidity in these hospitals especial with the inclusion of concrete flooring could be related to the exacerbated levels of asthma symptoms among the participants. The emission of 2-ethyl-2-hexanol is believed to be an indicator of the increased level of dampness in the building and is also related to the alkaline degradation of plasticizer DEHP used in PVC materials.

2.13.3.2 Fly Ash studies

Fly Ash is an aluminosilicate material that is a byproduct of coal combustion produced from the power plant. According to Arulrajah et al, the benefit of using fly ash material is the reduction of energy from the heat generated during concrete hydration [132]. Others define Coal fly ash as a silicate-based waste form of coal powder that is been utilized in some building material manufacturing businesses. From coal fly ash, manufacturers derive zeolites which are microscopic crystalline hydrate aluminosilicates that are used to adsorb NO_x, CO_2, and heavy metal ions removal in water Chang et al [133]. A study by Zhou et al [134] have studied the effect of zeolites on adsorbing VOCs and benzene and found out that zeolites that are derived from coal fly ash materials were able to absorb around 69% of benzene vapour, and they also found that they could potentially remove other contaminants like VOCs.

Using fly ash material helps to reduce the embedded energy by replacing a considerable amount of cement with fly ash. Using cement is very energy-intensive. For example, manufacturing one tone of cement could produce around 900 kilograms of CO_2. Therefore, using fly ash has proven to be very economical and environmentally friendly because of the less reliance on cement. However, according to Sarah et al, using fly ash may result in the intensification of concrete radioactivity and it could also lead to an increase in indoor progeny and radon exposure [135]. Researchers like Kant et al [136] suggested that fly ash can possibly contain concentrated levels of uranium compared to unburned coal. Even though fly ash only constitutes around 1-4% of the cement mixture, it still has a large amount of uranium specific activity compared to other cement and aggregate material [137]. A research study by Sarah et al [135] studied radon production rate from fly ash by preparing three samples: the first sample had no fly ash replacement for concrete; the second sample had 25% of the cement replaced with fly ash; the third sample had 40% of the cement replaced with fly ash. The result of the study indicated that on its own the average radium activity from fly ash is 8 times higher than cement and

25 times higher than normal aggregate. The second finding is that Concrete materials like floors made with 25% fly ash replacement showed that 90% readings for radium activity are caused by fly ash which led to indoor concentration of around 3.9 Bq/m^3. The researchers have concluded that fly ash materials have the capability to increase the level of radon indoors. Although, the possibility of increasing radon levels inside the building is not definitive. Generally, fly ash could be responsible for an increase of radon concentration from 4-8% of the total inhalation dose experienced annually by the global population

Fly ash may save a lot of energy during the manufacturing of recycled cement. Not only that, but it could also be effective in removing pollutants from indoor air. One study by Decio [138] analyzed the effect of three mortar materials differing in their mixture. The first mortar was made from regular cement mortar, the second is made from dehumidifying salt-resistant mortar, and the third mortar was made from cement-free mortar containing pozzolana (a natural binder). The result of that study revealed that all types of mortar used in the study have reduced the concentration of TVOCs during the twenty-four-hour testing. The regular cement mortar, for instance, reduced the TVOCs from 4500 $\mu g/m^3$ to 1000 $\mu g/m^3$. Another study by Krejcirikova et al [139] also studied the effect of cement and fly ash cement mortar on indoor air quality. The first mortar was a regular cement mortar and the second was a cement-ash-based mortar with a mixture of 30% of the cement was replaced by sewage sludge ash. The study concluded that (1) there was no discernable differences in terms of sensory emissions between the two types of mortar; (2) both types of mortar contributed to the reduction of organic acids; and (3) cement-ash-based mortar was not linked to ammonia emission at a detectable level.

2.13.3.3 Timber

Timber is a very common material that is used in many countries like the United State and the United Kingdom. These materials are regularly treated with some chemicals for preservation, termite treatment, and fire resistance. However, over the history of their production, many of these chemicals were very toxic and harmful. Like for example, creosote, and arsenic. These materials were replaced by other materials that are less harmful, but they still emit pollutants that could eventually affect the occupant’s health [124]. A new substance that is used for timber is naphthalene (petroleum). This substance has a low boiling point and is used as a fungicide and insecticide treatment. According to occupational safety and health administration, naphthalene is considered extremely flammable, irritant to the eye and respiratory system and it affects the central nervous system [101]. Plaisance et al [140] measured the emission of VOCs at different construction stages in three energy efficient buildings built using a timber frame structure. The authors have detected high levels of ethylbenzene and m,p-xylenes during the construction phase of the project. They attributed the reason for the high release of VOCs to the use of polyurethane adhesive mastic as a sealing agent. Additionally, they also found other sources of VOCs like aldehydes which were more prevalent at the last stages of the construction of the building. The researchers postulate that these levels of VOCs decrease over time, but nonetheless, they linger inside the building for a long time and traces of these compounds be found after several months or even years after the completion of the construction phase.

2.13.3.4 Wood formaldehyde emission

A study conducted by Bohm et al [141] shows the various amount of formaldehyde emission between different kinds of woods. They also stated that Beechwood seemed to have the highest emission of formaldehyde by 0.0068 ppm and 0.084 mg/m2 h. other types of wood have also been shown to emit formaldehyde like spruce wood at (0.0055 ppm), pinewood at (0.0053 ppm), and Birch at (0.0036 ppm). Testing for formaldehyde in wood panels can be achieved by using the test chamber. The European standard uses the prEN 717-1 to test the emission of formaldehyde Kim et al [142]. Wood typically emit a noticeable amount of formaldehyde if it is subjected to certain conditions. The process mostly involves thermal degradation of polysaccharides in the wood. The BUMA emission database suggested that the emission rate from a typical flooring should be 25 _g/m2 h (0.25 mg/m2 h). Meanwhile, the emission test from the BUMA association has found that emission from the wood-based panel was 144 _g/m2 h (0.144 mg/m2 h) with a range of 0–1580 _g/m2 h [141].

Some wood-based panels that are bonded with urea-formaldehyde resin may emit formaldehyde fumes. Many countries like the United States and the European Union are considering restricting the use of building materials that might emit excessive amounts of formaldehyde [142]. A study by Kim et al [142] used a testing chamber to analyze the formaldehyde emission from different particle boards. From their study, they have shown that particleboards emit several kinds of VOCs such as: (toluene, ethylbenzene, xylene, and styrene). In the same study, they have compared different types of wood-based boards like (particleboard, medium-density fiberboard, high-density fiberboard, and laminated boards). Their testing has shown that the particleboards and the medium-density fiberboards had the highest initial value of formaldehyde emission, while the high-density fibre boards and the laminated boards had the lower initial value of formaldehyde emission. The researchers suggested using the bake-out method to reduce the amount of formaldehyde from the material. The principle is to extract the VOCs out of the materials into the indoor air by raising the building temperature to a level of 32–40 C, while simultaneously increasing the outdoor air exchange rate in order to drive these VOCs out of the building[160].

Some wood products like oriented strand board (OSB), particleboard, and medium-density fiberboard can use wood residue and sub-quality wood [143]. Most wood-based panel product uses Urea-formaldehyde resin as a bonding agent between the boards [144]. Due to the prevalence of wood products in many buildings, the emission of VOCs from these wood products has become a growing issue. He [144] studied the effect of formaldehyde in different manufacturing stages. Testing the wood without the addition of urea-formaldehyde have shown that a typical wood material would emit 2-9 ppb of formaldehyde. This shows that most of the formaldehyde is coming from the urea-formaldehyde resin. The result of the study has shown that it was found that urea-formaldehyde resin has the highest formaldehyde content, followed by phenol-formaldehyde resin. The heating process has proven to be very successful in removing a considerable portion of the VOCs emitted by the wood product. A total of 34 individual VOCs were identified. Lastly, the researchers have noticed a direct correlation between the formaldehyde content in adhesives and the formaldehyde specific emission rate from wood-based panels

2.13.3.5 Rammed earth

Rammed earth construction uses layers of earthen mixture that are compacted together between two rigid frames [145]. Rammed earth walls construction is one of the many green and energy efficient construction methods and has many appealing factors.

Some architects and engineers would prefer to use rammed earth as a construction material because of the impressive thermal capacity of these walls. This leads them to be highly praised for their energy savings and sustainability [146]. What also makes rammed earth an energy efficient material is its very low embedded energy consumption. according to Keefe [146], earth materials tend to have very low energy embedded energy consumption as shown in table (2-16)

Building material	Energy consumption (kWh/m3)
Cement (OPC)	2,640
Fired brick (solid)	1,140
Chipboard	1,100
Lime	900*
Plasterboard	900
Concrete block	600–800
Fired brick (perforated)	590
Calcium silicate brick	350
Natural sand/aggregate	45
Earth	5–10
Straw (baled)	4.5

Table 2-16 shows the embedded energy of rammed earth compared to other materials [146]

Using natural material like rammed earth is economical and reduces a lot of embedded energy since rammed earth mostly works by reconstructing the sand to construct the walls. However, some research has shown that using rammed earth has some health complications that might come along with using earth materials. Radon is usually present in some soils that are rich in uranium and it is formed by the radioactive decay of uranium in deep geological formations, after that the radon is transported through the ground pours by natural convection [147]. It is considered an indoor contaminant depending on the concentration of the indoor radon. A study by Walsh and Jennings [148] measured the concentration in 10 rammed earth houses in Western Australia. In their study, they have radon and progeny around 24 and 9.3 Bq/m3 EEC, respectively. Similarly, thoron and progeny measurements were around 3.9 and 0.8 Bq/m3 EEC, respectively, these readings have led to the combined radiation dose of 4.1 and 2.2 mSv/year in each house. This was significantly above the recommended level of

0.7 mSv/year by the Australian authorities [149]. Using natural materials like rammed earth is very environmentally conscious. However, it still has some disadvantages. A study by Gramlich [150] pointed out that rammed earth has some problems associated with using rammed earth is the susceptibility of water damage and abrasion.

Burghele and Cosma [151] have carried out a preliminary survey which was conducted in 35 schools in Salaj, Bihor and Satu Mare counties located in the north-western part of Romania. The schools were constructed with red bricks, cement and concrete, and the floors are covered with parquet. The result shows that among the 35 schools sampled, 24 schools showed the presence of thoron with concentrations ranging between 3 to 235 Bq/m^3. On the other hand, radon was shown in all locations with concentrations ranging from 31and 414 Bq/m^3. The researchers also noticed that 60 % of the schools have shown radon Levels that are higher than 100 Bq m23, which is higher than the WHO recommended level for indoor homes

2.13.3.6 Insulation materials

Many manufacturers use chemical components in the manufacturing of thermal insulation. The main purpose of these materials is to mitigate the conduction of heat from either leaving or entering the building. Despite their impressive performance, many of them contain hazardous materials that could affect the occupants. Some manufacturers will argue that the use of thermal insulation will not affect the occupants since they are trapped between the layers of the building elements like wall cavities and rafters. Some materials are exposed to the building occupants like roof insulations in homes. Therefore, it is critical to investigate the effect of thermal insulation to ensure the health and safety of the building occupants. According to Kovler, K. [124] most foam plastic insulation that is used in the United State contain flame retardant chemicals that are known to be persistent and harmful to the health of the building occupants. Some examples of these materials are; polystyrene, polyurethane, and polyisocyanurate). Many architects prefer to use glass fibre insulation because of their thermal performance and because they are recycled. However, there is still a significant risk from using glass fibre insulation because some of the components that are incorporated in the fibres are carcinogens. For instance, many construction workers refuse to handle fibreglass insulation due to concerns of itchiness on the skin and skin rashes [124].

2.14 Green Biofilter technologies

Among all the previously mentioned technologies, almost all of them are geared toward energy efficiency and not specifically toward air filtration. These technologies had proven to reduce energy consumption but some of them have some detrimental effects on indoor air quality. Biofilters are systems that are employed to remove excess indoor air pollutants from the indoor space. According to Liua et al [152] biofilters are known as filters that use the process of micro-biotic oxidation to degrade the air contaminants. The system uses immobilized bacteria and fungi to filter the air that goes through the biofilm [152] to achieve this a large surface area is required to filter out a large number of air contaminants. This technique is very effective in removing VOCs from the indoor air and it could be also used for cleaning wastewater. Biological purifiers work by directing the air through substrate support and colonized by a microorganism that will biodegrade the VOC while the air passes through it [153].

It is important to maintain a healthy indoor environment by making sure that the HVAC system is using the latest technology that will ensure the best indoor air quality. Even though HVAC systems are equipped with air filters, these filters sometimes produced indoor pollutants. There are many factors that might contribute to indoor air pollution like inadequate system design, distribution, cross-contamination, etc. In new energy efficient and low carbon buildings, new technologies are being tested and introduced every year and some of them might have the right balance between energy efficiency and indoor air quality [152]. The new technologies of air filters have come a long way but they still pose potential problems when it comes to indoor air quality. One potential problem for air filters is the entrapment of bacteria and fungi inside of them [152]. Moreover, by entrapping bacterial and fungi in them, they could provide a nutrient environment for fungi to grow by feeding off the trapped organic particles and consequently produce spores that will spread through the rest of the building. this problem could be addressed by sterilization, see figure (2.20).

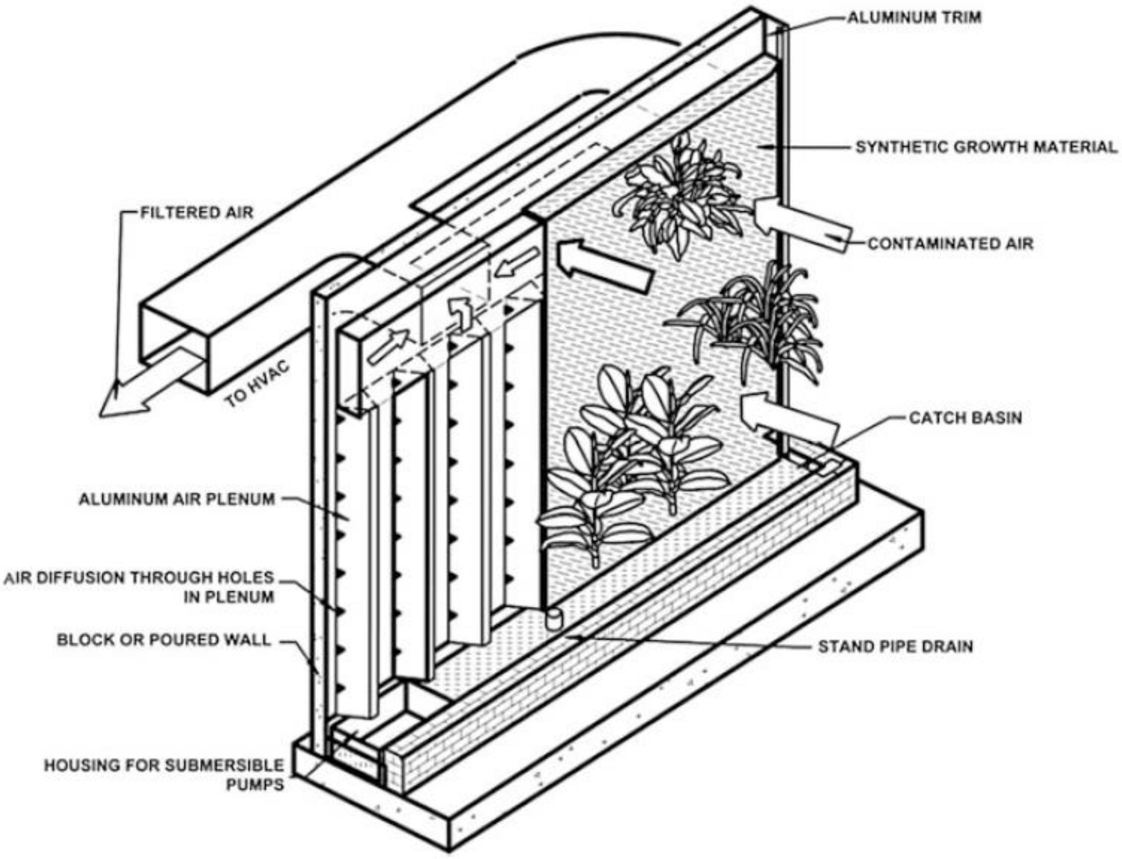


Figure 2-20 Schematic of an indoor air biofilters that utilizes plants. The biofilter consist of a vertical green wall on a porous support, which is irrigated by circulation from the catch basin. Indoor air is circulated through the

Inside most buildings, there are many kinds of pollutants and it will be very difficult to rely on one solution to remove all kinds of pollutants with a single method according to Liua et al [152]. Suspended particles can be removed by the use of filtration, electrostatic precipitation and water washing technology with filtration being the most effective among them. Harmful gases can be removed by the use of adsorption. The benefit of using an adsorption technique for the removal of gaseous pollutants is its low cost and simplicity. To remove VOCs from the indoor air, the best approach is to use photocatalytic and plasma cleaning technology. Microorganism can also be removed by photocatalytic and plasma cleaning technology, in addition, they could also be removed by Ultraviolet (UV) light technology.

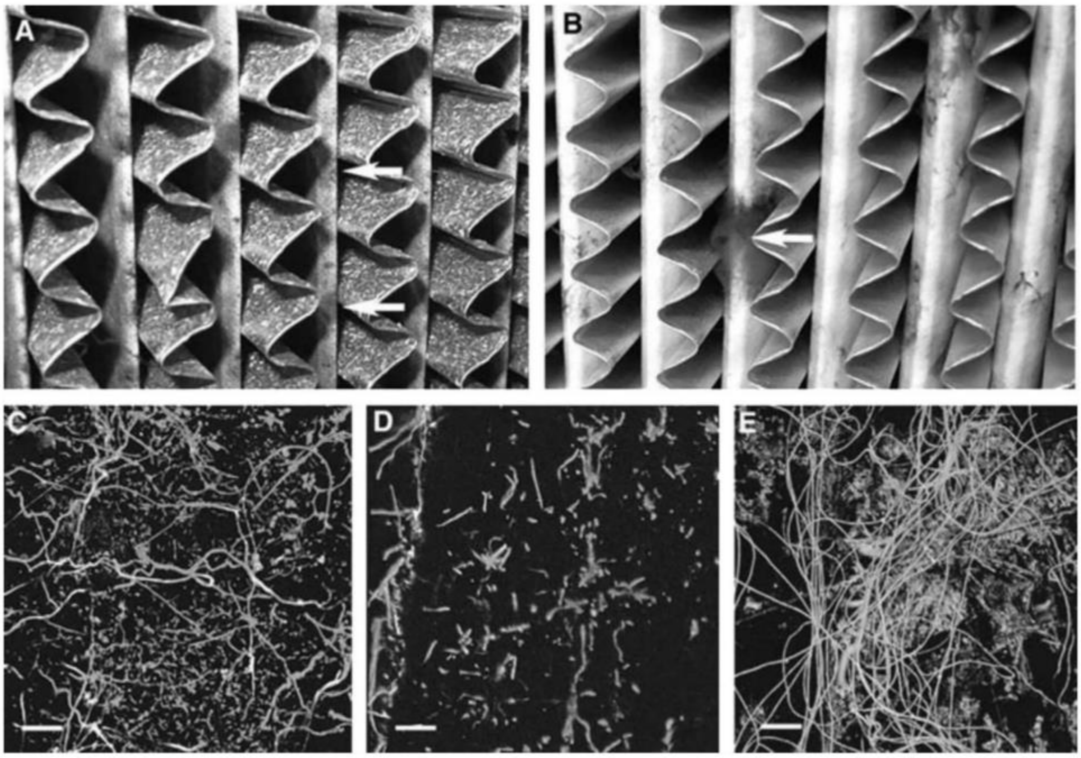


Figure 2-21 Fungal growth with penetration of micro-glass filter medium

Biofilters are not only used as air filters but they can also be utilized as an energy reduction tool, many researchers propose that biofilters can do more than filtering out the indoor air in which they could be used to increase energy efficiency. This is possible because a great portion of the energy consumed in the HVAC systems is due to the resistance of the air passing through the filters that are equipped in every HVAC systems. According to Matela [154] filters and specifically filters media consumes the bulk of the energy in the HVAC systems. The author also proposed that filters control the majority of an HVAC air handling system's energy consumption, and its operating cost. Therefore, in this article Matela [154] suggests that to conserve energy, it is important to consider improving the performance of filters and/or find different strategies to filter the air. Researchers like Strong and Burrows [155] suggest that when using systems like biofilters to reduce indoor air contaminants there will be less reliance on the HVAC system to filter the air and therefore less energy consumption [156]. Plants can help reduce the effect of thermal energy on the building and thus allow for energy-saving to take place. According to Wong et al [157], the growing medium of plants can aid in the insulation of the building and, therefore, reduce the energy consumption of the building. The way plants can reduce the effect of heat on the building is by reducing the heat reradiated by greened surfaces and with the help of evapotranspiration emitted from the plants [158]. According to Raji et al [159], biofilters can contribute to the reduction in energy consumption in three ways. The first is with the cooling effect of the plants and substrate through evapotranspiration. The second way is by the insulation factor that occurs by the microclimate of the plant. The third way is by the shading effect of the plant, see figure (2-22).

Green technology can be divided into two categories. Some systems are either rooted into the ground and use a regular soil for the plant to grow vertically on the wall using a climbing plants type, or the rooting of the plant could be used by an artificial substrate or potting soil. In these two categories, the systems could be described based on the reliance on the façade for the plant as a guide to grow upward figure (2-23) [158].

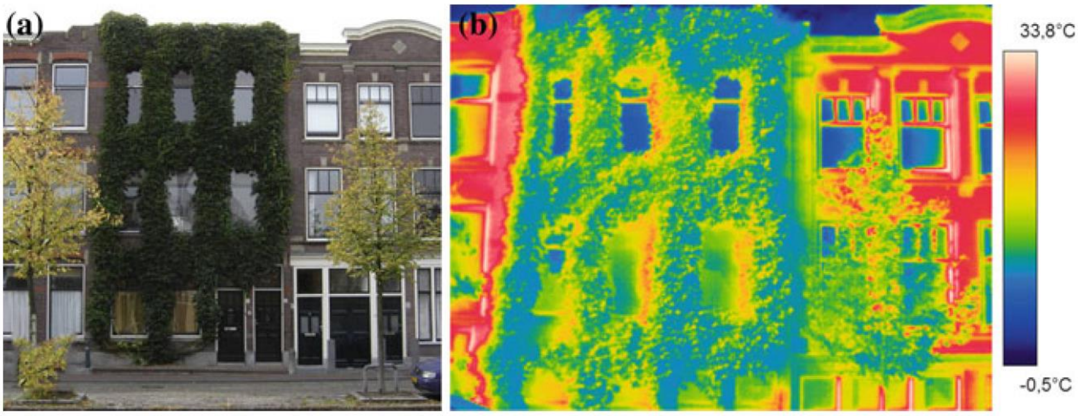


Figure 2-22 Boston ivy (parthenocissus) rooted in the soil and applied directly against the facade in Delft summer 2009. [158]

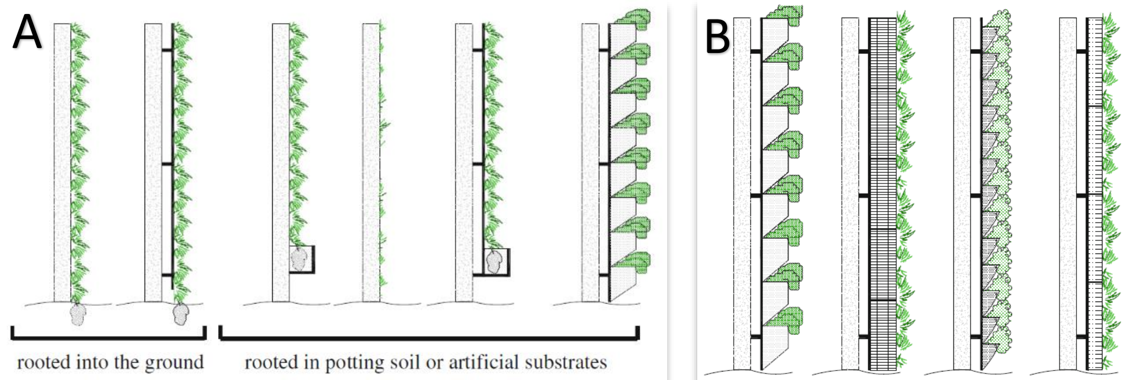


Figure 2-23 (A) Discoloured patches on the filter material of filter load side (arrows). (B) Brown fungal colony on the surface of filter supply side (arrow). (C) Fungi stained filter load side, hyphal elements on the filter medium surface, showed by laser confocal [158]

Plants are very effective in removing many kinds of pollutants from inside the building like VOCs, PMs, and CO_2 [158]. The plants use the absorbed VOCs to extract the carbon compound necessary for the microorganism to feed on. According to the previously mentioned research, this strategy is sometimes compromised due to the fact that VOC concentration inside the room may not be enough to provide a persistent source of carbon for the microorganism growth to be sustained. In order for the active green wall to perform properly, a constate rate of microorganism growth should be sustained and that could happen if a larger amount of air is supplied to the substrate that contains these microorganisms [158].

The most common kind of biofilters is known as the vertical active green wall system. Most biofilters either use an active system that will drive the airflow through the plant substrate, see figure (2-24). The air forced through the substrate is essential to filter out the contaminants of the air. Another active method is to use an intermediate mobile aqueous. This method relies on water essentially to carry out the pollutant as a medium [156].

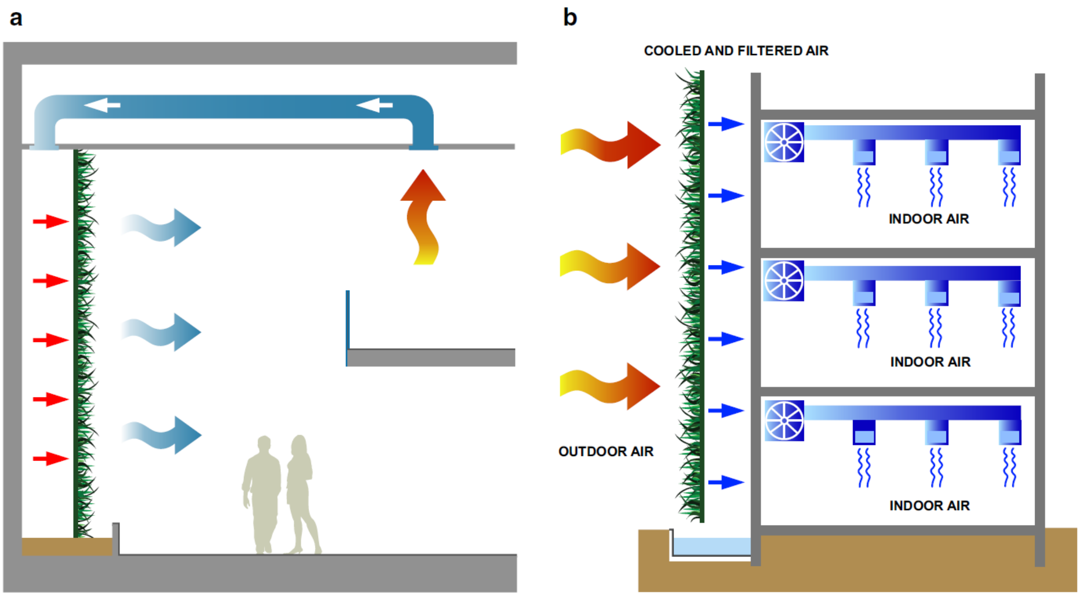


Figure 2-24 Operation of active living walls : A. indoor recirculating system, B. as a treatment for inlet outdoor air. blue arrows indicate filtered air, red arrows indicate pre-filtered air [156]

Active wall systems can be used to remove suspended particulates. According to Irga et al [156]. the substrate that is used to remove VOCs from the indoor air can also be used to remove PMs with the help of the mechanical ventilation system. The principal is very similar to the regular filter of the HVAC system in which a porous media is used to filter out the PMs from the air. In a study done by Irga et al. [160], they have analysed the potential to remove PM using biofilters using the same method to test standard air filtration media. When comparing the single-pass PM filtration efficiency the plant green wall maximum filtration efficiency peaked at an airflow rate of 11.25 L s-1 per 0.25 m^2 modular unit. Higher flow rates have shown lower efficiency. The best result recorded by authors was 53.51 ± 15.99% for PM_{10}, and 48.21 ± 14.71% for $PM_{2.5}$. It is worth noting that the study has used a single type of plant. In other studies like the one in Pettit et al. [156] they have studied the effect of the botanical component of an active green wall PM filter. The study has examined different kinds of plants. The study shows that all botanical biofilters have surpassed the efficiency of the biofilters that was made of substrate only. This result has shown that green walls plant play a significant role in PM filtration with fern specious being the most effective of them [156].

In a research study done by Ondarts et al. [161] where they have studied the biological treatment (biofiltration) for the removal of indoor air pollution by using a model effluent with low concentration of pollutants. Biofilters have shown to reduce a variety of contaminants such as ammonia, hydrogen disulphide, aromatic, ketones [161]. This procedure has proven to be effective in removing large range of volatile pollutants such as VICs (ammonia, hydrogen disulphide) or VOCs (aromatic, ketones) at concentration levels from particles per billion volume (ppbv) to particle per million volume (ppmv). The result of this study revealed that During the 75 testing days, all the VOCs included in this study were removed using the model effluent with an average efficiency of 90 % except for trichloroethylene (TCE). The test has shown that the concentration of butyl acetate was under the limit of quantification or detection (respectively 0.7 and 0.2 µg m -3) corresponding to efficiencies higher than 98.7% and 99.7%. The researchers also realized that there were some by-products detected in the biofilter outlet. These compounds are the result of the biodegradation of VOC compounds like (acetaldehyde, methanol, 2-propanol). The biofilter that they tested has shown correlation with the amount of water used for the irrigation of the plants and the removal efficiency of pollutants [161]. The researchers compared different watering rate and noticed that after 6 days without any watering, some removal efficiencies of hydrophilic and fairly hydrophobic compounds (butanol, formaldehyde and toluene) decreased. Other studies showed that when the water content is lower than 40%, the removal efficiencies decrease, see figure (2-25).

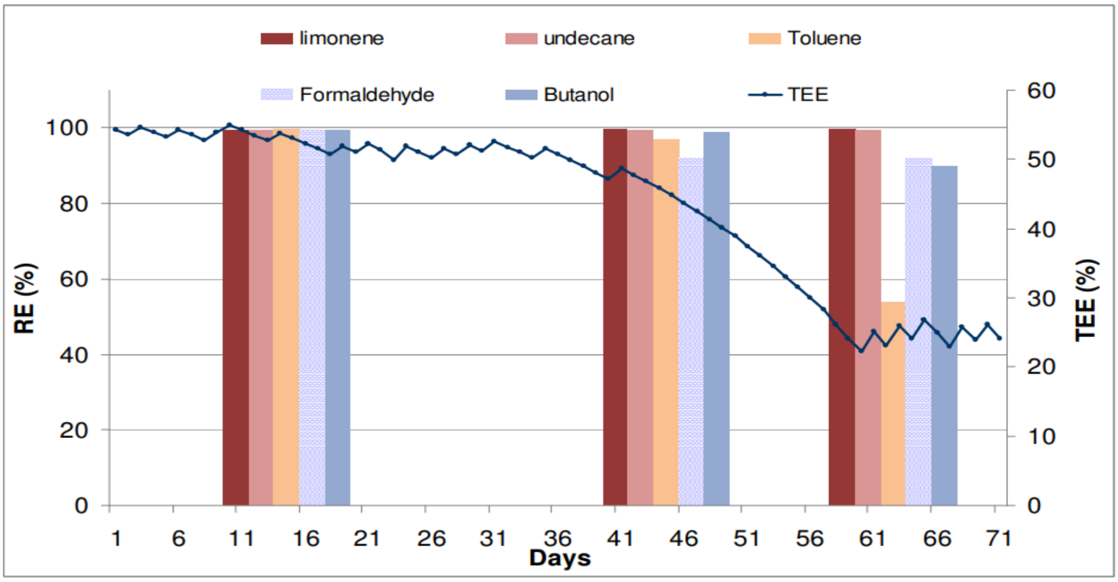


Figure 2-25 Biofilter water content (TEE) evolution and average removal efficiencies (RE) for hydrophobic (limonene and undecane), fairly hydrophobic (toluene) and hydrophilic (butanol and formaldehyde) compounds. [179]

Many studies have been conducted to measure the efficiency of biofilters to remove CO_2 from the indoor air atmosphere. In one study by Pennisi and Iersel [162] they analysed the removal efficiency using common indoor plants and found that the rate of photosynthetic is limited and therefore, it would require an exaggerated volume of plants to remove a considerable amount of CO_2 from the air. Another study by Tarran et al. [163] have tested the removal efficiency of three potted plants on the removal of CO_2 and found that three or more potted plants were able to reduce the concentration of CO_2 by 10 % in an air-conditioned building, and a 25 % reduction in a non-air-conditioned building. when it comes to energy consumption, the reduction of CO_2 can also help in the reduction of energy consumption. According to Afrin [164], the incorporation of phytotechnology or CO_2 mitigation can greatly help in reducing energy consumption by reducing the need to ventilate the air from the pollutants like CO_2. In fact, the reduction in HVAC energy consumption was estimated to be 10 % with the use of appropriate green plant design [158].

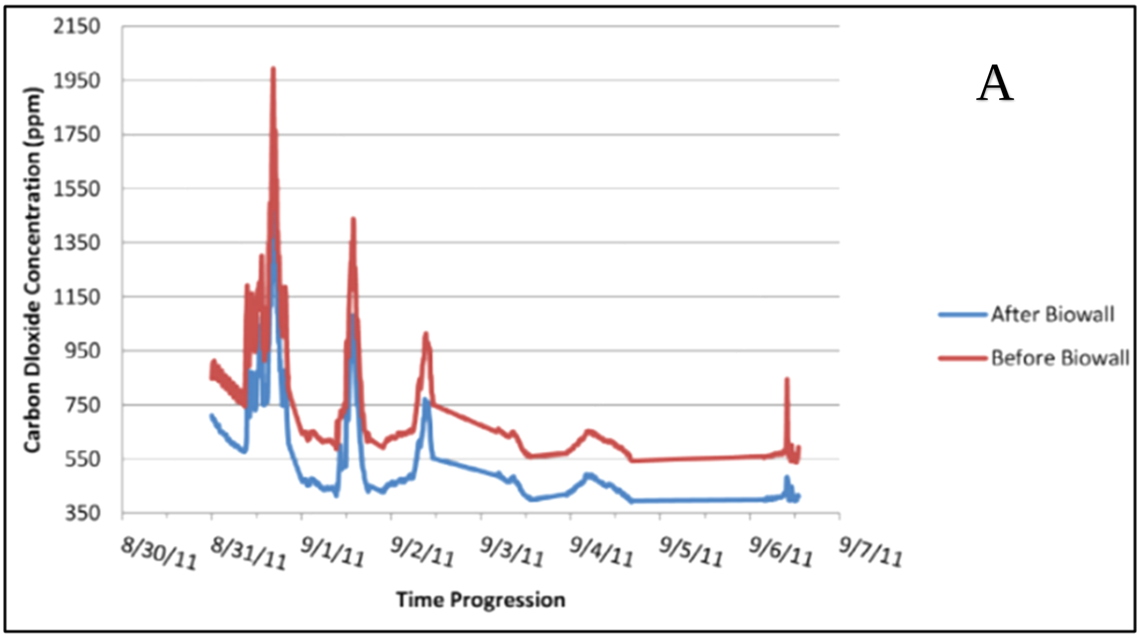
Most biofilters rely on microorganisms to filter out the air inside the space. These microorganisms themselves could cause problems inside the indoor environment. According to Torpy et al [165] some microorganism can lead to problems like fungi.

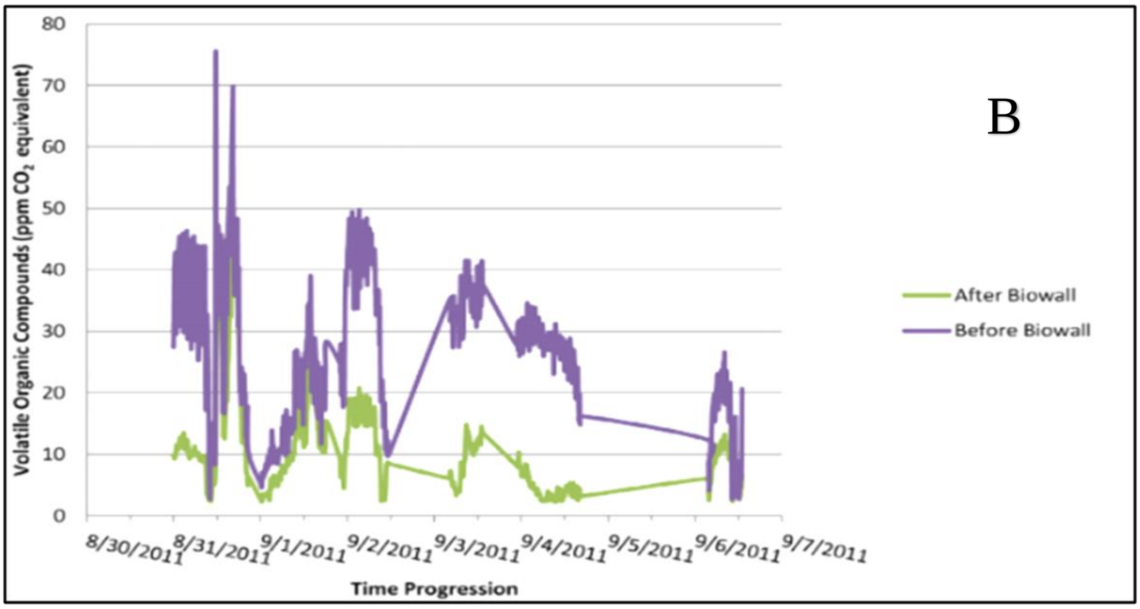
They can proliferate when the relative humidity inside the space increases over 80% [166]. A research study by Torpy et al. [165] have tested the cleaning potential of potted plants. The study was conducted in 54 offices. The researchers have tested the presence of fungal spores with and without potted plants presence. They have found that there is an increase in fungal spores with the use of plants but the increase was within the safety limit and it is still lower than the outdoor samples [158].

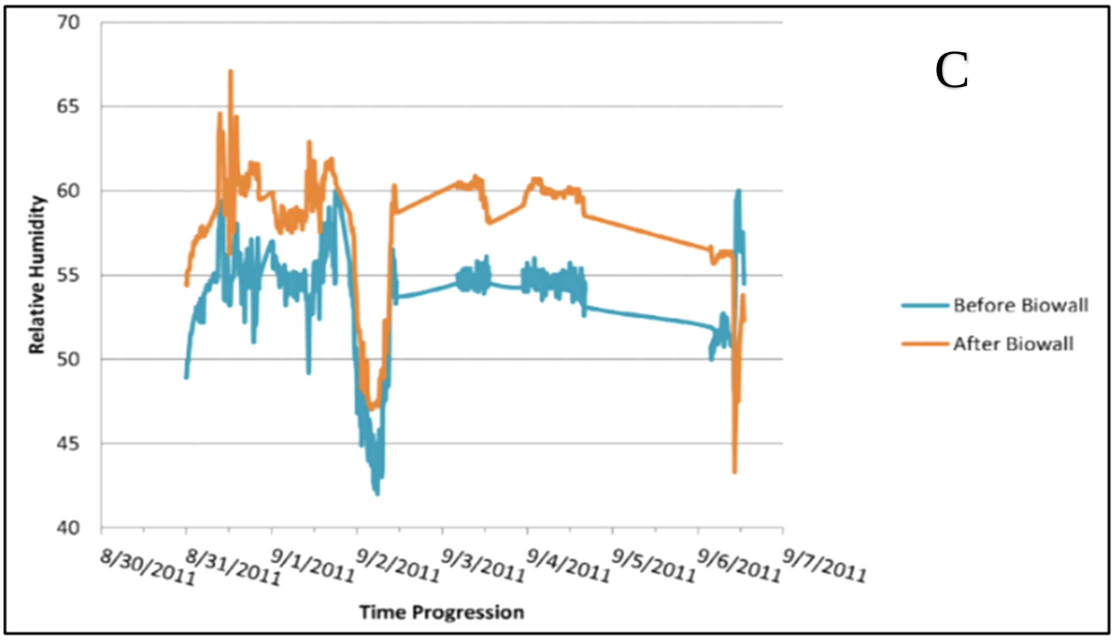
Rodgers et al [167] suggested that the main objective of a biofiltration system is to filter the indoor air inside homes. The authors expected that a certain amount of energy conservation to be achieved by using biofilters or “Bio-wall” over other conventional methods of filtration in energy efficient homes. The authors of the study [167] used a piloted study to examine the efficiency of the Bio-wall filtration. They had chosen several types of pollutants to monitor including carbon dioxide, and (VOCs), along with the monitoring of ambient temperature and relative humidity. The study was conducted in a highly efficient home that is powered by solar panels. The Biofilter or “Bio-wall” was integrated into the HVAC system and it was designed so that the HVAC system can operate independently from the Bio-wall. In case the Bio-wall was inactive figure (2-26).

Figure 2-26 A. Novel biofilter unit installed in home for pilot study; B. An example of an original biofilter design for indoor applications [4-185].

The charts in figure (2.27) show that the changes in indoor air pollution, temperature, and relative humidity occur due to the introduction of bio-wall. The downstream of VOCs decreased by 25% (3–41 ppm of CO_2 equivalent units) compared to the upstream values of (3–76 ppm of CO_2 equivalent units). The CO_2 concentration has also decreased by 35% in the downstream (360–1370 ppm) compared to the upstream of (550–1975 ppm). The temperature decreased was between 3-5 degrees Fahrenheit. The relative humidity on the other hand has increased by 7% (43–67%) in the upstream while measuring (42–60%.) in the downstream. From these results, the researchers have concluded that a noticeable amount of energy could be conserved by using bio-walls in energy efficient buildings [167].







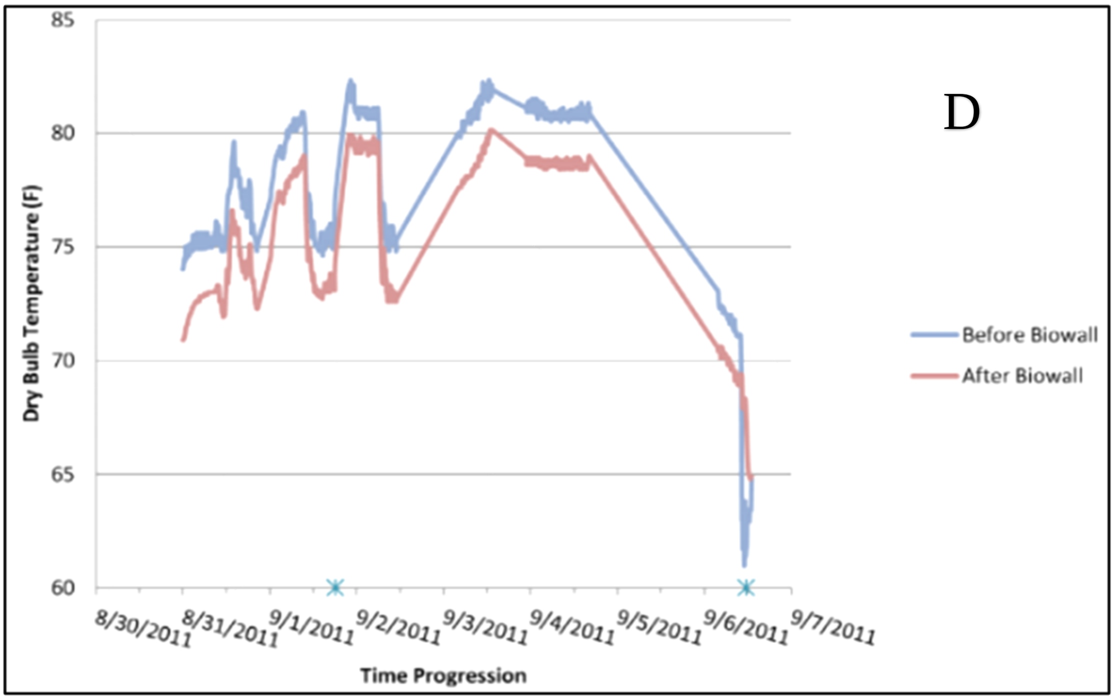


Figure 2-27 A. CO_2 reduction in residential test building using bio-wall; B. VOC reduction in residential test building using bio-wall; C. Relative humidity increase in residential test building using bio-wall; D. Temperature decrease in residential test building using bio-wall [167]

A study by Torpy et al [168] tested the efficiency of green wall system's capacity to remove CO_2 from indoor air. The researchers concluded that indoor plants have the ability to remove CO_2 from indoor atmosphere even in low light levels. The best plants to remove CO_2 were Chlorophytum and Epipremnum. These plants have managed to remove a considerable level of CO_2 at light level of 50 µmol/ m^2.s. The result shows even greater removal of CO_2 in higher light levels at 250 μmol/ m^2.s. The researchers have pointed out that in order for green wall system to function properly some conditions needs to be present. The first condition is that the plant choice should be taken into consideration because not all plants have the same effect on CO_2 removal. This should be important in case a smaller installation is required, the more efficient plant should be chosen. The second condition is that a reasonable amount of light must be present. This is important because the researchers realized that at high levels of luminescent light like 250 μmol/ m^2.s the plant was removing CO_2 at the maximum rate. While at low light levels like 10 – 15 μmol/ m^2.s, the reverse happened where the plant started to increase the levels of CO_2 concentration [168].

A study done by Irga et al. [169] have used laboratory settings as well as two field studies to test the cleaning efficiency of active green walls. The result of the study has shown that in all field experiments there was no noticeable increase in the culturable fungal counts. The overall fungal propagule density of 91 ± 12 CFU/m3 [169]. This is a huge reduction compared to the outdoor culturable fungal count which is near 523 ± 72 CFU/m3 table (2.17) shows the different fungal counts in an active condition, passive condition, and reference condition (not plants implanted).

Fungal genera	Density of fungal propagules (cfu/m^3)			
	Reference indoor	Active	Inactive	Reference outdoor
Cladosporium	46 ± 10	44 ± 8	32 ± 12	237 ± 62
Alternaria	20 ± 8	22 ± 10	21 ± 8	18 ± 13
Penicillium	10 ± 6	8 ± 4	5 ± 3	15 ± 6
Sterile mycelia	9 ± 4	15 ± 9	19 ± 8	31 ± 23
Aspergillus ochraceus	4			
Veronea	2	1		
Aureobasidium pullulans	2			4
Yeast	2	4	9 ± 5	7
Geotrichum	2			
Phoma	2			
Rhizopus		3		
Chaetomium			4	
Chrysosporium			2	
Cladophialophora			3	
Curvularia			3	4
Aspergillus niger		3 ± 2	2	
Paecilomyces				53 ± 42
Epicoccum				17
Acremonium				36 ± 33
Fusarium				12
Scopulariopsis				

Table 2-17 Mean concentration (CFU/m3) and SEM of airborne fungal detected in an office with two plant wall modules (office experiment 2) [169]

Mallany et al [170], compared two biofilter systems in regards to their contribution to ambient airborne spores. The first system was the Canada Life Environmental Room (CLER) system which is a prototype biofilter built into a 160 m2 ground floor meeting located in the Canada Life Assurance Company (Toronto, Ontario, Canada). The system incorporates 20/m^2 of hydroponically grown tropical species, a 12 m^2 moss wall cover, and a 3.5 m^3 aquarium that works as a bioscrubber. The air is forced into the wall by dedicated air handling units see figure (2-28). The second system is the Northern Centre for Advanced Technology (NORCAT) (Sudbury, Ontario, Canada) biofiltration system. This system also houses hydroponically species but, in this system, they used the northern plant species. Another similarity between the two systems is that the NORCAT system also contains a moss wall covering of 4 m^2 which acts as a bioscrubber. The air delivered into the system is through a variable speed exhaust fan. Theoretically, these systems could provide the conditions for bioaerosols introduction to

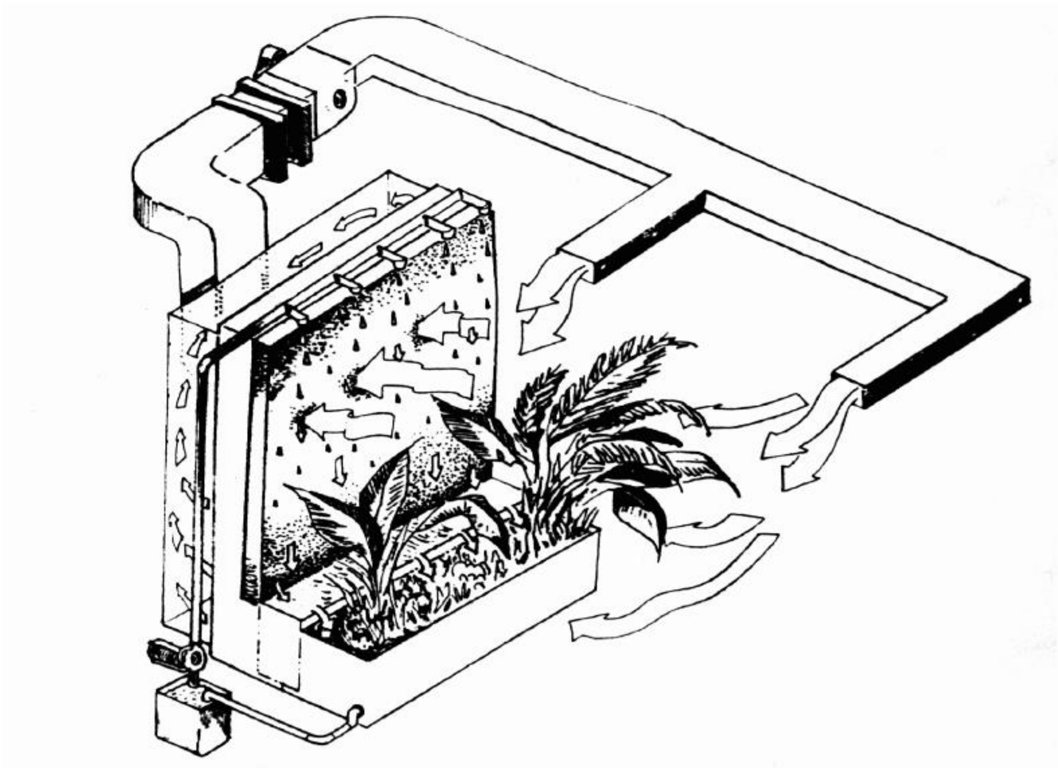


Figure 2-28 schematic of an indoor air biofilter [170] the indoor space. For example, the wet biomass can be a source of bioaerosols and spores to proliferate and travel to the indoor space.

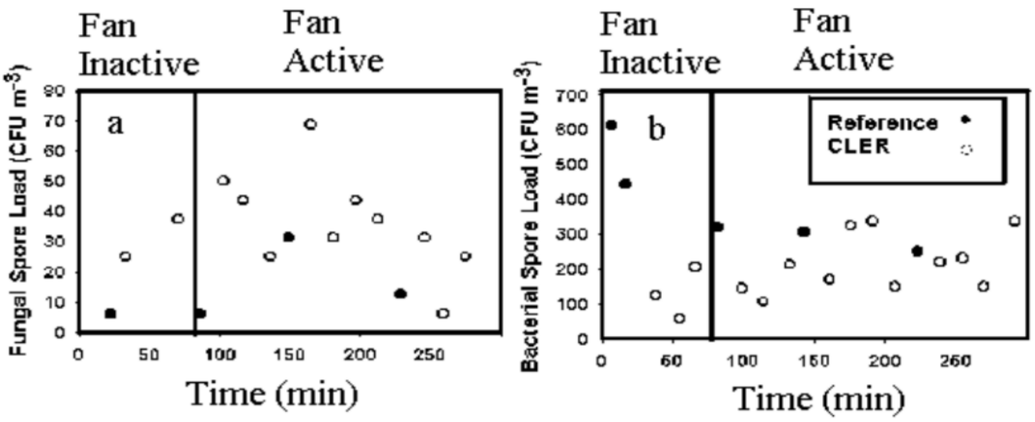


Figure 2-29 fungal (a) and bacteria (b) spore loads (CFU/m3) following biofilter fan reactivation [[170]

The result of the two tests shows that there was no viable fungal spore neither there were significant bacteria concentrations increase over the reference site, see figure (2-29). the mixing experiment Results indicated that increased bacterial concentrations were correspondent to the watering system. The increase in bacterial concentration was not high to be unsafe and with modification to the irrigation and maintenance schedules, the bacterial and fungal concentration could be reduced [170].

According to Mallany [171], indoor air biofilters that contain mosses and microbes have the ability to take contaminated air from the indoor space (the influent), pass it through the wet biomass that will absorb and degrade contaminants such as VOCs and then return the clean air (the effluent) to the indoor air space [171]. The result of the tests revealed that an increased bioaerosol measurement has been observed in the affected airspace after a major disturbance to the biofilter either by a short-term increase observed during the initial airflow injection start-up or after extended periods of no airflow. The disturbances with the biofilter operation are inherent like the changes in airflow. These changes in airflow produce only a minor increase in the biofilter concentration recorded in the exhaust and no observable effects in the indoor space. The presence of pathogens such as Legionella pneumophila was measured and the result reveals no detected levels in any sample. From these results, the researchers can concur that at normal operation, the biofilter system does not compromise indoor air quality through the production of microbes like (bacterial or fungal spores), or through the production of the pathogen like (Legionella pneumophilia) [171].

A study by Darlington et al [172] examined the performance of a large biofilter composed and its impact on indoor air quality. The study included different ecological zones including aquatic, hydroponic and pseudo wetland regions in a relatively sealed office building space. The examination includes the analyses of VOCs in terms of total TVOCs levels and formaldehyde levels and the inclusion of aerial spores. The aerial spore measurements were conducted on two separate occasions with one year in between the two measurements. The measurements were conducted either during the watering of the biomass or after watering of the bio Mass with an automated low-pressure mist irrigation system. Irrigation water was taken from the recirculating water of the aquatic system [172]. The data collected from the room are presented in table (2-18). The result in general showed that fungal spore levels preset in the room were higher than mean levels reported for other commercial indoor spaces. However, the fungal levels were within the reported ranges). More than 90% of the office buildings in the Paris area with HVAC systems had fungal spore levels below 50 CFU/m^3.

During irrigation cycle	Year	Total spore CFU m^{-3}	Yeast CFU m^{-3}	Mould CFU m^{-3}	Bacteria CFU m^{-3}
0	95	174	14	107	53
0	96	112	9	76	27
1	95	443	117	179	146
1	96	161	1	98	62

Table 2-18 Airborne spore measurements in the room housing the biofilter affected by irrigation. (0) refers to sprayed hydroponic and epiphytic planting with water from the recirculating aquarium or were collected 5 minutes after the cycle; (1) samples collected during the irrigation cycle [172]

According to Raji et al [159], there are a couple of systems that uses plants on the vertical side of the building. One of these systems is called the green façade system. In this system, the plants are placed on the outer side of the building right on the façade. The other system is called the living wall system. Living walls are more complex compared to green facades. Their complexity lays in their structure including special supporting elements, growing media, the requirement of an irrigation system, and the variety of plants types installed in the system. Due to their complexity, living wall systems are more expensive than green façade and require more maintenance. Fortunately, because of the modular structure of living walls, plants can be pre-cultivated and then transferred to their place, as a result of which they can grow more efficiently. See Table (2-19) for detailed definition and comparison between green façade and living wall system [159]

Table 2-19 Vertical greening systems, definitions and their characteristics [159]

	Green wall system	Definition	Characteristics
Green facade	Direct façade greening	This is counted as the traditional way of greening facades. In this system climbing plants are directly connected to the façade and using building materials as a support. Plants are mainly rooted in the ground or planter boxes	Climbing plants can hardly grow up to 25 m without supporting structure and it takes a long time They accelerate façade materials deterioration and make maintenance more difficult
	Indirect façade greening	In this system for providing a gap between the façade and the green layer, some structural supports e.g. wire, mesh or trellis are used. Plants can root in the ground, on the roof or in substrates attached to the wall	Double skin green façade increases the insulation properties of green walls by introducing a stagnant air layer between wall and green layer, protects the facade materials from demolition and supports plants to grow faster
Living wall	Living wall	Living walls consist of modular pre-cultivated panels; each contains a growing medium and irrigation system to provide all of the nutrients for plants. They have also a waterproof layer to isolate the façade from moisture penetration	In these systems a large variety of plants can be added including ferns, small shrubs, and perennial flower If necessary, the modular structure makes the replacement of plants easier
	Indoor living wall (Bio-filters)	Bio-walls are indoor vertical greening systems that are mostly used for filtration of the indoor air and enhancement of aesthetic values of the indoor environment especially in office spaces. They can purify the air passively through natural convection or by using a fan to facilitate the circulation and improve its efficiency	These systems need a high maintenance and are more expensive compared to green facade

Some researchers propose indoor active living walls as a good method to enhance indoor air quality. most importantly, the living wall system can work either independently or codependent with the existing HVAC system. The cooling effect of indoor living walls is the result of two characteristics inherited in plants which are the evaporation from constant irrigation and transpiration from vegetation. In addition, their capacity in

Oxygen production and biofiltration of volatile organic compounds (VOCs) and CO_2, reduce the need for air filtration [159]. In a field study conducted by Franco-Salas et al [173] in the Mediterranean climate in Spain. The study compared four different types of substrate of living walls. Two of the substrate were synthetic and the other two were organic substrates. The objective of the study was to examine the effect these living wall systems have on the indoor environment. The measurements taken by the researchers indicated that there was a reduction in the indoor ambient air temperature by 4 °C. The temperature reduction was even higher close to the vegetation with a reduction of up to 7 °C. However, there was an increase in relative humidity near the living wall of around 15%.

2.15 UK Building regulation and CIBSE Guide

The development of low carbon building needs to meet several conditions set by the UK regulation and it also needs to be compliant with the Chartered Institution of Building Services Engineers (CIBSE). These institutions have developed the building code in order to ensure that new buildings are preserving energy and are compliant with the new building regulation in terms of energy efficiency. When it comes to fuel and power consumption the Part L1A building regulation [174], states that reasonable provision shall be made for the conservation of fuel and power in the building by first Limiting heat gain and loss. To achieve this, the design of the building must ensure that the building construction is optimized to conserve as much heat as possible. Not only that but also the pipes, ducts and vessels should be also optimized for energy efficacy. The second strategy listed in the Part L1A of the building regulation is to incorporate building services that are energy efficient, have effective control, and are commissioned by testing and adjusting as necessary to ensure they use no more fuel and power than is reasonable in the circumstances [174].

Another area discussed in the UK building code regulation to ensure the compliance of newly constructed building is applied five main criteria that have to be met by the developers of the building. The first Criteria states that in accordance with regulation 26, the calculated rate of CO_2 emissions from the dwelling (the dwelling CO_2 emission rate DER) must not be greater than the targeted CO_2 emission rate (TER). Additionally, in accordance with regulation 26A, the calculated Dwelling Fabric Energy Efficiency

(DFEE) rate must not be greater than the Targeted Fabric Energy Efficiency (TFEE) rate. The second criteria state that the performance of the individual fabric elements and the fixed building services of the building should achieve reasonable overall standards of energy efficiency. The third Criteria states that the dwelling should appropriate passive control measures to limit the effect of heat gains on the indoor temperature in summer regardless of whether the dwelling has mechanical cooling. The fourth Criteria states that the performance of the dwelling, as-built, should be consistent with the DER and DFEE rate. The fifth Criteria state that the necessary provision for enabling energy-efficient operation of the dwelling should be put in place.

2.15.1 Indoor air quality and ventilation Guide

Good indoor air quality is defined as air with no known contaminants at harmful concentrations [175]. When constructing a building, air quality should not be compromised for the sake of reducing energy consumption. Therefore, Ventilating the building is very important for removing excess moisture and contaminants from the building and bringing in fresh air for breathing. Ventilation is simply the removal of stale indoor air from a building and replacing it with fresh air from the outside [176]. According to the CIBSE [177], There are several reasons as to why ventilation is required the first is to provide fresh air from metabolism and dilution and removal of pollutants from the air. The second is to extract contaminants from their source. The third is to satisfy the combustion need for appliances such as gas cookers, boilers and unvented heaters. The fourth reason is to spread and distribute the contaminated air. The fifth reason is for space pressurization to inhibit the infiltration of pollutants from outside. The sixth reason is to suppress the emission rate of internal sources of pollution [177].

Regulations and standard:

Regulation or standard	Area covered	Requirements
Building regulation part F1 (England and Wales)	Provision of adequate air	Size of opening areas for Background ventilation Rapid ventilation
Building regulation part J1 (England and Wales)	Provide adequate fresh form combustion devices	
EH40/2002. Workplace exposure limit.	Limit exposure to various pollutants	Provide adequate fresh air, infiltration.
Air quality guide and cleaner air for Europe	As above	As above
Ambient air quality and clean air for Europe- EE directive 2008/50/EC	Limit exposure to SO_2 and suspended particulates	
HSE approved code of Practice L24: workplace health, safety and welfare	Ensuring minimal contamination of mechanical systems including air conditioning system.	Regular maintenance of the system
BS EN 13986: 2002	(Emission From) wood panels	Selection of materials with low emission, regular cleaning replacement at end life.
BS EN 14080: 2005	(Emission From) glued laminated	As above
BS EN 14342: 2005	(Emission From) parquet flooring	As above
BS EN 14041: 2004	(Emission From) vinyl, laminated and rubber flooring, linoleum and carpet	As above
BS EN 13964: 2004	(Emission From) suspended ceiling tiles.	As above

The building regulation approved document F gives all the details that architects and engineers need to establish new buildings with adequate amount of ventilation. According to the building regulation approved document F, by following the regulations and under normal conditions, the building will be capable of limiting the accumulation of moisture, which could lead to mould growth and pollutant originating within the building [177].

The most common way of providing the building with fresh air is by using a mechanical ventilation system. The mechanical ventilation system will use energy to heat the outside air, and to extract air from the inside to the outside of the building. Consideration should be taken if in certain circumstances there is no need for mechanical ventilation systems [177]. In the design stage, architects and building engineers should consider the air permeability of the building and whether or not natural ventilation or infiltration will be considered as a secondary source of ventilation [177]. The ventilation provision recommends for new dwellings in the approved document:

(1) The default option in which the guidance assumes that the building has an air permeability of zero (air change per hour) ach. Thus, no infiltration inside the building. The building will be entirely relying on installed purpose-provided ventilation.

(2) The alternative option, the guide assumes an infiltration of 0.15 ach. The reliance on mechanical ventilation is less than the first option. This option is suitable for buildings that are leakier than 5 $m^3/h.m^2$.

2.15.2 The ventilation strategies adapted in the approved document F:

Extract ventilation

These devices are best installed in regions of the building where most of the contaminants and water vapour accumulates. Some examples like the kitchen, the bathroom, or mechanical rooms [176].

2.15.2.1 Whole building ventilation

These devices are designed to provide fresh air and to dilute and disperse residual water vapour and pollutants that have not been dealt with by the extract ventilation device. In addition, they can remove other sources of pollution and excessive water vapour from other parts of the building [176].

2.15.2.2 Purge ventilation

The purge ventilation would be best utilised as a ventilation aide in the incidence of high concentrations of pollutants and water vapour released occasionally in certain activities such as painting, decorating, or burnt food smoke [176].

2.15.2.3 Occupants comfort and indoor air quality

Table 2-20 approximating thermal comfort variable and their effect on (IAQ) [176]

Variable	Value		Effect on (IAQ) of exceeding these values
	Winter	Summer	
Dry resultant temperature (°C)	21-23	22-24	Increasing the dry bulb temperature will increase the release of VOCs, and possible reduction I (IAQ)
Relative humidity (%)	40-70	40-70	High levels of relative humidity will increase condensation, thus mould and other organics might form
Local air speed (m/s)	0.1	0.3	Increasing airspeed may improve the (IAQ), but it might also increase the levels of discomfort.

2.15.2.4 External sources of pollutions

Condition	Perceived air quality	CO_2 (mg/m^3)	CO (mg/m^3)	NO_2 (mg/m^3)	SO_2 (mg/m^3)	Particulate (mg/m^3)
Excellent	0.0	680	0.0-0.2	2	1	< 30
Intown, good air quality	< 0.1	700	1-2	5-20	5-20	40-70
Intown, poor air quality	> 0.5	700-800	4-6	50-80	50-100	> 100

Table 2-21 External sources of pollutions:

2.15.3 Ventilation system [176]

The natural ventilation flow rate depends on a number of factors:

1- Inside and outside air temperature.

2- Local wind speed and pressure coefficient.

3- Location, size and nature of the opening.

4- Nature of airflow path within the space.

5- Airflow regime.

2.15.3.1 Mechanical ventilation [176]

The mechanical ventilation system uses the inlet and outlet ducts to ventilate the space. In some cases, the system could have either supply only or extract only with natural ventilation.

2.15.4 Required ventilation flawless for good IAQ

Room	Main ventilation	Continuous extract (l/s)	
		Minimum high rate	Minimum low rate
Kitchen	30 (adjacent to cooker) 60 (elsewhere)	13	Greater than hole building
Utility room	30	8	Ventilation rate given in 3.1
Bathroom	15	8	Ventilation rate given in 3.
Sanitary		6	Ventilation rate given in 3.

Table 2-22 Required ventilation flawless for good IAQ:

2.15.5 Fresh air

In an office environment, the ventilation rate is 10 l/s per person. Thus, the total fresh air flow rate for a room is given by the flow rate per person times the number of occupants [176]. Flow rate required:

$$V = \frac{Qhtq}{\rho\ CP\ (Ts - Tr)} \text{ (Equation 1)}$$

V = required warm air ventilation rate (m^3/s)

Q_{htq} = room heating load (W)

ρ = air density (Kg/m^3)

CP = specific heat capacity of air (1020 J/K)

T_s = air supply temperature

T_r = room air temperature

2.15.6 Flow between spaces and pressurization

Ventilation is used to maintain pressure differences between spaces. Extract ventilation drives the contaminated air through the fan and out of a roof or wall-mounted exhaust vent. The resultant under-pressure cause make-up air to come from adjacent spaces. The flow rate must be maintained at an equal pressure rate of extracted rate and intact air. Pressurization may be obtained by assuming the sum of the flow rate into and out of the space is equal to zero.

$$\sum_{i=1}^{n} \rho i\ vi = 0 \text{ (Equation 2)}$$

P= is air density (Kg/m^3).

V_i= flowrate (m^3/s).

N= number of flowrate paths.

pollutant	Type	Sources	Effects	Short term		Long-term	
				Concentration	**Average time (hours)**	**Concentration**	**Average time (hours)**
Benzene	VOC	Solvent, fuel combustion	Carcinogen			5 (ppb)	1
Carbon dioxide	Gas	Combustion appliances, occupants	Causes loss of concentration	500 (ppm)	8		
Carbon monoxide	Gas	Combustion appliances	Lethal at low levels	26 (ppm) 86 (ppm)	1 0.25		
Formaldehyde	VOC	Insulation, products, particle board	Strong irritant, carcinogen	80 (ppm)	0.5		
Hydrogen sulphide	Gas	Decaying organic waste	Strong odor, irritant	5 (ppb)	0.5		
Nitrogen dioxide	Gas	Combustion appliances	Lung irritant	150 (ppb)	1	21 (ppb)	1
Ozone	Gas	Electric equipment, (e.g. motors), Ultra violet light source	Lung irritant	60 (ppb)	8		
Particle (non-biological)		Combustion appliances, aerosols sprays, clothing, carpets, wallboard	Allergen, cause of bronchial asthma and allergic rhinitis and my aggregate eczema symptoms	150 (μ/m^3)	24	50 (μ/m^3)	1
Particles (biological)		Humans, pets, insects, moulds, air conditioners, plants	Allergen, cause of bronchial asthma and allergic rhinitis				
Radon	Gas	Building materials (e.g. various rocks), soil	Risk of lung cancer	400 Bq/m^3	2160	200 Bq/m^3	1
Sulphur dioxide	Gas	Traffic exhaust, combustion appliances	Lung irritation	100 (ppb) 46 (ppb)	0.25 24	19 (ppb)	1
Tetrachloroethylene	VOC	Solvents		250 (μ/m^3)	24		
Toluene	VOC			68 (ppb)	168		
Water vapour		Washing, cooking, respiration	Mould/fungi growth (relative humidity should be maintained below 60%). High and very low concentrations cause thermal discomfort				

Table 2-23 CIBSE guide for common indoor pollution sources and exposure limit [177]

2.16 Types of ventilation system

There are four main types of ventilation systems according to Awbia [178]

2.16.1 Mixing ventilation (MV)

The main objective behind Mixing ventilation (MV) is to mix the contaminated air with fresh air to dilute the air contamination of the room. The supply of air is usually from the ceiling at high velocity (around > 2.0 m/s). in general, the ventilation effectiveness of these systems is not great compared to other types of ventilation [179].

2.16.2 Displacement ventilation (DV)

The main principle of the displacement ventilation system (DV) is to replace the contaminated air with fresh air from the outdoors. In this scheme, the fresh air is supplied at a low speed (usually less than 0.5 m/s) near the floor and then the air heats up and moves upwards. What is unique about this scheme is that it creates a thermal and contamination gradient inside the room where the lower parts of the room are different from the higher parts. It is more energy efficient because of the lower fan speed required and it has higher ventilation. Although, the penetration of the air is not too deep and lower the cooling capacity of (less than 40 watts / m^2 of the room area) [179].

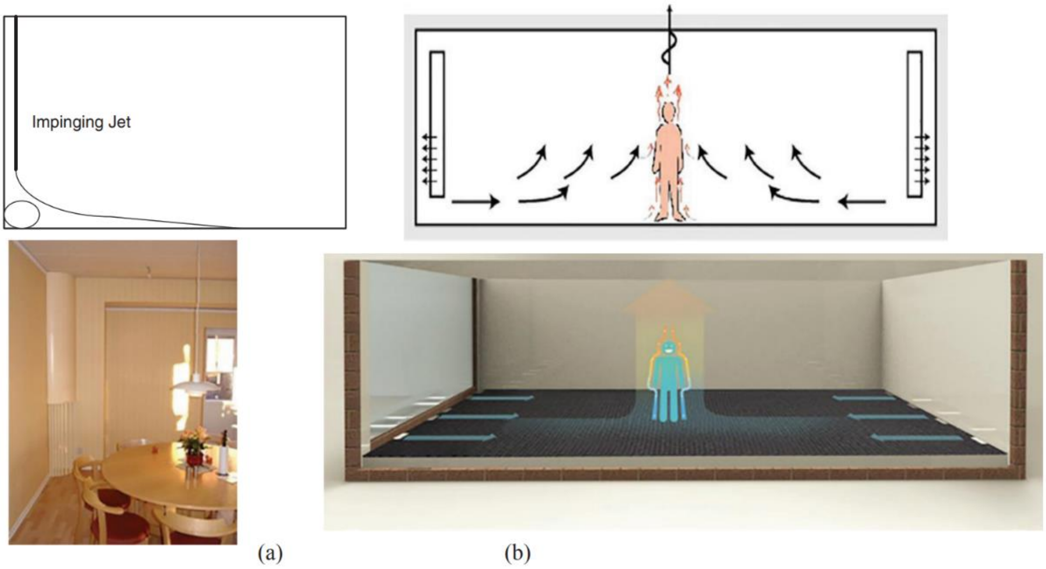
2.16.3 Personalized ventilation (PeV)

Melikov [180] have suggested that in some situations, it is best to focus the ventilation in a certain area of the room. This method of ventilation directs the air to a certain location like an occupant or a hospital bed. The problem with this scheme is that it is not suitable for public use where fresh air is required by everyone in the room [200].

2.16.4 Hybrid air distribution (HAD)

The hybrid system was developed to overcome the problems of DV system which are 1) it is not suitable for heating mode and 2) its penetration range is not deep. A system uses the impinging jet (IJ) system and the confluent jet (CJ) system see figure (2-30). The impinging jet supplies the air through a vertical thin jet that is directed towards the ground and spreads throughout the floor area. While the confluent jet consists of a number of jets spread over a slot close to the wall. The two streams then join together and move toward the floor to create the same effect of the (IJ) system, therefore, creating a better horizontal stream of air that spreads throughout the floor. Then a displacement jet system is replacing extracting this air out of the room [178].

2.16.5 The difference between the four systems:



(a) (b)

Figure 2-30 diagram shown the flow of the impinging jet and the confluent jet (a) impinging jet system, and (b) the confluent jet system [178]

2.16.6 Evaluation of air distribution using ADI New

The performance in terms of thermal comfort and indoor air quality of the four systems were calculated using the newly developed Air distribution index (ADI). A test chamber was built. Four men and four women were asked to participate in the trials. The difference of temperature was used to calculate the ventilation effectiveness for heat removal ($\mathcal{E}_t$) and CO_2 was used to calculate the ventilation effectiveness in contaminating removal ($\mathcal{E}_C$) and the local mean age of air was calculated also (τ_p) near the breathing zone. The occupants have helped in providing data for the thermal sensation |S| using the CBE thermal comfort model. The air supplied was at an airflow rate of 15 ls/1 and supply temperature of 18 o C with a total room cooling load of 21.2 Wm-2 (ventilation load of 9 Wm-2) of the floor area [178]. The results of the testing show that MV has a higher |S| experienced by the human subjects. However, the DV system allowed for better thermal comfort and indoor air quality check table (2-24).

Ventilation System	$\|S\|$	ε_t	N_{TC}	τ_n (hr)	$\bar{\tau}_p$ (hr)	ε_c	N_{AQ}	$(ADI)_{New}$
DV	|0.17|	1.10	1.04	0.33	0.23	1.35	1.98	3.02
IJ	|0.34|	1.08	0.95	0.33	0.25	1.28	1.68	2.63
MV	|0.49|	0.97	0.81	0.33	0.40	0.93	0.76	1.57

Table 2-24 parameters for the (ADI new) index based on CFD simulation (Air flow rate = 15 l/s and air supply temperature of 18 C [178]

To ensure that the building is maintaining a good indoor environment the United States Environmental Protection Agency (EPA) suggests three basic strategies to ensure good indoor air quality: Source control, ventilation improvement, Air Cleaners.

2.17 Methods to improve the quality of air inside the building

According to Wargocki [181] who presented the findings of the workshop organized by the Air Infiltration and Ventilation Centre (AIVC) and commissioned by the Joint European Medical Research Board (JEMRB) through fundings provided by the European Insulation Manufacturers' Association. (EURIMA). In this workshop many experts have presented their findings and agreed that in order to achieve acceptable indoor air quality in highly energy-efficient buildings and reduce the health risks the following must be covered:

1. Review all new ventilation solutions inside the building for health and comfort and identify any barriers that will hinder the innovation in the building process towards the goal of good indoor environmental quality.
2. Involve the building occupants in the design process of the building to make sure that they are aware of the health aspect of the design.
3. A flexible design that will take into account the variable aspect of ventilation and indoor air quality.
4. Alternating between natural ventilation and mechanical ventilation to ensure both energy efficiency and indoor air quality.

According to the European Lung Foundation, there are several methods that are used to improve the indoor air quality inside the building. the first of these methods is source control, the second is ventilation improvement, the third is air cleaners. The following sections will expand these methods further [37].

2.17.1 Source Control

The Scientific Committee on Health and Environmental Risks (SCHER), one of the independent scientific committees managed by the Directorate-General for Health and Consumer Protection of the European Commission, have stated that there are approximately 900 varies compound were detected in the indoor air environment coming from different sources inside the building. Some estimates show that around 1.5 – 2 million heats per year can be related to indoor air pollution according to the European lung foundation [37]. The first strategy in combating indoor air pollutants is to stop their initial emission. One example of how to stop the initial emission of indoor air pollutants is to cover materials that contain asbestos from emitting it to the surrounding air. Another example is to adjust the heating or the cooking stove to reduce the number of emissions. Reducing the initial emission of indoor air pollution is critical because it is not only healthy for the occupants, it could also reduce the amount of energy that is needed to ventilate the space [37].

2.17.2 Ventilation Improvements

The second strategy in the process of controlling the emission of indoor air pollutants is to improve the ventilation inside the building [37]. If the house uses air forced system inside the dwelling, then there will not be any opportunity for the outdoor air to enter the building other than infiltration, and if the building is very airtight, that could cause even more problems by trapping the indoor air pollutants inside the building with no chance of replacing that air from the outside. Therefore, installing a mechanical ventilation system is necessary if the option of using passive ventilation would not be feasible at the time. Likewise, using new technologies like Mechanical Ventilation with Heat Recovery (MVHR) system will be the right solution to reduce energy and ventilate the space simultaneously [37].

2.17.3 Air Cleaners

The third strategy is to install indoor air cleaners [37]. Indoor air cleaners are designed to draw air from the room via a filter that will collect most of the indoor air pollutants inside the space. However, not all filters are the same. Some filters can remove large and small particles and others are good at removing gas pollutants. According to the EPA, there are several different types of air filters [182].

The first type of filter is the typical mechanical air filters that use high-efficiency particulate air filters or (HEPA) filters. These filters remove indoor particles by using filter materials to capture them. HEPA filters can remove larger airborne particles like pollen, dust, mould spores, and animal dander. One problem that might affect the filtering process of these filters is that the particles settle quickly on surfaces which will hinder the ability of the filter to remove them [182].

Gas-phase air filters remove gaseous pollutants with the help of a material that is called a “sorbent”. These filters are designed to remove certain types of gases and they are not usually found in houses. some of the issues regarding the use of gas-phase filters are their inability to remove all kinds of gaseous pollutants and they need to be placed very often [182]. Some filters use ultraviolet light to remove air pollutants. The first of these filters is the UVGI cleaners that use ultraviolet (UV) radiation from UV lamps that could eliminate biological pollutants such as, bacteria, viruses, and moulds. These contaminants could be found on HVAC surfaces like for example cooling coils, drain pans, or ductwork. However, these filters are not designed to remove particles from the indoor space. On the other hand, regular air filters cannot destroy all sorts of biological contaminants [36]. Another example of these filters is the photocatalytic oxidation (PCO) cleaners that use UV lamps along with a substance, called a catalyst, which reacts with the light. These cleaners are designed to destroy gaseous pollutants by changing them into harmless products, but they are not designed to remove particulates. The last example is the Ozone generators which use UV lamps or electrical discharges to produce ozone that reacts with chemical and biological pollutants and transforms them into harmless substances [182].

2.18 The literature on research methodology:

2.18.1 model simulation:

To study the effects of the indoor air pollutants inside the building, a numerical solution is used to calculate the airflow and pollutant concentration. The commercial software ANSYS FLUENT was chosen to calculate the numerical solution for indoor air quality. Many studies have used the software ANSYS FLUENT to calculate the concentrations of indoor air pollutants. For instance, in a study by Chang et al [183], they have used ANSYS FLUENT to simulate the airflow and the concentration of the PMs using the Eulerian-Lagrangian model. In another study by Liu et al [184] they have investigated the gaseous pollutant transmission characteristics in a typical chemical laboratory with a fume hood under different scenarios using the CFD software ANSYS FLUENT 16.2. the researchers have used the Realizable k-ε model because it provided the best performance of all the k-ε model versions for several validations of different flows which have shown to give a better airflow simulation than the Standard and RNG k-ε model.

A study by Black et al [185] have examined the effects of fired coal and biomass under air and oxy-fuel conditions in an existing 500 MWatt-e coal-fired boiler. The researchers have used ANSYS FLUENT 14.0 for the simulation. Similar to the previous study, they have also used the realizable K-Ɛ model instead f the standard K-Ɛ model. In a study by Sarli & Di Benedetto [186] they used ANSYS FLUENT 15.2 to simulate the effect of a two-dimensional mathematical model of soot regeneration that is developed for a single-channel catalytic diesel particulate filter. A similar study by Collazo et al [187] used ANSYS FLUENT to establish a consistent CFD model for an 18-kW pellet boiler. Many researchers are using the software to also simulate the pollutant emissions emitted by building materials like for example, in the study conducted by Bourdina et al [188] they have investigated formaldehyde emission behaviour emitted from building materials from on-site measurements of air phase concentration at the material surface using the commercial software ANSYS FLUENT 15.0. The simulation of PMs was not just simulated for indoor pollutants, but also for outdoor emissions.

In a study by Blocken et al [189] In this research, the researchers have conducted a preliminary assessment of the potential to reduce outdoor PM concentration through semi-enclosed parking. The researchers have used ANSYS FLUENT base on a steady Reynolds average number equation and an Eulerian advection-diffusion equation in indoor applications. In a study by Chang et al [190] in this paper, the researchers have studied a newly developed method for estimating the concentration of PMs using the Lagrangian modelling in the indoor environment. They have utilized the new cubic spline kernel function with the smoothing length and solid building boundary treatment. The researchers have used two 3d numerical models in which the Eulerian method was used for the airflow and the Lagrangian method was used for PM concentration using the commercial ANSYS FLUENT 12.0 software. Another study was conducted to simulate PMs indoors by Al-sarraf et al [191] The purpose of this study is to model the indoor air movement of $PM_{2.5}$ from second-hand smoking. The commercial software ANSYS FLUENT Version 6 (ANSYS Inc., 2010) was used to simulate the wind flow and pollutant dispersion within the street canyon. The CFD modelling was constructed in order to solve the pseudo-steady state incompressible Reynolds averaged Navier–Stokes (RANS) equations equipped with j-e turbulence models.

2.18.2 Data collection

Using instrument to collect data for indoor air pollutant have been used in many studies in the literature. A study by Hanoune & Carteret [192] have investigated the emissions from a kerosene space heater. The heaters were unvented and spread the smoke inside the building, therefore, the researchers have used an instrument like the HD37B17D probe in six different dwellings in France and Belgium. They have measured the carbon dioxide (CO_2) levels. They have also measured the carbon monoxide measurement using the Dräger Pack III probe (Drudgework AG & Co., Allemagne). Another study by Kolarik et al [193] have measured fifty types of VOCs in a simulated office that is been ventilated with different stages of ventilation (0.6, 2.5, and 6 ACH) using different measuring techniques: sensory assessments of air quality made by human subjects, Proton- Transfer-Reaction Mass Spectrometry (PTR-MS) and chromatographic methods (Gas Chromatography/ Mass Spectrometry and High-Pressure Liquid Chromatography with UV detection). In a study by Kalimeri et al [194] two primary schools and one kindergarten school have been chosen for indoor air quality sampling in Greece. Two periods were selected for monitoring a heating period and (January to February) and a cooling period (August-October). The researchers have measured Temperature, relative humidity and CO_2, Formaldehyde, benzene, trichloroethylene, pinene, limonene, NO_2 and O_3 with an interval of 30 minutes. In addition, Radon was measured for four weeks with short term radon detectors and the $PM_{2.5}$ was gravimetrically determined. The relative humidity and temperature were monitored using a HOBO data logger. CO was monitored using an aeroQUAL. $PM_{2.5}$ was monitored using Derenda LVS3.1/PMS3.1-15.

A study by Zuo et al [195] takes place in Beijing. This study is aimed to investigate the $PM_{2.5}$ exposure indoors. The objectives of this study were to 1) measure the indoor-to-outdoor ratio of PM concentration, 2) measure the different concentrations of $PM_{2.5}$ inside the building, and 3) calculate $PM_{2.5}$ exposure and population risk. The researchers in this study have used the Laser Egg®, which is produced by Kaiterra company, as real-time measurement equipment, the Laser Egg® measures the $PM_{2.5}$ concentration by using the Laser-based light scattering technique. A study by Ciuzas et al [196] analysed the characterization of dynamic patterns of indoor PM during various pollution episodes for real-time IAQ management. Twenty buildings were chosen for this investigation. A full-scale test chamber was built that represents a standard usual living room with a ventilation rate of 0.5 ACH. Two parameters were measured. 1) particle number concentration (PNC), and 2) particle size distribution (PSD). These two parameters were measured using two instruments to represent a size range from 0.01 to 10 mm, including scanning mobility particle sizer (SMPS 3910, TSI Inc., USA) and optical particle counter (OPC, Handheld 3016 IAQ, Lighthouse Inc., USA). Lohani & Acharya [197] have proposed a novel context-aware Android smartphone-based mobile adhoc sensing system that senses various data from the indoor environment around the user and analyses it in real-time. In this research, they have demonstrated how to sense and analyse data from two setups, (a) an Arduino based setup fitted with temperature, humidity and air quality sensor, and (b) an off-the-shelf Android phone compatible sensor. Using both these setups, they build an IoT system where anyone or both of these systems can be used to measure IAQ and ventilation rate. A study by McGill et al, [198] was aimed to examine the state of indoor air quality and thermal comfort in energy efficient building. The researchers have monitored six energy efficient buildings that were equipped with mechanical ventilation with heat recovery (MVHR) systems and with an airtight level of 2m3/m2/hr at 50 Pascal's. three devices were used to collect the data from the building. The first device was the Extech® Easy-View model EA80 that was used to collect the temperature, carbon dioxide levels (CO_2) and the relative humidity indoors. The second device Wohler CO_2 data-logger was selected to collect the temperature, carbon dioxide levels (CO_2) and the relative humidity outdoors. The third device HalTech (HAL-HFX205) was used to collect Formaldehyde levels.

The next two studies were conducted in a smoking lounge that allows smoking in which the researchers have investigated the effect of smoking on second-hand smoking using indoor pollutant instruments. The first was conducted by Neil et al, [199] This research was conducted in one of the casinos in California, USA. The purpose was to evaluate the indoor air quality inside one of these casinos due to the fact that these casinos allow smoking inside the casino. Not only that but also the effect of smoking inside the casino on second-hand smoking. With this research, the researchers are hoping to evaluate the actual impact of air quality on customers and conduct a survey that reflects their opinion about allowing smoking inside the casino. The researchers have used the SidePak™ AM510 Aerosol Monitors (TSI, Inc., Shoreview, MN, USA) with inlets in their breathing zones. This device was utilized to measure $PM_{2.5}$ personal exposure concentrations. The second research was conducted by Fiala et al, [200] Similar to the previous study. The researchers have investigated the effect of smoking in one of the Hookah lounges in Oregon, USA. The same device SidePak™ AM510 Aerosol Monitors (TSI, Inc., Shoreview, MN, USA) was used in this study to measure the concentration of $PM_{2.5}$ inside the Hookah lounge.

2.18.3 Survey questionnaire

The third step is to take a survey questionnaire from the occupants of the building that were working during the time the data was collected. The Chemistry Building is occupied by researchers and graduate students. Their typical hours are from 9:00 AM up until 18:00 PM. There are many laboratories in the building. Each laboratory has its own team of researchers and grade students working in that laboratory. The offices are adjacent to their corresponding laboratory. The Eco-House has a very limited number of occupants. Some employees were situated in offices and others are situated in the open space office located on the ground floor. Just like the Chemistry Building, the Eco-House building is occupied by both researchers and graduate students. When studying the literature, many studies of indoor air quality include questionnaire surveys that were designed to assess the human sensation regarding the indoor air quality inside the occupied space.

The first study by Wallner et al [201] where they investigated the occupants' perception of the use of mechanical ventilation in a highly energy efficient building. The researchers have revealed that some occupants do not prefer mechanical ventilation due to the fact that some of them feel that the mechanical ventilation system is supposedly causing harmful health effect. In this research, a quasi-experimental field study was conducted using a survey questionnaire. The researchers investigated two groups of building the first group was the test group which comprised of buildings that house a mechanical ventilation system, the other group was comprised of buildings that relied solely on natural ventilation which was the control group. The researchers included 123 modern houses built between 2010 and 2012. A standardized questionnaire was developed and distributed among the residents of the buildings. In total, the study covered 575 participants with a mean age of 37 +/- 9 years. The result of the study showed that within the test group the occupants of the mechanically ventilated building complained about dry eyes significantly more frequently than the control group. However, the test group also confirmed that the indoor air quality in the mechanically ventilated houses is very acceptable and they show no significant health problems. In regards to the eye dryness, it could be attributed to the low relative humidity level inside the mechanically ventilated houses. The thermal comfort in the test group houses was shown to be very satisfactory according to the residents of these houses. Lastly, there was a general content among most of the participants with their existing house, however, the test group participants did report higher percentage of satisfaction [201].

The second study was conducted by Sakellaris et al [202] which had two objectives, the first is to examine the relationship between perceived indoor environment and occupants' comfort. The second is to examine the modifying effects of building characteristics and personal perception. The researchers have advised a questionnaire survey that was distributed to 7441 workers who were present in 167 contemporary office buildings in eight European countries (Finland, France, Greece, Hungary, Italy, The Netherlands, Portugal, and Spain). The researchers were assessing the indoor environmental quality through the analysis of crude indoor environment quality parameters like; thermal comfort, light, noise and indoor air quality. In addition, they used other parameters like: predicted mean vote to measure if the temperature inside the building is either too hot or too cold, whether the relative humidity is too dry or too humid, odour presence, sound levels inside and outside, and natural versus artificial lights. The analysis of the result showed that the highest rate of satisfaction was associated with the sound levels inside the offices, after that was the indoor air quality followed by light and thermal comfort [202].

The third study was conducted by Vornanen-Winqvist et al [203], where they did a survey questionnaire study to determine the effect of ventilation improvements on the indoor air quality in an energy efficient building. The method used to improve the ventilation inside the building was the use of a supply air fan-assisted hybrid ventilation. The researchers had chosen the VOC concentration as a parameter to determine the quality of the air inside the building and indoor mycobiota. The questionnaire used in this study was developed to assess the human perception about the indoor air quality. The result of the study has shown that the new improvement in ventilation had removed the presence of Trichoderma citrinoviride that was not detected after the use of a new ventilation strategy. They also found that the levels of CO_2, VOCs, toluene, decamethylcyclopentasiloxane, and TVOCs decreased considerably. The participants have confirmed the improvement of indoor air quality by stating that the quality of the air inside the space had improved since the introduction of the supply air fan-assisted hybrid ventilation.

In the fourth study that was done by Moses et al [204], a group of researchers have developed a face-to-face questionnaire that included around 302 participants living in social housing in the southwest of England. The objective of this study was to investigate the effect of indoor dampness on the health and wellbeing of the residence inside the social housing building. The result of the study has shown that Adult-Asthma diagnosis was reported from 26% of the respondent to the questionnaire. In addition, 34% of the participants reported having problems with wheezing and 18% of the participants said that they had allergies. Around 32% of the participants said that they have noticed visible mould and 42% of them reported mouldy odour.

The fifth study was done by Satish et al [205] which included an experiment that was aimed to measure the effects of CO_2 Concentration on the cognitive ability for decision making. The study included twenty-two participants who were exposed to different concentrations of CO_2 (600-1000) and (2,500) ppm in a chamber that resembles an office environment. The participants were divided into six groups and in each group, the researchers exposed them to different levels of CO_2 concentrations. After each stage, the participants were asked to perform a computer-based task to test the decision-making ability and complete a survey questionnaire. The result of the study revealed that with concentration levels between 600 and 1000 ppm, moderate and statistically significant decrements occurred in six of nine scales of decision-making performance. With higher concentration at 2,500 ppm, greater and statistically significant reductions occurred in seven scales of decision-making performance (raw score ratios, 0.06–0.56), but performance on the focused activity scale increased. The researchers have concluded that the effects of high levels of CO_2 concentration have proven to be affecting not only the health and wellbeing of the people residing in these buildings but also affecting the economical and productivity of any company that would compromise the safety of its employees in order to preserve energy.

The sixth study was conducted by Vornanen-Winqvist et al [206] where they did a case study investigation into the ventilation intervention effect on perceived indoor air quality. The aim of the study was to determine if increasing the positive pressure of the building (about 5–7 Pa) would hinder the infiltration of microbiological agents and harmful chemicals into the indoor space through the structure of the building, therefore, reducing symptoms and discomfort. The experimental work took place in the section of the building comprised of 12 classrooms. The researchers relied on indoor air quality measurement and a survey questionnaire. The result of the study showed that after the application of intervention ventilation strategy into the tested part of the building, the concentration of TVOCs and $PM_{2.5}$ noticeably reduced and the participant perception about the indoor air quality had improved.

The seventh study by Schiavon et al [207], took place in the warm and humid climate of Singapore. The researchers have theorized that using personally controlled fan might be able to compensate for the negative effects associated with increased temperature set point. The researchers have advised a questionnaire that included 56 "tropically acclimatized" participants. The participants were introduced to five different stages of air temperature at (23, 26, and 29°C) while in the last two stages, the researchers gave the participant the chance to control the air movement at one stage and at the other stage they did not allow them to do so. The result showed that with and without occupant-controlled air movement. thermal comfort and sick building syndrome symptoms are equal or better at 26°C and 29°C than at the common set point of 23°C that is if the occupants would have the opportunity to personally control the fan. The results also showed that the best cognitive performance was obtained at 26°C and at 29°C. however, the lowest cognitive performance was seen at the 23°C set point.

2.19 Conclusion

Indoor air quality is an often neglected subject in the building sector. However, many kinds of research have shown that the subject of indoor air quality is an important issue that faces many building occupants. The objective to reduce energy consumption is a major task that awaits architects as well as building engineers. Nevertheless, indoor air quality issues should remain a top priority. This literature has shown the importance of air ventilation and how to strive for the right balance of energy efficiency and indoor air quality without sacrificing either one of them. Many factors have been shown to contribute to the increasing problem of indoor air quality like technologies that are introduced inside the building and the building materials. The study of indoor air quality has proven to be effective in improving the health and wellbeing of the occupants. Therefore, it is important to change the way building materials and other products are manufactured by reducing the harmful chemicals that are introduced to enhance the thermal performance of these materials, or bond the materials together or reusing older materials that contain hazardous chemicals that will only worsen their effect on indoor air quality. In addition, new technologies that are used to heat and cool the building should be designed with respect to the indoor air quality inside the building. It is not enough to ensure that the building is reducing energy consumption, or that the thermal insulation material is reserving the heat inside the building and that the MVHR system is providing enough heat to the occupied space. It is equally important to ensure that these materials and heating systems also provide acceptable indoor air quality. The occupant's awareness is also a major contributor in ensuring that the air inside the building is kept intact. The occupants should be aware of any harmful effects generated from heating technologies and how to use them properly and they should be also aware of the introduction of VOCs from building materials and furniture to avoid any health complications that might occur from the indoor air pollutants.

3. Chapter three

3.1 Research methodology

The first method was to develop the theoretical modelling and create the exact conditions of the people working inside the investigated space. Using CFD software was imperative to study the current condition of the interior space and to assess any problems that might be generated inside the simulated room. The second method was to verify the CFD simulation with the data collected from the rooms that were been selected for this study. An instrument was placed inside the selected rooms and it was used to collect key information about the indoor air quality and the thermal conditions inside the room like PM, VOCs, CO2, temperature and humidity. These data were analyzed and compared to the CFD simulation to verify the theoretical model. The third and last method was to develop a survey questionnaire that is given to the occupants and get their feedback in regards to the indoor air quality conditions inside the building. These methods were implemented to give a complete picture of the conditions of the indoor air quality inside the occupied space not just through data collection but also through human perception.

3.2 Types of research methods

There are many ways of research method but in most cases, there are two main types of research method according to Plonsky & Weiss [208] the first is observational or descriptive studies; the second method is the quasi-experimental designs.

3.3 Observational/Descriptive Designs

According to Plonsky & Weiss [208], they define observational and descriptive research method as the study that seeks to evaluate a certain phenomenon without any attempt to alter its outcomes. This also means that this type of research will not perform any type of experimental work but rather describe the existing condition as it is. This is very similar to the kind of research that is needed in this dissertation. The reason for that is to study the current condition of indoor air quality without altering anything in the working space like air volume intake, adding new technology, or removing any materials from the space.

3.3.1 Qualitative & Quantitative Research

According to Plonsky & Weiss [208], the observational research method could be both used as a qualitative and as a quantitative method of research. On the one hand, observational studies are more often qualitative in nature in which they are inductive in nature and rely on a large set of data to extract principles and interoperate the emerging pattern gathered from the data. In regards to this research, the survey questionnaire incorporated some open-ended questions that were composed to elicit a human response from the surveyed participants. The answers to these questions had given a human perspective about the indoor air quality condition inside the two designated buildings for this study.

On the other hand, observatory research could also be interpreted as quantitative research based on the fact that the data collected from the survey as well as the data collected from the buildings in this research will be analyzed quantitatively and according to Plonsky & Weiss [208] observational research method focuses on collecting and analyzing quantitative data, with the emphasis on how often a certain phenomenon occurs. In this type of research, the focus is still on the description and contextualization of data but is related to the frequency of occurrences. The data collection will be a tool to collect as much reading as possible. These data will be analyzed quantitatively to assess the condition of the indoor air quality inside the space.

3.3.2 combining qualitative and quantitative method

Qualitative and quantitative research has their strengths and weaknesses. Qualitative research has the opportunity to bring out the human perspective into the outcome of the research which could be very hard to do from using copious amounts of data and analyzing them without understanding any of the implications of these data on the people that are occupying the space. However, qualitative research according to Bryman [209] has been known to be impressionistic and subjective because it relies on the researcher's point of view as well as the view that is being given by the participants of the study. In addition, it is hard to replicate the result because the research methodology is unstructured and analysis relies on the researcher's ingenuity.

By contrast, the quantitative research method focuses on quantity in the data collection and analysis. By using a quantitative method, a more deductive approach will be mostly utilized. An example of a quantitative research is the use of a survey questionnaire. The use of such method is to measure, generalize, and demonstrate the connection between the data set and the theories proposed in the research design stage Bryman [209].

The two methods might be used separately or together. When they are implemented together it is called a mixed method. Many researchers have argued that there is a great benefit of using mixed-method research because it allows a profound understanding of the research problem. In addition, the benefits that come with the quantitative approaches (for example numbers, trends, and generalization) and qualitative approaches (for example words, context, and meaning) will strengthen the two methods by compensating for each other's weaknesses (Hesse-Biber & Leavy, 2008) [158].

3.4 Using CFD simulation and theoretical modelling

The first of three steps in this research was to start with the theoretical model and CFD simulation. The result of the simulation was compared to the data collected from the buildings to validate the model. The dimensions of the rooms have been taken for two buildings. There were three rooms that were included in this research two rooms located in the Carbon Neutral Chemistry Building inside the university of Nottingham in the jubilee campus. The first room was the open space office room that is located on the ground floor of the building adjacent to the winter garden. The second room was located on the first floor above the open office room mentioned earlier. The third space was located in the Eco House located in the University of Nottingham that is part of the Creative Energy Homes project in Park campus. All the important information related to the simulation were taken from the site like; rooms dimensions, inlet openings, outlet opening, airflow speed, the size of the inlet and outlet, and windows and doors dimensions. All this information was entered into the software ANSYS Fluent R20 TM.

The CFD model was closely related to the data collection. The airflow was set at 2.0 m/s inlet airflow with an air pressure outlet. The result of the airflow shows that the air speed in one of the areas dedicated to the measurements of the air speed is showing to be zero. This result is very similar to the data collected from the room. The results observed from the CO_2 and PM is similar to those within the range of 0.02 mole fraction (equivalent to 750 ppm). To simulate the airflow, the K-Ɛ method of airflow simulation was chosen due to the fact that the level of turbulence is very restricted, however, the possibility of turbulence cannot be ruled out because in some instances there could be some turbulent flow close to the outlet or extract fans induced some times by natural ventilation. The Eulerian-Lagrangian method was utilized to simulate the particle trajectory and concentration in regards to simulation $PM_{2.5}$. The simulation of VOCs, CO_2, and formaldehyde was conducted using the species transport method. The sources for the pollutant have been diversified. The $PM_{2.5}$ source was considered to be the inlet opening itself since the MVHR system introduces fresh outside air inside the room after passing through the filtration system. The CO_2 source was considered to be the human subjects that were introduced inside the space that represent a typical human presence inside the space.

The simulation of the airflow in the Eco-House was conducted by simulating the natural ventilation of the room. the result of the simulation is closely related to the data collection. The airflow was set at 1.0 m/s inlet airflow with a passive extract fan. The result of the airflow shows that the air speed in one of the areas dedicated to the measurements of the air speed is showing to be zero. the method of simulation in the Eco House is very similar to the Chemistry building. However, the sources of pollutants were different because the room that was chosen for the simulation was Kitchen. Therefore, most of the sources of pollutants are generated inside the kitchen.

To study the effects of the indoor air pollutants inside the building, a numerical solution was used to calculate the airflow and pollutant concentration. The commercial software ANSYS FLUENT was chosen to calculate the numerical solution for indoor air quality. Many studies have used the software ANSYS FLUENT to calculate the concentrations of indoor air pollutants. For instance, in a study by Chang et al [183], they have used ANSYS FLUENT to simulate the airflow and the concentration of the PMs using the Eulerian-Lagrangian model. In another study by Liu et al [184] they have investigated the gaseous pollutant transmission characteristics in a typical chemical laboratory with a fume hood under different scenarios using the CFD software ANSYS FLUENT 16.2. the researchers have used the Realizable k-ε model because it provided the best performance of all the k-ε model versions for several validations of different flows which have shown to give a better airflow simulation than the Standard and RNG k-ε model.

3.4.1 Data collection

The second step was the use of data collection in the form of a case study analysis. The use of case study analysis had proved to be very beneficial to study the current condition of the two buildings that have been designed with the best low carbon and energy efficiency standards. The data collected include ambient temperature (℃), the relative humidity (%), the Carbon Dioxide (ppm), the volatile organic compound ($\mu g/m^3$), PM ($\mu g/m^3$), and the airflow speed (m/s).

3.4.2 Survey questionnaire

The third step was to take a survey questionnaire from the occupants of the building that were working during the time the data was collected. The Chemistry Building was occupied by researchers and graduate students. Their typical hours are from 9:00 AM up until 18:00 PM. There are many laboratories in the building. Each laboratory has its own team of researchers and grade students working in that laboratory. The offices are adjacent to their corresponding laboratory. The Eco-House has a very limited number of occupants. Some employees were situated in offices and others are situated in the open space office located on the ground floor. Just like the Chemistry Building, the Eco-House building is occupied by both researchers and graduate students. When studying the literature, many studies of indoor air quality include questionnaire surveys that were designed to assess the human sensation regarding the indoor air quality inside the occupied space.

3.5 Building description

3.5.1 The Carbon Neutral Laboratory building:

Figure 3-1 Pictures of the Chemistry building

The first building is located in the award-winning campus of Jubilee in the heart of the University of Nottingham and is designed to be a carbon-neutral building that generates most of its energy from renewable sources such as biomass combined heat and power generator and photovoltaic panels that covers 45% of the roof area. The building receives 25 years of credit for the access energy that is diverted back to the grid and it will be used to pay back for the carbon mission used in its construction. The building is built on a 4500 square meters area that comprises a laboratory space for around 100 researchers, dedicated rooms for instruments, teaching laboratory for advanced undergraduate classes, and space for outreach activities [210].

The chemistry building uses several renewable technologies like Photovoltaic panels (PVP) to harvest the energy from the sun. these panels generate 230,000kWh per year. The second renewable source of energy was the inclusion of the biofuel combined heat and power (CHP) system. This technology uses liquid biomass fuel that will deliver 200 kWh of electrical power and 193 kW of heat. It acts as the primary heat source, with a biofuel boiler as the primary backup. In case the main CHP was operational the building has a secondary gas-fired boiler if there are problems with biofuel delivery. Heat from the CHP is collected in a thermal store big enough for 3-4 hours of operation. Space heating is by underfloor heating [211].

The building has different ventilation equipment in each area of the building to manage the airflow inside the space and to conserve as much energy as possible. For example, the main labs are ventilated using low face velocity, variable-volume fume cupboards with automatic fast closures. when the employees are not occupying the space, the system switch to volume-based ventilation. The concept behind it is to minimize the air supply to exactly what is required based on the fume cupboards. Not only that but in each laboratory, there is a dedicated air handling unit to satisfy the temperature required for each laboratory and save energy. There is also a plate heat exchanger is used to exchange heat from the fume cupboard extract with the incoming air, giving big savings on energy. The ground floor has its own air handling unit. These ventilation systems are temperature sensitive. The type of ventilation used on the ground floor is the variable air volume system without cooling, again using a heat-recovery heat exchanger unit on the ridge [211].

The building is designed to take advantage of the rainwater by allotting the rest of the roof for the green roof that will utilize the rainwater and for providing extra insulation for the building. Other technologies are incorporated into the building to aid in wastewater reduction by installing a water leak detection system and a sustainable drainage system designed to absorb water that is discharged from the green roof. The BREEAM calculation estimated that the building will use 5.47 cubic meter of water per person annually which is a 63% improvement in water efficiency. In addition, heat recovery technologies are also embedded in the building to utilize the excess heat generated by the biomass CHP generator [210].

The chemistry building uses significantly less energy because of the innovative method that is used to store the chemical specimens which would normally need to be stored in certain temperatures. This was achieved by allocating the storage area to a different location so that the rest of the building could shut down without compromising the specimens. The expected annual energy consumption of the building is 572 mWh which is 37% of the construction benchmark for a similar building. The building will generate 201 mWh of solar-generated energy, and the biofuel CHP will generate 410 mWh of power and 503 mWh of heat annually. The frame walls and roof are built using PEFC and FSC certified timber that is imported from Europe as part of the LEED certification requirement. The south side of the building has a winter garden that is allocated for recreational events, and it is designed to capture low-level heat in the spring while the roof is incorporated with a variety of biodiverse and drought-resistant crops [210].

The winter garden is located at the south side of the building. It is a big open space that is constructed with wood framing and glass curtain walls. The room is open on three sides. The south wall has the widest façade, and the east and west façade are smaller in width. There are open space offices and regular offices adjacent to the winter garden. However, the winter garden does not have a mechanical ventilation system with the exception of a single extracting grill on the upper floor that extracts the air from the winter garden. Windows are used at the ceiling to extract air from the garden with the use of stack ventilation and windows on the south façade to provide outdoor air whenever needed. In terms of sensor location, the room has different areas that exhibit different air characteristics.

Figure 3-2 image of the winter garden located at the south side of the chemistry building

3.5.1 data collection from the Carbon Neutral Chemistry Building:

the first location for the data collection was the Open Space Office (OSO) located in the ground floor of the carbon-neutral chemistry building. The devices that were chosen for the data collection have been placed in the centre of the room with a height of 65 cm above the ground on an office table connected to a power source for constant operation and data collection. The time interval for the data was 30 minutes, and the devices were in constant operation with the exception of data collection periods that last for a few minutes.

Figure 3-3 the interior view of the Chemistry building and the location of the sensors

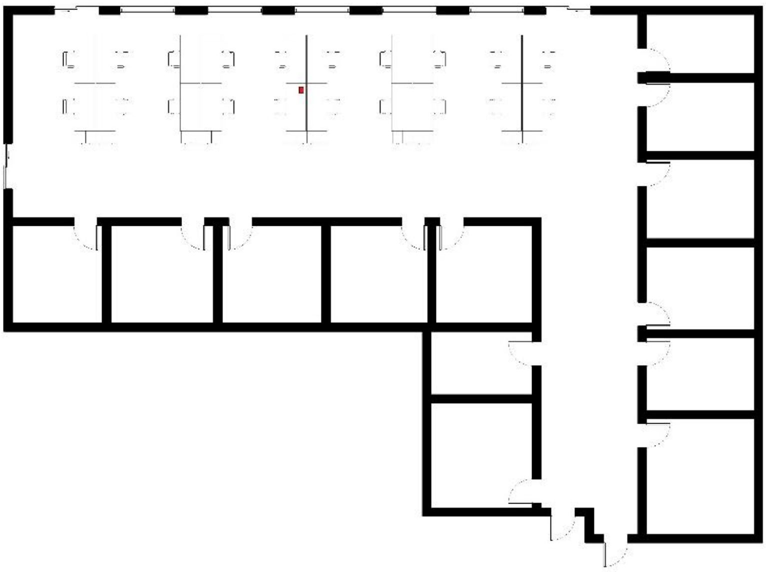


Figure 3-4 A floor plane of the Chemistry Building OSO

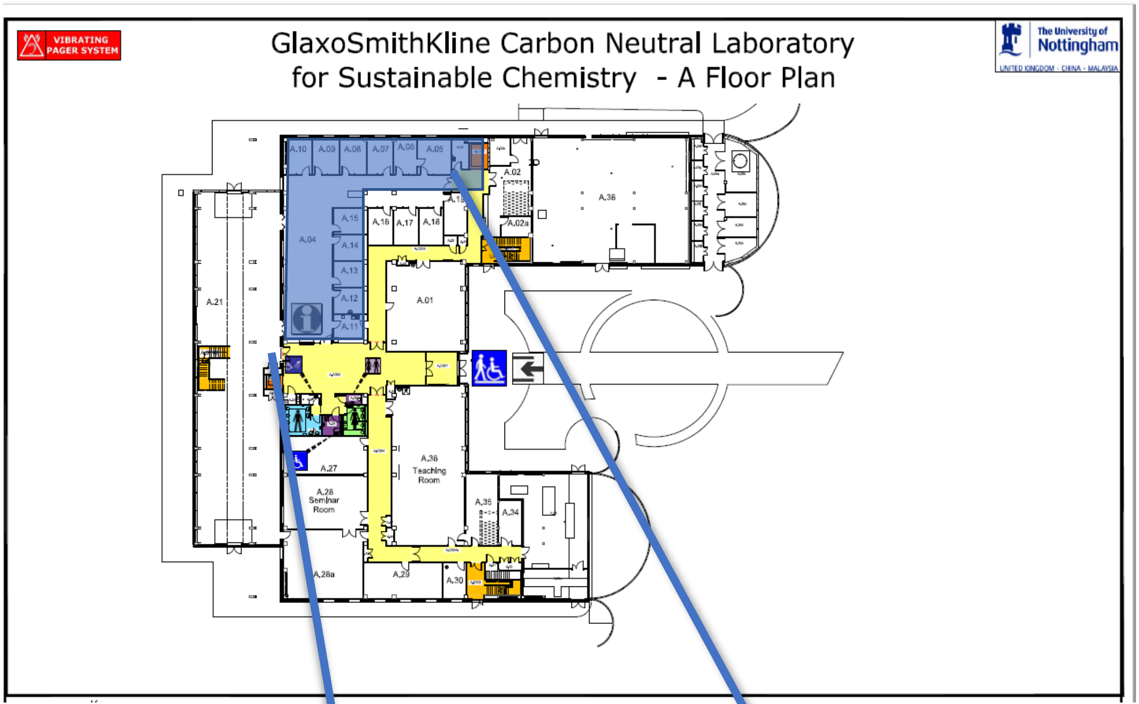


Figure 3-5 GSK Carbon Neutral Building Ground Floor Plane

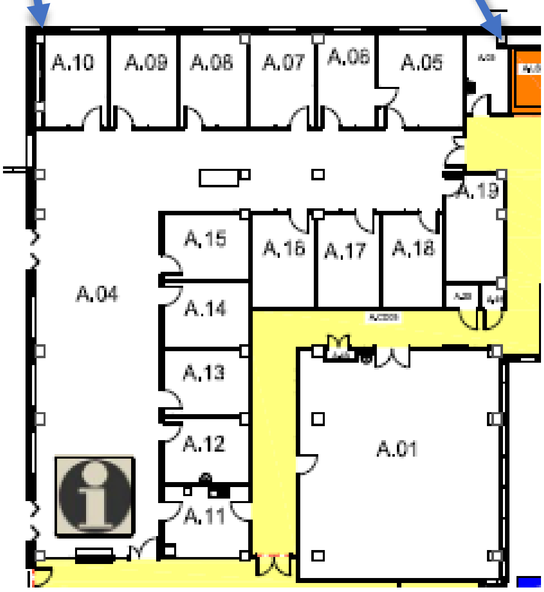


Figure 3-6 an enlarged Section showing the open space office

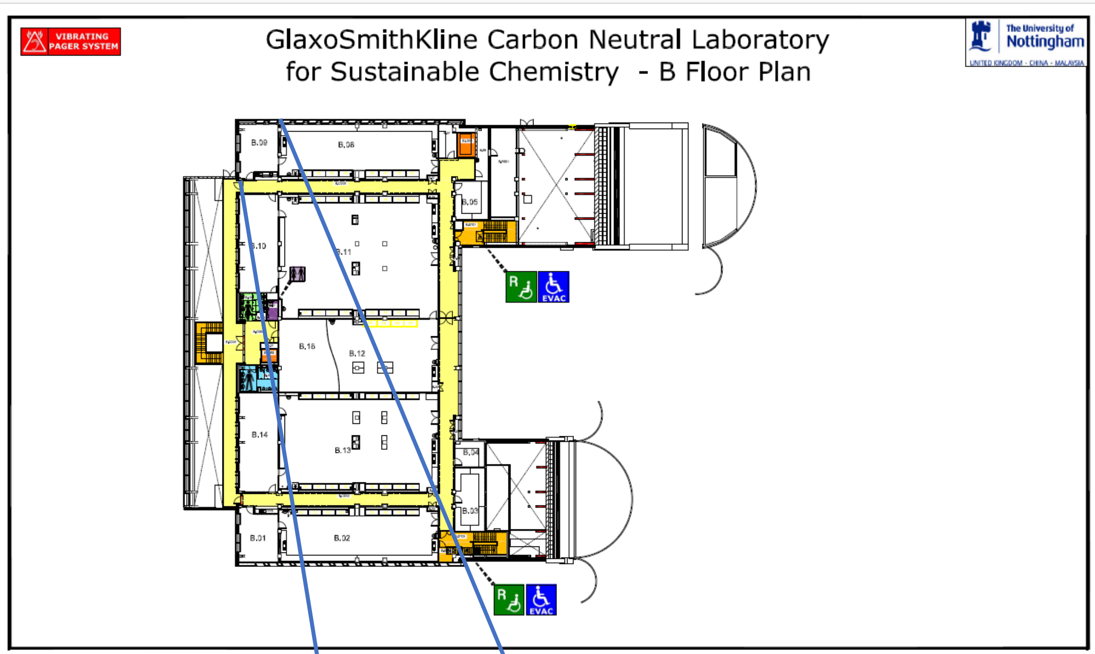


Figure 3-7 the first floor showing the location of the second room

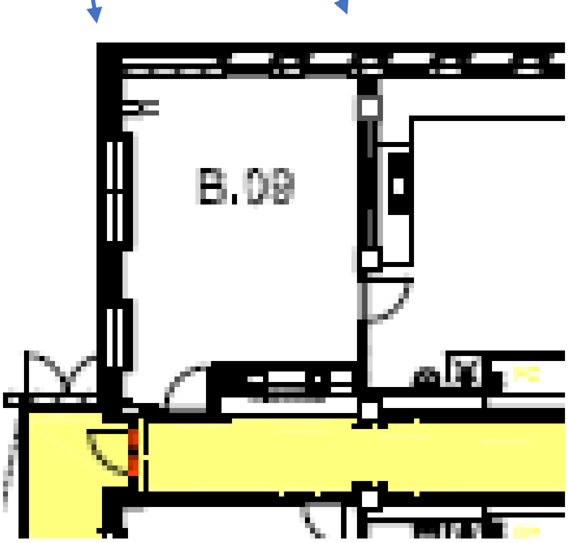


Figure 3-8 an enlarged view of the second room in the first floor of the chemistry building

3.5.3 The 3d model

The simulation was performed using the software (ANSYS R20). the software ANSYS Fluent was used to analyze the airflow inside the office space. The 3d model consists of three main spaces; the main office space [figure 3.9 (1)], the north side spilt offices [figure 3.9 (2)], and the west side split offices [figure 3.9 (3)]. The room dimensions were around 24 m by 6 m. the height was determined to be 4.5 m. The air speed from the grills was measured to be around 1.2-1.6 m/s. and the extract grill was measured at 1.5-2.1 m/s. the main office space has four main intake grills and two main extract grills. The north side spilt offices were contacted to the main offices though separated with a wall between the two offices. Each one of these offices has its own air inlet inside the office, and the air is transferred into the main using an opening that will direct the air from inside the room into the main office space figure (48 and 49). The same system is used in the west offices.

Figure 3-9 the ventilation system in the GSK chemistry building: A) the outlet grill, B) an opening that brings mixed air from adjacent offices, C) outlet of adjacent offices, D) extract grill

3.5.4 The Mark Group house case study

The Creative Energy Homes is a £1.9 million pound project that is a key resource particularly with respect to micro-smart grids, energy storage, demand-side management and occupants' acceptance of innovative technologies. This project provides a test site for the university and adjoining firms such as E.ON, David Wilson Homes, BASF, Roger Bullivant, the Mark Group, Tarmac and Saint Gobain for the study of integrating energy efficient technologies into these houses. The research findings have been fed into the UK government's Green Deal strategy and the Nottingham Community Climate Change Strategy and have received widespread acclaim through a number of public engagement activities, reaching out to over 5 million people [212].

The Mark Group house (also known as Eco-House) is one of the houses established under the creative energy homes project. The building achieved level 6 code for sustainable homes. It comprises three levels including a basement and an additional two floors above the basement. A team of interdisciplinary members of teaching staff and students have cooperated to design the house. A construction workforce of undergraduate students studying architecture and building technology has worked on the build providing valuable experience of construction practices. Some of the technologies that are used in the building are 1) solar hot water heater, 2) Mechanical Ventilation with heat recovery (MVHR), 3) air source heat pump and 4) solar panels [227].

Figure 3-10 a picturing showing the kitchen inside the Eco-House

3.5.5 Eco-House building simulation

The Eco-house is built as a residential building, though it is used as an office for the employees working on the building. In figure (3.13) the three spaces are numerated: 1) is the kitchen; 2) is the sunroom; 3) is the office. The height of the room is around 3 m however, the sunroom is a double-height room that goes all the way up to the second floor. The (mechanical ventilation with heat recovery) MVHR system is located in the offices and in the hallway. An extract ventilation opening is located in the kitchen. The supply grill is shown in figure (3.11 B) and the passive air vent is shown in figure (3.11 C). During the winter, the MVHR is the main source of ventilation. In the spring, the MVHR system shuts down and the windows and doors are used to ventilate the space. The simulation was carried out in (ANSYS fluent R 21). In the simulation, one source of pollution was introduced in the kitchen, one in the office and three sources in the sunroom. The inlet MVHR air speed was determined to be 1.5 m/s.

Figure 3-11 photos from inside the Eco-house: A) ventilation opening at the top of the sunroom, B) an enlarged photo of inlet opening for the MVHR, C) a passive exhaust air opening, D) the inlet opening for the MVHR

Figure 3-12 pictures of the Eco-House located in the University of Nottingham_ Park campus

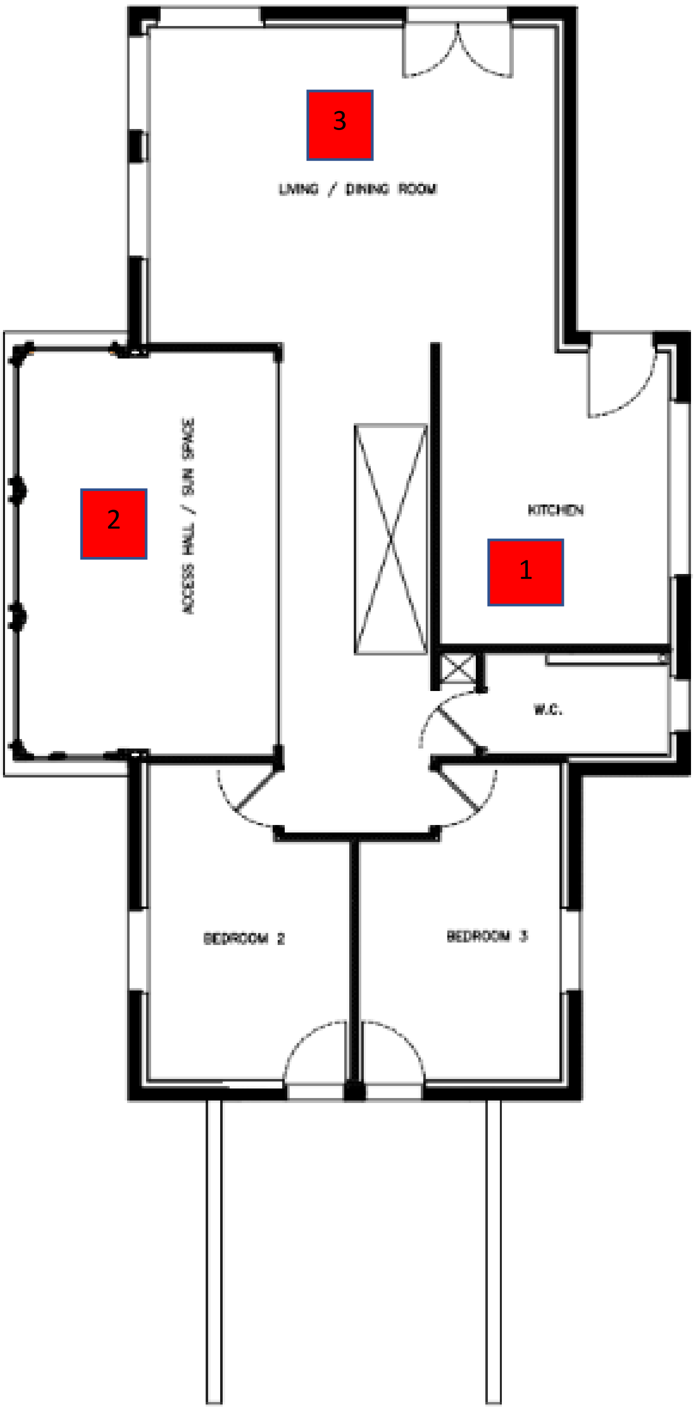


Figure 3-13 A floor plan for the Eco-house showing the location of the sensors: 1) the PM an VOC sensor; 2) the CO2 sensor

3.6 The instruments

1- Perfect-Prime CO2000 Carbon Dioxide (CO_2) Air Temperature & Humidity Data Logger Meter:

This device has been used to collect the temperature, humidity, and CO_2 readings. The CO_2 measurements ranges from 0 to approximately 9999 ppm with an accuracy ± 50ppm ± 5% reading (0~ 2000).

Figure 3-14 Perfect-Prime CO2000 Carbon Dioxide

2-TES 5322 $PM_{2.5}$ Air Quality Monitor:

This device has been used to collect the Volatile Organic compound (VOC), Particulate matter ($PM_{2.5}$), temperature and humidity. Measurement of the PM2.5 ranges from: 0 to 500µg/m3. The (VOCs) ranges from: 0 to 50ppm, Humidity: 1% to 99%R.H, and Temperature: -20°C to +60°C (-4°F to +140°F). The accuracy is : ≦50µg: ±5µg >50µg: ±10% of reading for PM2.5 ; : ±10% of reading±1ppm of VOCs; ±0.8°C, ±1.5°F for Temperature; ±3%RH for Humidity.

Figure 3-15 TES 5322 PM2.5 Air Quality Monitor

3--IGERESS Indoor Air Quality Monitor Formaldehyde (HCHO) Detector PM2.5/PM10/TVOC:

This device is used for the on-site measurement of Formaldehyde, $PM_{2.5}$, VOC and TVOC. Test Range: HCHO:0-1.999 mg/m3; TVOC:0-9.999 mg/m3; PM2.5/PM10:0-999μg/ m3.

Figure 3-16 IGERESS Indoor Air Quality Monitor

4- The 1-wire temperature and humidity sensor:

This device was very instrumental in taking temperature and humidity measurement from different locations inside and outside of the occupied space.

Figure 3-17 the 1-wire temperature and humidity sensor

3.7 survey questionnaire

The third step in the research is to conduct a survey questionnaire. The survey was developed to compare people responses to the data collected from the building. The Carbon Neutral Building is occupied by both students and employees. A quantitative method of the questionnaire was used to gather as much information as possible from most of the users inside the building. The survey consists of 15 multiple response questions that will inquiry about some of the most important issues related to indoor air quality like (sick building syndrome, nasal or respiratory diseases, and the air perception inside the space). The number of participants who completed the questionnaire was 64 participants.

3.8 Concluding remarks

Three key steps were implemented to investigate the state of indoor air quality inside two low carbon buildings located in the University of Nottingham campuses. The research started with the theoretical model to study the current condition of the rooms and infer if the current design of the rooms is suitable for human occupation. This was followed by a three-year period of data collection that started in the year January 2017 all the way until January 2020. During that time a large number of samples have been collected from the three rooms and analyzed to observe an emerging pattern within the data and to compare it with the theoretical model. The last step was the survey that covered most of the occupants in the chemistry building. The survey was conducted to juxtapose the result from both the CFD simulation and the data collection and to show if the occupants have noticed any issues regarding the indoor air quality. By applying the three steps, a more comprehensive result will show the conditions of the indoor air quality inside a low carbon building and it will also show if energy efficient technologies and new green materials have any impact on the air quality inside the space and if people have been affected by these technologies and materials.

4. Chapter four:

4.1 Mathematical model

In this chapter, all the mathematical modelling was addressed along with the theoretical modelling that has been used to analyze the indoor air pollution concentration in the two buildings that have been chosen to study the effect of new energy efficient technologies on indoor air quality.

These mathematical models are important to study the airflow inside the chosen rooms in this thesis like for example in the carbon-neutral laboratory building, the predominant system used to ventilate the space is the mechanical ventilation system. The mechanical ventilation system runs constantly, especially in the winter season. A brief description of the mechanical ventilation settings in the carbon-neutral building will be discussed in the following section. In the spring, however, the space has a double door on the west side of the open office space that allows the winter garden air to enters the space allowing more source of natural ventilation in addition to the mechanical ventilation system.

To study the indoor air quality condition of the chosen spaces, it is important to use the governing equations to study the state of ventilation inside the building. The first mathematical equation needed is the governing equations for ventilation.

4.1.1 The purpose of ventilation

ventilation is the process of replenishing the indoor contaminated air with fresh outdoor air that would dilute the air pollution inside the occupied space. According to the world health organization (WHO), ventilation moves outdoor air into a building and distributes the air within the building with the intention to provide healthy air for breathing by both diluting the pollutant air in the building and removing them outside of the building [213].

The ventilation flow rate can be referred to as either an absolute ventilation flow rate in letters per second (l/s) or m^3/s, or an air change rate relative to the volume of the space the relationship between [213].

4.1.2 ventilation rate in l/s and ACH rate is [214]

$$(Air\ change\ rate) = \left[ventilation\ rate\ \left(\frac{l}{s}\right) \times 3600\ \left(\frac{second}{hour}\right)\right] \times 0.001\ (\frac{m^3}{s})]\ /[room\ volume\ (m^3)] \quad (1)$$

4.1.3 Stack natural ventilation

$$air\ change\ per\ hour\ (ACH) = \frac{0.15\ \times smallest\ openning\ area\ (m^2) \times 3600\ \left(\frac{s}{h}\right) \times \sqrt{indoor-outdoor\ air\ temperature\ (K) \times stack\ height}}{room\ volume} \quad (2)$$

$$ventilation\ rate = 0.15\ \times 1000\ \times smallest\ opening\ area\ \times \sqrt{indoor - outdoor\ air\ temperature\ (K) \times stack\ height} \quad (3)$$

4.1.4 The ventilation required to prevent the mean equilibrium concentration of pollutant [214]

$$\boldsymbol{Q} = \frac{\boldsymbol{P}(\mathbf{10^6} - \boldsymbol{C_{pi}})}{\boldsymbol{E_V}\,(\boldsymbol{C_{pi}} - \boldsymbol{C_{Po}})} \quad (4)$$

Where:

Q= the outdoor air supply

P= is the pollutant emission rate (L/S)

E_v= is the ventilation effectiveness

C_{pi}= is the limit of concentration of pollutant in the indoor air (µg/m^3, or ppm)

C_{po}= is the concentration of pollutant in the outdoor air (µg/m^3, or ppm)

4.1.5 The governing equation for indoor air pollution concentration can be written as [214]

$$V\frac{dC}{dt} = q\ (C_o - C) + V_{pol} \quad (5)$$

Where:

V= volume space (m^3)

C= concentration (µg/m^3, or ppm)

q= ventilation rate (m^3/s)

C_o= supply air concentration (µg/m^3, or ppm)

dc= change in concentration

dt= change in time

V_{pol}= pollutant generation rate in the room (µg/m^3, or ppm)

The ventilation equation (equation 4) shows the basic relationship between concentration, ventilation rate, initial indoor concentration, outdoor concentration and pollutant generation rate [214]:

$$C = (C_{out} + C_G)\,(1 - e^{-nt}) + C_{Initial}\; e^{-nt} \quad (6)$$

$$C_G = \frac{V_{pol}}{q} = source\ concentration$$

Where:

$C_{initial}$ = initial concentration at time t=0

n = air change rate

$$C = C_{out} + \frac{V_{pol}}{q} \quad (7)$$

In [equation 4], the right side of the equation has two parts. The first part demonstrates how the concentration approaches its steady-state solution, and the second part demonstrates how the initial concentration decays as time progress. If there is sufficient time, the second part will diminish while the pollutant concentration approaches the steady-state solution [214]. However, in [equation 5], the steady-state concentration of the pollutant is verified by the pollutant generation rate and the ventilation rate

4.1.6 The ventilation effectiveness could be calculated using equation [214]

e = (Ce-Ci)/(Cm-Ci) (8)

The following equations are used to calculate the air movement dependent on the forces that derive these movements. The first equation (8) is used to determine the air movement that depends on the pressure difference between indoor and outdoor and the differences in height.

where:

C = Concentration of contaminant

Ci = C of inlet/supply air

Ce = C of exhaust air

Cm = Mean C in the space.

4.1.7 Buoyancy-driven natural ventilation [214]

$$\Delta Pi = To\ \rho o\ g(h2 - hn)\left(\frac{1}{To} - \frac{1}{Ti}\right) = Ti\rho ig(h2 - hn)\left(\frac{1}{To} - \frac{1}{Ti}\right) \quad (9)$$

Where:

- g= gravitational acceleration (m/s^2)
- h= height (m)
- P= pressure (Pa)
- T= air temperature (K)
- ρ= density (Kg/m^3)
- i= indoor
- n= neutral plane
- o= outdoor
- 1= inlet opening
- Outlet opening

4.1.8 Wind driven natural ventilation [214]

$$\Delta P = \frac{1}{2}\rho \, \Delta \, Cp \, Vr^2 \quad (10)$$

Where:

V_r= wind velocity at a reference height

$C_{p=}$ pressure coefficient

4.1.9 K-Ɛ turbulence model [214]

$$\frac{\boldsymbol{\partial(P\phi)}}{\boldsymbol{\partial t}} + \nabla \bullet (\boldsymbol{\rho u \phi}) - \nabla \bullet \left((\mu_{\boldsymbol{t}} + \mu)\,(\nabla \boldsymbol{\phi})\right) = \boldsymbol{S_\phi} \quad (11)$$

Where

μ_t = Turbulent viscosity

S_ϕ = source

4.1.10 General flow equation [214]

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla \bullet (\rho u\, \phi - \, \Gamma_e \, \nabla \, \phi) = S_\phi \quad (12)$$

4.2 Energy conservation for turbulent flow

$$\frac{\boldsymbol{\partial(P\phi)}}{\boldsymbol{\partial t}} + \nabla \bullet (\boldsymbol{\rho u \phi}) - \nabla \bullet \left((\mu_{\boldsymbol{e}})\,(\nabla \boldsymbol{\phi})\right) = \boldsymbol{S_\phi} \quad (13)$$

4.2.1 Navier-Stokes equation [215]

According to the National Aeronautics and Space Administration (NASA) [215], The Navier-stokes equations are used to illustrate the relationship between the velocity, pressure, temperature, and density of a moving fluid. These equations were derived from the Euler equations and include the effects of viscosity on the flow. They consist of partial derivative equations that calculate the changes in the three-dimensional space. The Navier-stokes equation takes into account the time-dependent continuity for conservation of mass, three time-dependent for conservation of momentum equation, and time-dependent conservation of energy [215]. The independent variables are the velocity changes in the three-dimensional special coordinates and time. Also, there are six dependent variables like P (pressure), density (ρ) and temperature (T), which is contained in the energy equation through the total energy Et, and the three Cartesian coordinate of the velocity vector (u in the X direction, v in the Y direction, w in the Z direction) [215].

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad (14)$$

U in the X direction

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = B_x - \frac{\partial \rho}{\partial x} = \cdots \quad (15)$$

V in the Y direction

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho vu)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = B_y - \frac{\partial \rho}{\partial y} = \cdots (16)$$

W in the Z direction

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho wu)}{\partial x} + \frac{\partial(\rho wv)}{\partial y} + \frac{\partial(\rho ww)}{\partial z} = B_z - \frac{\partial \rho}{\partial z} = \cdots (17)$$

4.2.2 General Scalar Transport Equation: Discretization and Solution in ANSYS FLUENT [216]

$$\int_V \frac{\partial p\emptyset}{\partial t}\, dv + \oint p\emptyset Vv \,.\, da = \oint \Gamma\emptyset\, \nabla \,.\, da + \int_V S\emptyset\, dV \qquad (15)$$

Where

Vv = velocity vector

Sϕ = source of ϕ per unit volume

r = diffusion coefficient for ϕ

4.2.3 Transport Equations for the standard κ- Ɛ Model by ANSYS FLUENT [217]

$$\partial/\partial t (p\kappa) + d/dxi (p\kappa vi) = d/dxj [(\mu + (\mu t)/\sigma\kappa) d\kappa/dxi] + G\kappa + Gb - p\varepsilon - Ym + S\kappa$$

(16)

Where:

Gk = generation of turbulent kinetic energy due to the mean velocity gradient

Gb = generation of turbulent kinetic energy due to buoyancy

Ym = contribution of the fluctuation dilation incompressible turbulent to overall dissipation rate

α κ = inverse effective Prandtl number

α Ɛ = inverse effective Prandtl number

Sκ = sources of kinetic energy (user-defined)

SƐ = sources of emissivity (user-defined)

4.2.4 The ideal gas law [217]

The ideal gas law stipulates that the volume taken up by a given number of molecules of any gas is the same, regardless of what the molecular weight or composition of the gas if the pressure and temperature remain constant [217].

$$P\ V = n\ R\ T \quad (18)$$

Where:

P= pressure (Pa)

V= volume (m^3)

n= number of moles

R= gas constant

T= temperature (k)

4.2.5 Mass energy balance

the use of the energy balance equation is important in calculating the concentration of pollutants in a given system. According to R.E. Hornath [217] if there is an increase in the amount of pollutant concentration in a certain system (e.g. a lake). Then that increase is either generated by introducing a new pollutant source to the system or produced through chemical reaction occur in the system. The use of mass conservation law will distinguish the amount of pollutant in the system. This method will determine the pollutant coming into the system, leaving the system or the amount being destroyed or formed by chemical reaction [217].

{mass at time t+Δt} = {mass at time} + {mass that entered from t ⟶ t+Δt} – {mass that exited from t ⟶ t+Δt} + {net mass of pollutant produced from other compounds by chemical reaction between t and Δt} (19)

from this equation, the mass flux (the rate at which mass leaves or enters the system) could be calculated by dividing (equation 10) by (Δt) [217].

$$\frac{(\textit{mass at time } t+\Delta t) - (\text{mass at time})}{\Delta t} = \frac{(\textit{mass etering from } t \rightarrow t+\Delta t)}{\Delta t} - \frac{(\textit{mass leaving from } t \rightarrow t+\Delta t)}{\Delta t} + \frac{(\textit{net chemical production between } t \text{ and } t+\Delta t)}{\Delta t} \quad (20)$$

This equation is only useful if the boundary conditions are identified as a lake or a tank and are commonly referred to as the control volume.

4.2.6 Mass accumulation rate [217]

Assuming that the pollutant inside the system is well mixed with fluid, then the concentration of the pollutant inside the system will be written as:

$$\frac{\Delta m}{\Delta t} = \frac{\Delta(CV)}{\Delta t} = \frac{V \, \Delta \, C}{\Delta t} = V \frac{dC}{dT} \quad (21)$$

Where:

m= mass (kg/m^3)

C= concentration (ppm, or µg/m^3)

V= volume (m^3)

t= time (hours)

4.2.7 Mass flux in [217]

$$m_{in} = Q_{in} * C_{in} \quad (22)$$

$$\left[\frac{mass}{time}\right] = \left[\frac{volume}{time}\right] * \left[\frac{mass}{volume}\right]$$

Where:

Q_{in}= is the volumetric flow rate entering the system (m^3/s)

C_{in} = is the add pollutant to the system (ppm, or µg/m^3)

4.2.8 Mass flux out [217]

$$m_{out} = Q_{out} * C_{system} \quad (23)$$

4.2.9 Net rate of chemical reaction [217]

The Production or loss of a compound by a chemical reaction is usually described in terms of concentration, not mass [4]. Therefore, it is important to multiply the rate of chemical change of *concentration* by the volume of the closed system to obtain units of mass/time:

$$m_{reaction} = \frac{dM}{dt}\Big|reaction = V * \frac{dC}{dt}\Big|reaction \quad (24)$$

4.3 Net rate of chemical reaction [217]

The Production or loss of a compound by a chemical reaction is usually described in terms of concentration, not mass [217]. Therefore, it is important to multiply the rate of chemical change of concentration by the volume of the closed system to obtain units of mass/time:

$$m_{reaction} = dM/dt \mid reaction=V* dC/dt \mid reaction \quad (25)$$

4.3.1 Species Transport Equations ANSYS FLUENT [216]

Equation (26) is used to solve the conservation of chemical species using ANSYS FLUENT. It predicts the local mass fraction of each species (Yi) through the solution of a convection-diffusion equation for the (i) species.

$$d/dt\ (pYi)+ \nabla .(pvYi)= - \nabla .\ Ji+Ri+Si \quad (26)$$

Where:

Ri = is the net rate of production of species

Si = is the rate of creation by addition from the dispersed phase plus any user-defined sources for species (i)

Yi = mass fraction of each species (i)

i = the measured species

Ji = diffusion flux of species (i)

4.3.3 Equations of Motion for Particles by ANSYS FLUENT [216]

This equation predicts the trajectory of a discrete phase particle (or droplet or bubble) by integrating the force balance on the particle, which is written in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle and can be written (for the x-direction in Cartesian coordinates)

$$(du. p)/dt=F\_D (u-U\_P) + [gx(p\_p-p)]/p\_p + F\_x \quad (27)$$

Where:

F_x = the additional acceleration (force/unit particle mass)

F_D = the drag force per unit particle mass

U = the fluid phase velocity

U_p = the particle velocity

ρ = the fluid density

ρ_p = the density of the particle

dρ = the particle diameter

4.4 concluding remarks

This chapter has listed all the equations necessary for the numerical study of the airflow simulation, Particulate Matter ($PM_{2.5}$), and species transport (which include VOCs, and formaldehyde). In the chemistry building, the airflow is mostly driven by the MVHR system. Especially in the winter when the open space office is closed most of the time to restrict the hot air from moving to the outside. However, in the summer the airflow inside the open space room is mixed with the air coming from the winter garden adjacent to the open space room. The second room is located on the first floor of the chemistry building. The room is filled with grade students and the door to the space is mostly open throughout the year in both summer and winter season. Therefore, when simulating the airflow inside this room it will be a mixed ventilation type simulation. The third space that will be simulated is the kitchen space located in the Eco-House. The airflow in that space is different from the chemistry building in which the heat is supplied by radiant heat flooring and combined with natural ventilation. The windows are only open in the summer times and are closed throughout the winter periods. The airflow simulation of the Eco-House will be mostly natural ventilation with extract fans pulling out the air by a passive ventilator located at the ceiling of the kitchen space. The next step is to take real-time data from the three spaces and compare them to the simulation that will be done on ANSYS FLUENT R 20. The data will be used to verify the result generated by the simulation. This will be followed by a survey questionnaire that will be distributed to the occupants of the two building to not only study the effect of the indoor air pollutant numerically but also to understand the human response to the conditions in these two buildings.

5. Chapter Five:

5.0 The simulation software and simulation setup

To understand the conditions inside the interior space in terms of indoor air quality and indoor pollutants distribution, it is beneficial to use specialised software that could mimic the conditions inside the assigned spaces for this research. One popular method is to use Computational Fluid Dynamics (CFD). According to Chen [218], computational fluid dynamics uses numerical partial differential equations to solve several groups of conservation equations like mass, momentum (Navier–Stokes equations), energy, chemical-species concentrations, and turbulence quantities. Using these equations could present a field distribution of air pressure, air velocity, air temperature, the concentrations of water vapour (relative humidity) and contaminants, and turbulence parameters for both indoor and outdoor spaces [218]. Many researchers are relying on CFD modelling to study indoor air quality, thermal comfort, HVAC system performance in many types of building like residential buildings, commercial buildings, health care facilities, schools, and industrial buildings, etc [218]. In most of these researches, the CFD software is used in conjunction with experimental testing or with field data collection.

The simulation conducted in this research was conducted using the commercial software ANSYS FLUENT 2021 R2®. This software is specialised in computational fluid dynamics simulation in both 2-D and 3-D models. The software allows the simulation of several elements of indoor air quality like static temperature, CO_2 concentration, airflow velocity, and PM concentration. At first, the model has to be drawn in the software using the specialised 3-D drawing software called SpaceClaime® this software allows the user to draw the outer surface of the boundary condition. The next step in the software is to apply the mesh using the specialised mesh application which is a separate application from the previous software. In the meshing software, the user can fine-tune the mesh, apply inflation to certain boundary layers, set the inlet, outlets, and pollutant sources. The third step is to set up the model for calculation in the specialised setup software. In this application, the user is allowed to enter all the parameters of the simulation like the gravity direction, setting the density and pressure of air, add the injection point for the PM sources, set the initial surface temperature of some important surface inside the system, and to specify special properties of the boundary conditions, and to set up monitoring point to monitor the temperature, CO_2, PM concentration, and airflow velocity.

In most applications for CFD modelling, the software uses Reynolds Averaged Navier–Stokes equation (RANS) modelling and Large Eddy Simulation (LES). RANS modelling is used to calculate the set of transport conservation equations for continuity, momentum, energy, and chemical-species concentrations. The software also uses eddy viscosity models. these eddy viscosity calculations can be categorised as zero-, one-, two-, three-, and four-equation models. The most well-known are the two-equation models and among them, there are two kinds of eddy viscosity equations used very commonly which are the standard k–epsilon model and the RNG k–e model [218]. According to Zhai et al [219], The standard k- epsilon model developed by Launder and Spalding (1974) is commonly used for indoor airflow simulation due to its simple format, robust performance, and wide validations. Also according to Zhai et al [219] the literature in general shows that The standard k- epsilon model with wall functions (Launder and Spalding, 1974) provides acceptable results and it is widely used especially for global flow and temperature pattern. Despite that, this model may not be able to deal with special room situations like for example, large temperature gradient and/or high buoyancy effect. Besides, the literature has assessed the accuracy of different RANS models and concluded that the v2f-dav and the RNG K-epsilon model yielded the best performance for predicting the ventilation performance in buildings [218] other researchers also concluded that when comparing the different RANS models, it is revealed that the RNG k-epsilon model was more stable in its results. In this research, the main model used to calculate the airflow is based on the k-epsilon model base on the information provided by the previously mentioned literature.

The software also uses both the Eulerian and Lagrangian approach to simulate the concentration of PM inside the space. According to Chang et al [220] In each method, there are certain advantages and disadvantages. First, the Eulerian method is mainly using a continuous phase approach to calculate the concentration of particulate matter. Some researchers say that the main advantage of using the Eulerian method is that it takes less time for software calculation. However, this approach is adequate for a small, noninitial particle that follows the same airflow pattern [220]. Second, the Lagrangian method simulates PM in a discrete phase and it tracks the trajectory of the PM through dynamic equations. This method incorporates fluid mechanic principles and it is the ability to accurately calculate the spatial and temporal information regarding PMtrajectory and dispersion history. One drawback of using the Lagrangian method is that it takes a lot of calculation to predict the concentration of particulate matter. This is because the Lagrangian approach has to calculate an extensive number of trajectories to approximate the average concentration in a certain spot inside the model.

In this research, three spaces were simulated using the aforementioned software. Two of these spaces are located in the same building which is the chemistry building, the third space is located in the Eco-house building. All three interior spaces have very similar conditions like the main fluid simulation as air being the main fluid simulated in the system. the airflow simulation was based on the use of k-ε base calculation, the use of the Eulerian-Lagrangian method to calculate the PM trajectory and concentration. Also, some of the setups for the simulation is very identical in all three models. One such similar set-up is the density of the PM used in the system. according to Mutlu [4], the density of PM can range from 1000, 1400, 1550, 1800, and 2000 kg/m^3. However, in this research, the particle density was set to 1000 kg/m^3. Another, similar set-up is the CO_2 mole fraction exiting from human exhale and CO_2 entering the system. many research studies indicate that the CO_2 mole fraction is between 35000 ppm and 40000 ppm [221] [222].

5.1 Chemistry building ANSYS simulation

The simulation for the OSO in the chemistry building will be the first among the other spaces selected for this research (fig. 5.1). This space is located on the ground floor of the chemistry building. the room has an L-shape geometry with a length of 23-meter, 7.7-meter width, and around 4-meter height with a total area of around 211 m^2. The drop ceiling is at 3-meters high and the air inlet is also located at the same height as the drop ceiling. The room has 10 main inlet registers that blow air at a speed of 1.7 m/s. Two main exact vents extract the air at a speed of 2.7 m/s with a size of 1.5 meters by 70 centimetres and four extraction fans the withdraws air near the entrance of the OSO. The floors are covered in carpet and the area is furnished with office equipment. As can be seen from (figure. 5.1) that the winter garden is located on the south side of the building. the atmosphere of the winter garden is very similar to the outdoor atmosphere that works as an intermediary space between the OSO and the outdoor region. On the west and north side of the OSO are small individual offices. These offices are supplied with their own separate air inlet but the air inside these offices is then been transported to the OSO then the mixed air in both spaces is being extracted using the extract vents. The main source of ventilation is the MVHR system that uses biofuel as the source of energy generation. The MVHR system supplies air for the offices and the other offices that are attached to their respective laboratories (figure 5.1). Meanwhile, the laboratories rely only on the extract fans to extract the air from the adjacent office they are attached to.

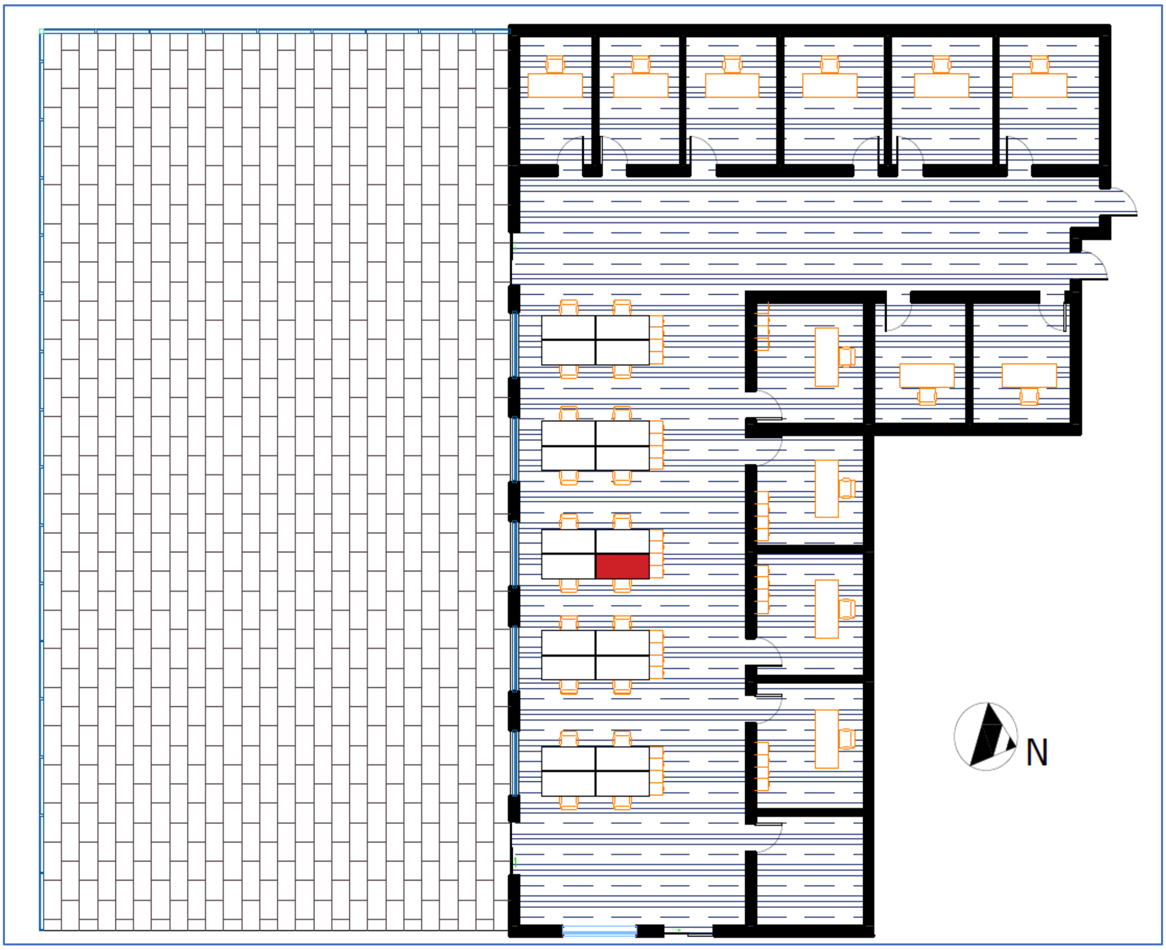


Figure 5-1. A schematic drawing of the OSO. The red square represent the desk at which the measuring equipment were placed.

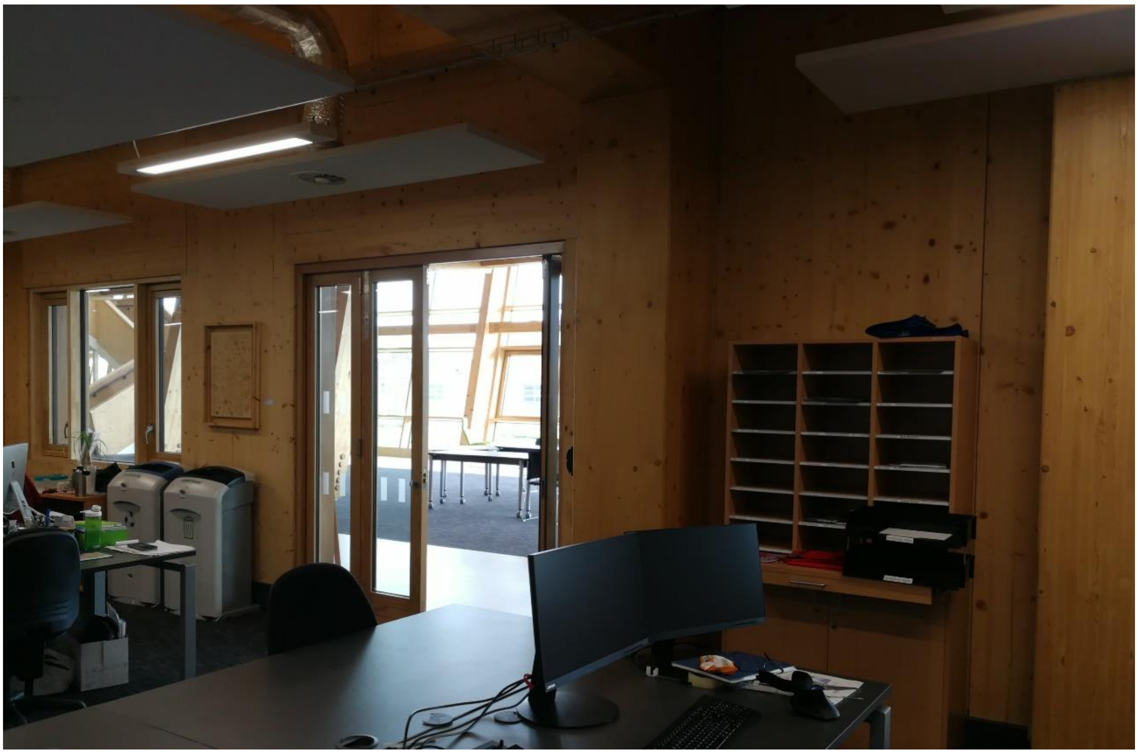


Figure 5-2 image of the OSO which shows the adjacent winter garden the attached offices

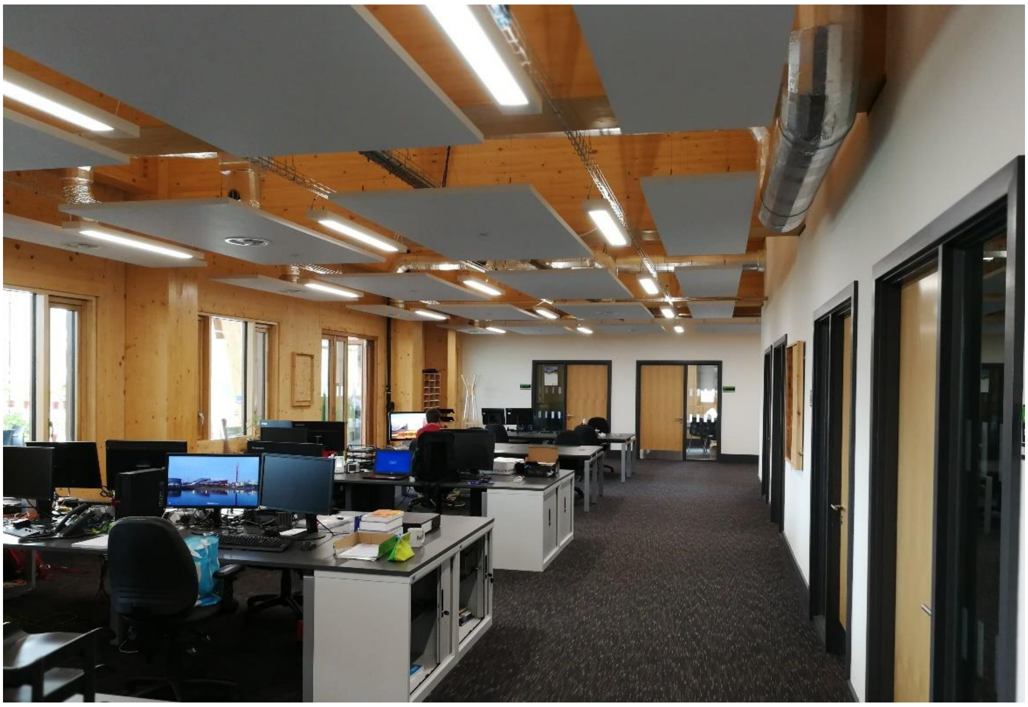


Figure 5-3 image of the OSO which shows the adjacent winter garden the attached offices

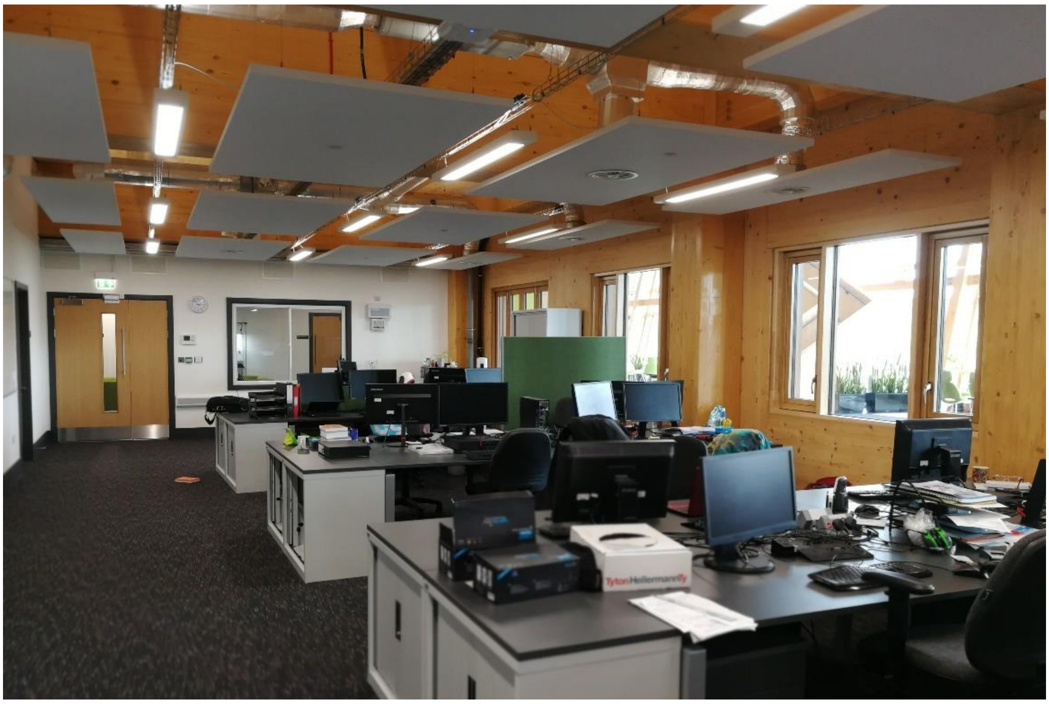


Figure 5-5 images of the OSO that shows the location of the extraction fans near the entrance

Figure 5-4 image of the air tunnel that extract the air from the small offices to the main open space office

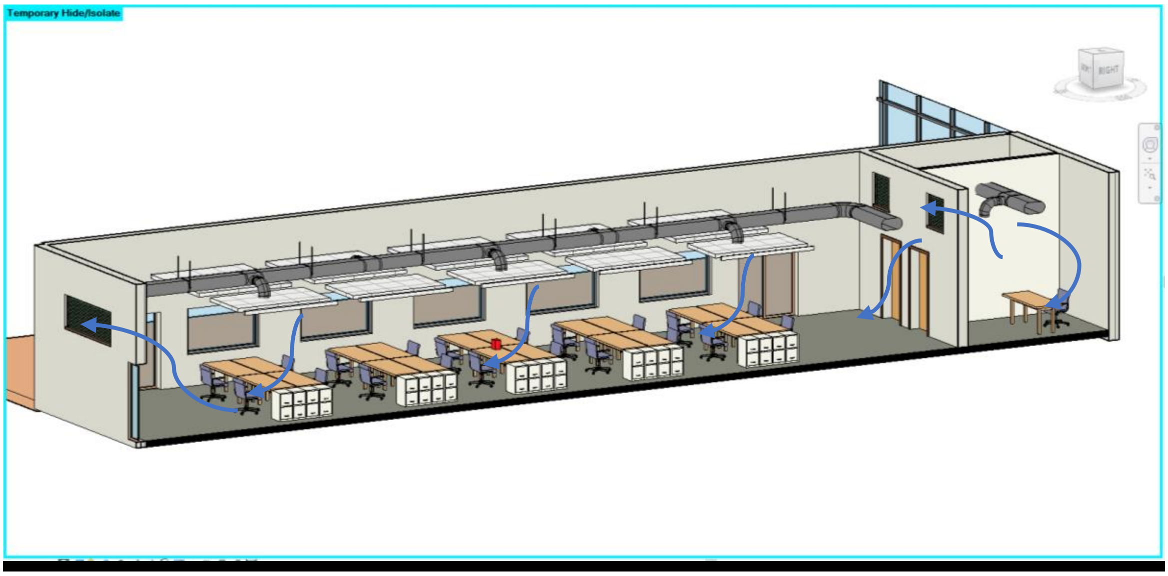


Figure 5-6 a 3-D schematic drawing of the OSO that shows the air flow movement pattern inside the space

simulation setup

The simulation of the three spaces was conducted in three distinct scenarios. The first scenario was the winter scenario in which the space has a more restricted airflow. The second scenario was the summer scenario in which there is an ample amount of air entering the space. The last scenario is an intermediary scenario that represents both the autumn and spring season. The first indoor space simulated will be the OSO which is located in the Chemistry building. Figure (5.7) shows the 3-D model of the space. The mesh consists of 504401 tetrahedral cells. The average element size is 16 centimeters. The aspect ratio is around 1.16

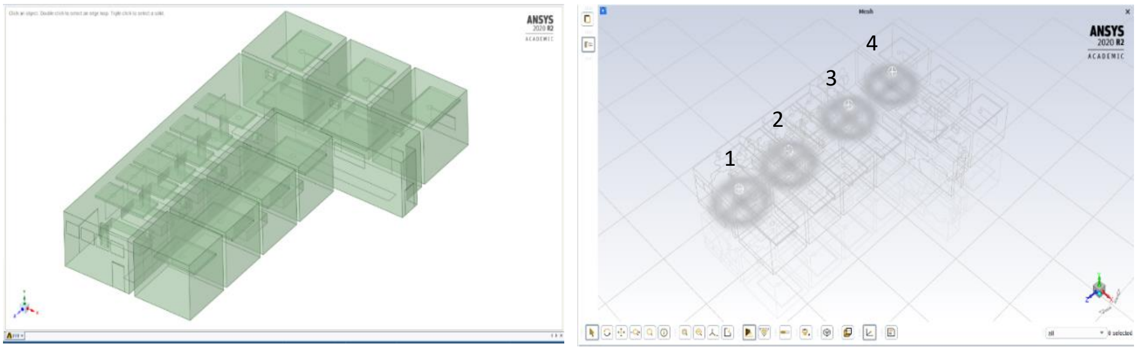
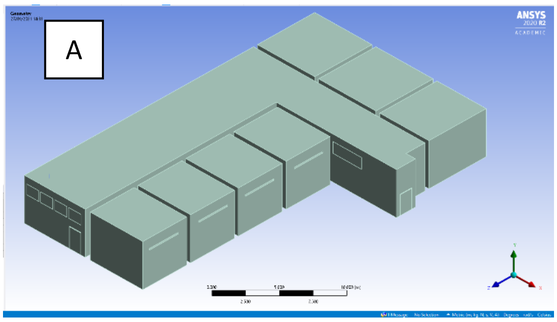
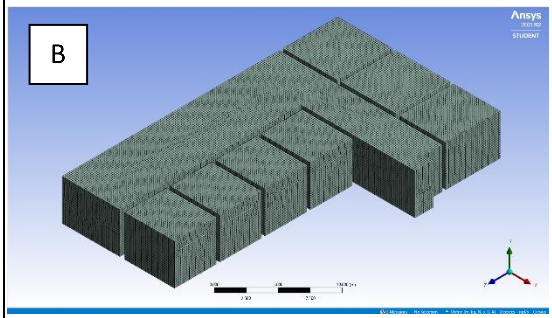
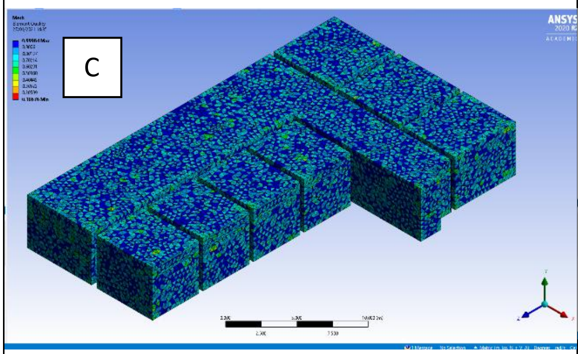
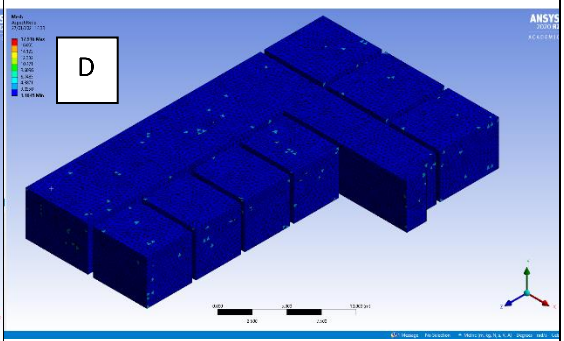
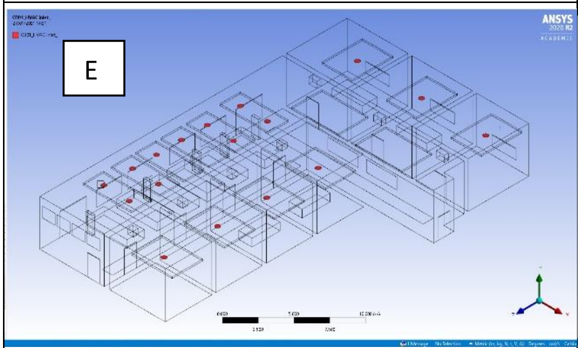
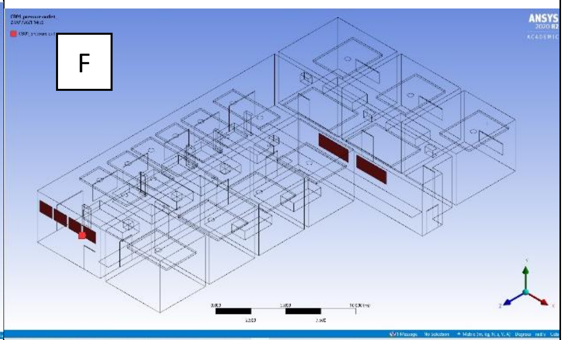
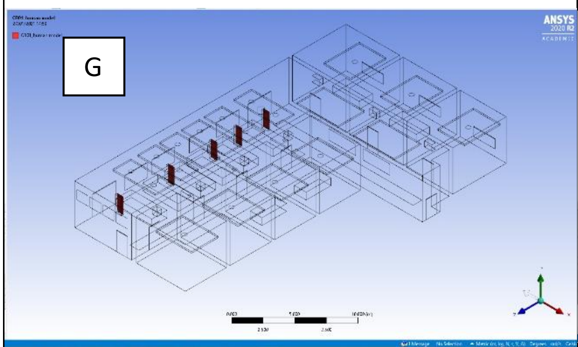
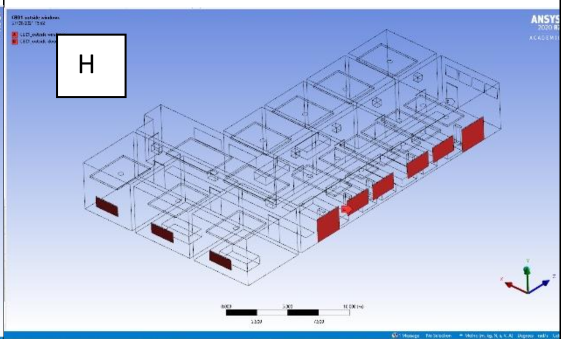


Figure 5-7 3-D model of the OSO on the right , and the location of sensors on the left

Table 5-1 OSO simulation set up

	
	
	
	
These images represent the following: **A)** shows the 3-D geometry of the OSO, **B)** shows the mesh structure of the simulation model, **C)** mesh quality, **D)** shows the aspect ratio, **E)** shows the HVAC inlet, **F)** shows the outlet exhaust, **G)** CO2 inlet location, **H)** border windows.	

5.2 OSO_Winter simulation

5.2.1 OSO_Winter simulation_ PM concentration

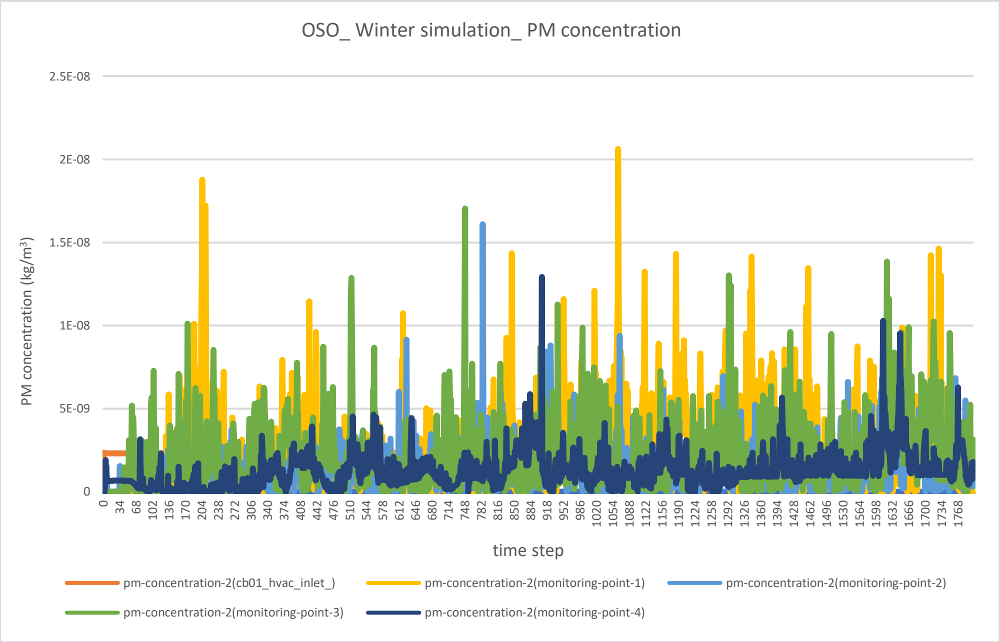


Figure 5-8 OSO_ Winter simulation_ PM concentration

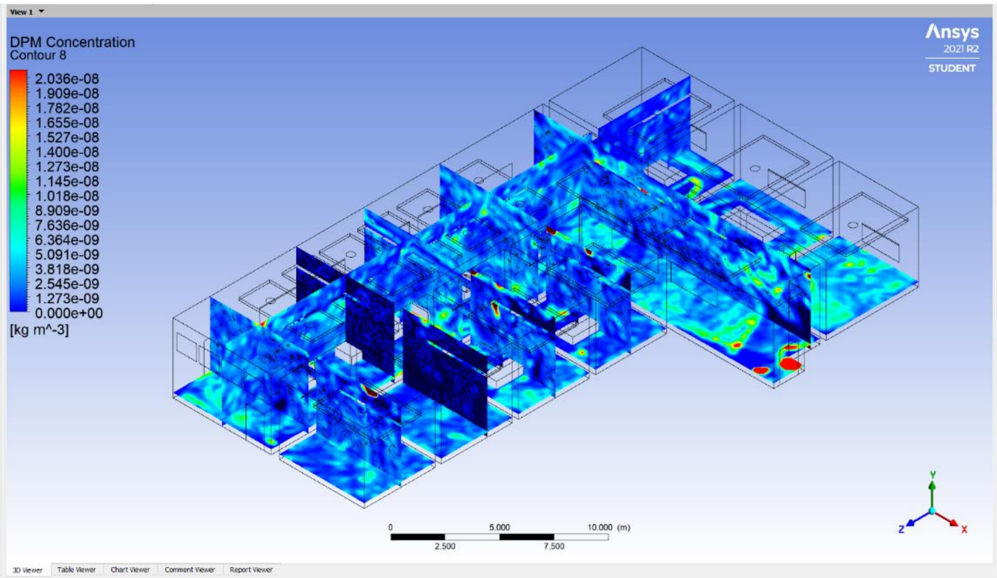


Figure 5-9 OSO 2-D surfaces illustrating the contour of PM concentration_ winter simulation

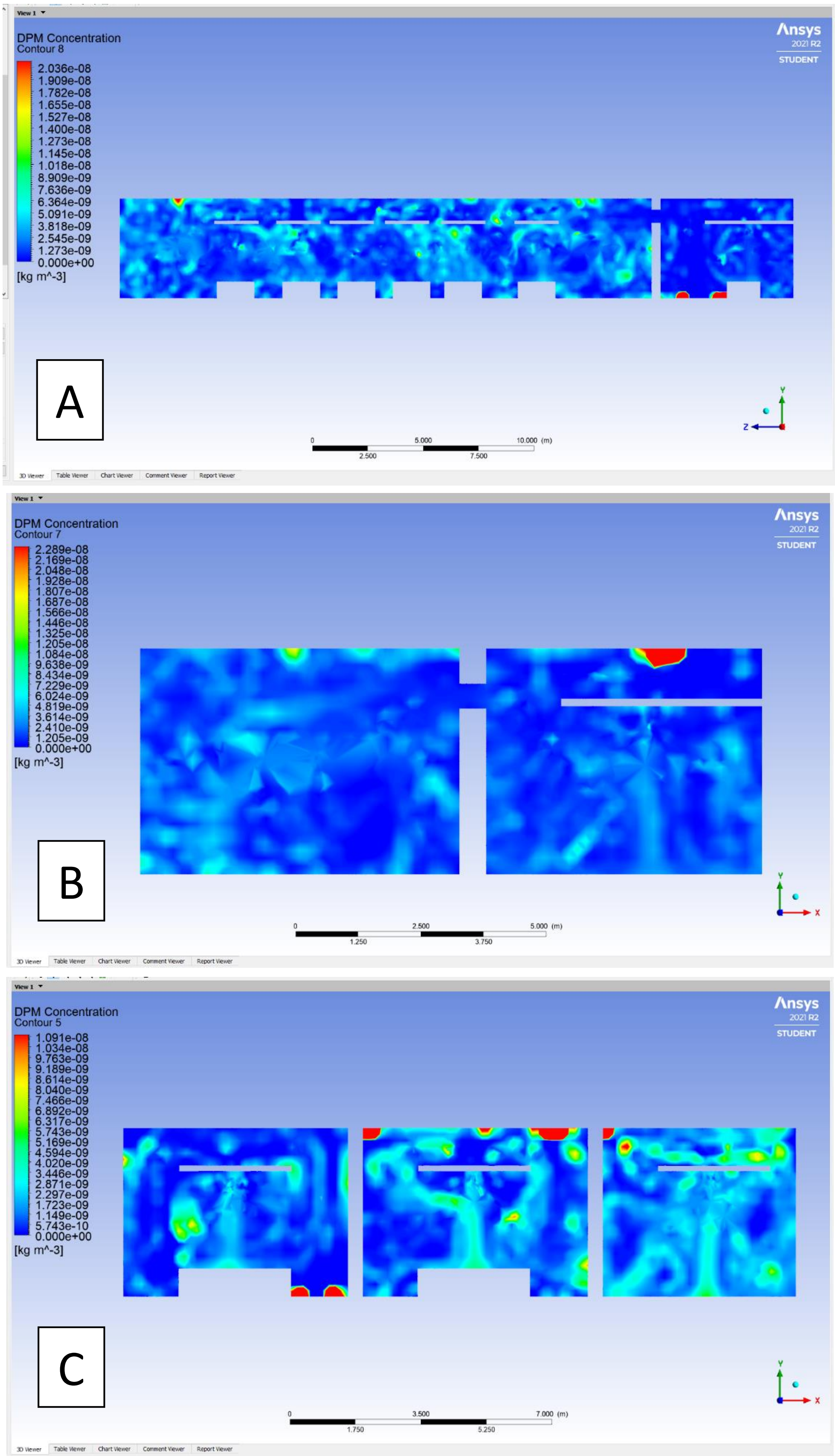


Figure 5-10 OSO multiple 2-D surfaces illustrating the contour of PM concentration_ winter simulation

Table 5-2 OSO_ Winter simulation_ PM concentration

Monitoring point	PM-concentration (HVAC inlet)	PM-concentration (pressure outlet)	PM-concentration (monitoring-point-1)	PM-concentration (monitoring-point-2)	PM-concentration (monitoring-point-3)	PM-concentration (monitoring-point-4)
Average readings (Kg/m^3)	2.3129E-09	3.083E-09	2.271E-09	1.439E-09	2.103E-09	1.235E-09

The winter scenario is the first one of the four scenarios that were simulated. In each scenario, the PM concentration, the ambient temperature, the airflow velocity, and the CO_2 concentration were measured. The introduction of the (PM) inside the space needs to have a source. There are a couple of familiar sources of (PM) like resuspension of particles from the floor, printers and other electronic devices, humans and human movement inside the space either by walking over certain floor surfaces like carpet which could resuspend a considerable number of particles into the air or moving their clothing materials which could also resuspend a measurable number of particles into the space. Another source of (PM) is the infiltration of these particles through outside openings. Lastly, the MVHR system itself can introduce a number of particles into the space depending on the type of filter that is used and how well maintained are these filters. In this simulation, there were three chosen sources of (PM) which are the MVHR opening, floor resuspension and infiltration. To monitor the concentration of (PM) there were several monitoring surfaces that were set up to measure the average weighted area of the (PM) concentration either coming out of these surfaces or going into these surfaces and these surfaces are the 1) the MVHR intel and 2) the exhaust fan outlet. Additionally, there were four monitoring points allocated in the space. These monitoring points were used to measure the concentration of the (PM) in four different locations inside the space. Figure (5.8) shows the result of the (PM) concentration inside the space. From looking at table (5-2) it is clear that the (PM) concentration inside the space almost uniform throughout the entire OSO. The four-monitoring points have an average (PM) concentration of 2.4 µg/m^3 with monitoring point 1 having a slightly higher value of 2.2 µg/m^3 and this could be attributed to the increased airflow near the exhaust fans where this registering point is located. It is important to note that a large portion of the (PM) particles is closely located near the ceiling of the space which is shown very clearly in figure (5-10). This could lead to large numbers of particles attaching to the top surface of the dropped ceiling. In fact, when examining the top surface of the dropped in the actual OSO the surface completely covered dust particles that have been accumulating for a long period of time which might act as an additional source of (PM) inside the space.

5.2.2 OSO Winter simulation_ Ambient Temperature:

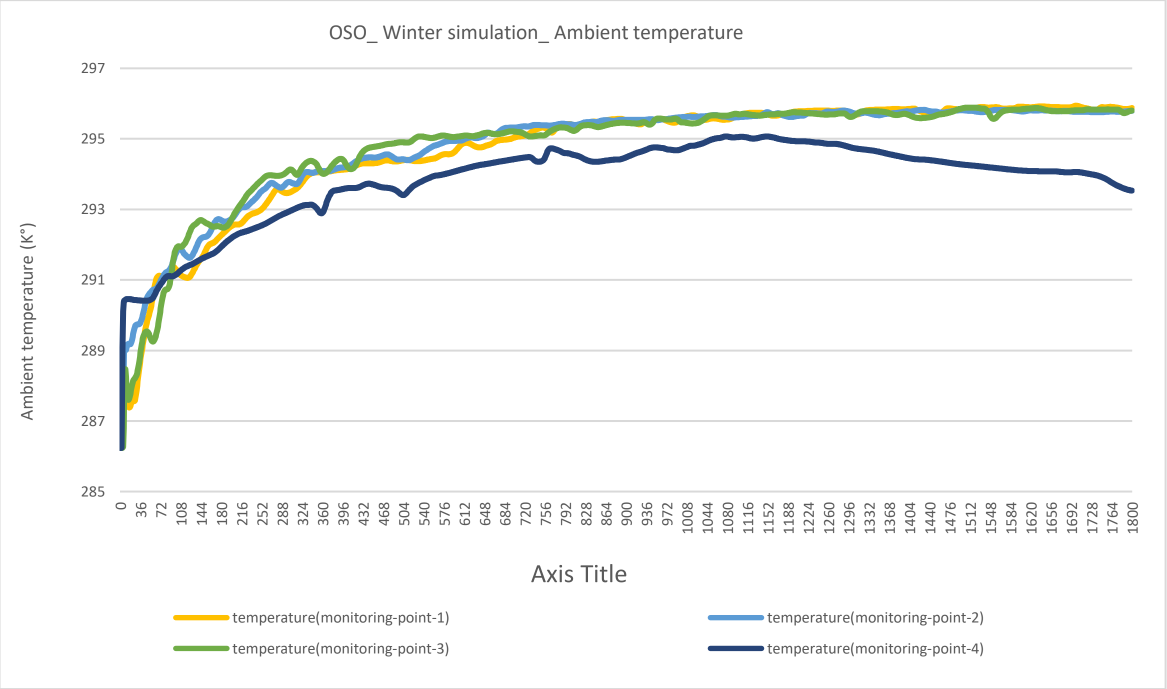


Figure 5-11 OSO_ Winter simulation_ global temperature

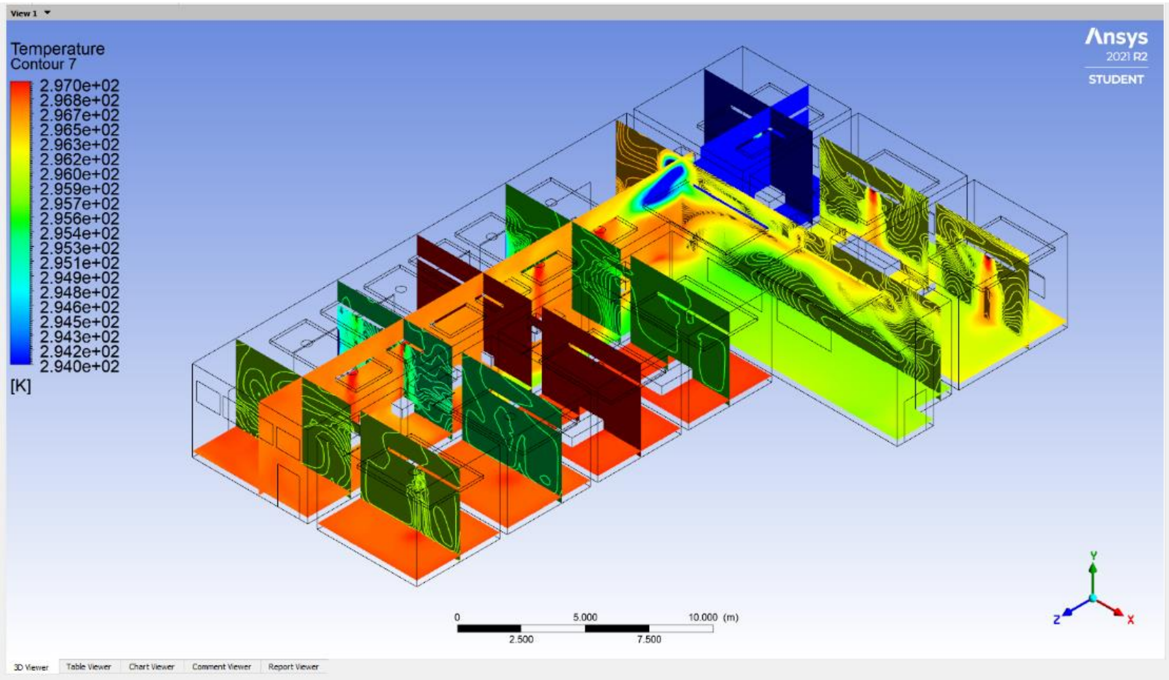


Figure 5-12 OSO 2-D surfaces illustrating the contour of Ambient temperature_ winter simulation

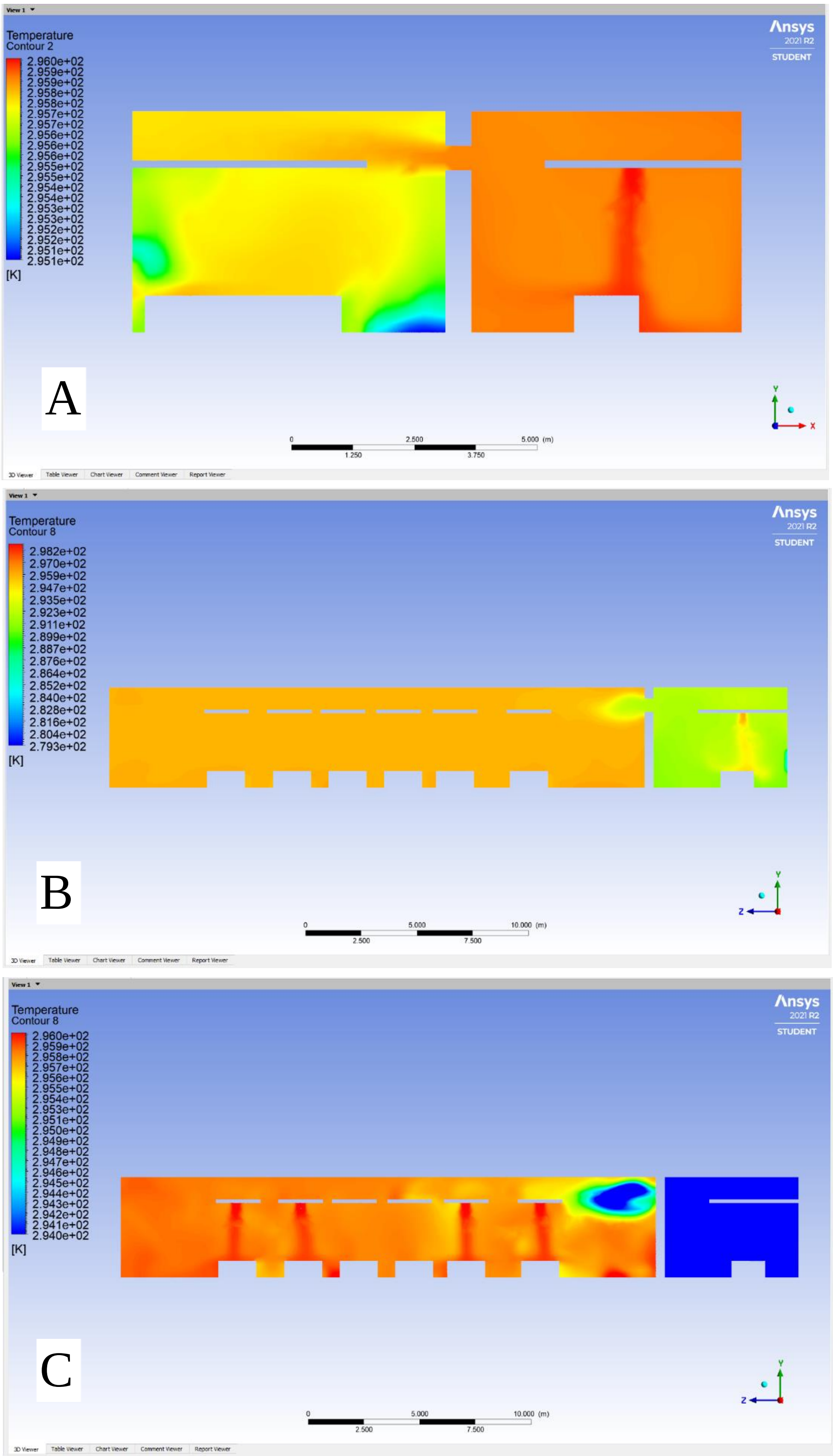


Figure 5-13 OSO multiple 2-D surfaces illustrating the contour of Ambient temperature _ winter simulation

Table 5-3 OSO_ Winter simulation_ Ambient temperature

Monitoring point	Temperature (HVAC inlet)	temperature (pressure outlet)	Temperature (monitoring-point-1)	Temperature (monitoring-point-2)	Temperature (monitoring-point-3)	Temperature (monitoring-point-4)
Average readings (Kelvin)	296	293.827	294.691	294.797	294.794	293.841

The temperature simulation of the OSO in the winter scenario showed that the ambient temperature inside the space had reached a stable value of 294 K° (20 C°) some of the source of heat inside the OSO was the MVHR system that introduces a constant airflow at 296 K°. As mentioned before, there are 10 air registers that input the same amount of air into the space with the same ambient temperature level. The second source was the windows that are close to the outside of the building and the windows that are adjacent to the winter garden. Each of these windows has a low surface temperature due to the ambient temperature of both the winter garden and the outdoor of the building. The temperature in the city of Nottingham can be as low as -8 C° with an average outdoor temperature at 4 C°. Figure (5.13) illustrate the effect of the windows on the temperature inside the space. It is important to note that just as previously mentioned, the effect of infiltration might play a role in the ambient temperature inside the OSO. In addition, many employees and students are constantly opening the doors to go in and out of the space. The third source is human breathing inside the space. The temperature of the air entering the OSO from people was set at 310 K° (37 C°). An increase in the number of people would have had a significant impact on the ambient temperature inside the space. However, on most occasions, the number of people inside the space is limited to between 5 to 7 people present at the same time. Other sources of temperature like electronics have been ignored because the effect of electronic devices on the ambient temperature is not prominent.

5.2.3 OSO Winter simulation_ Airflow velocity

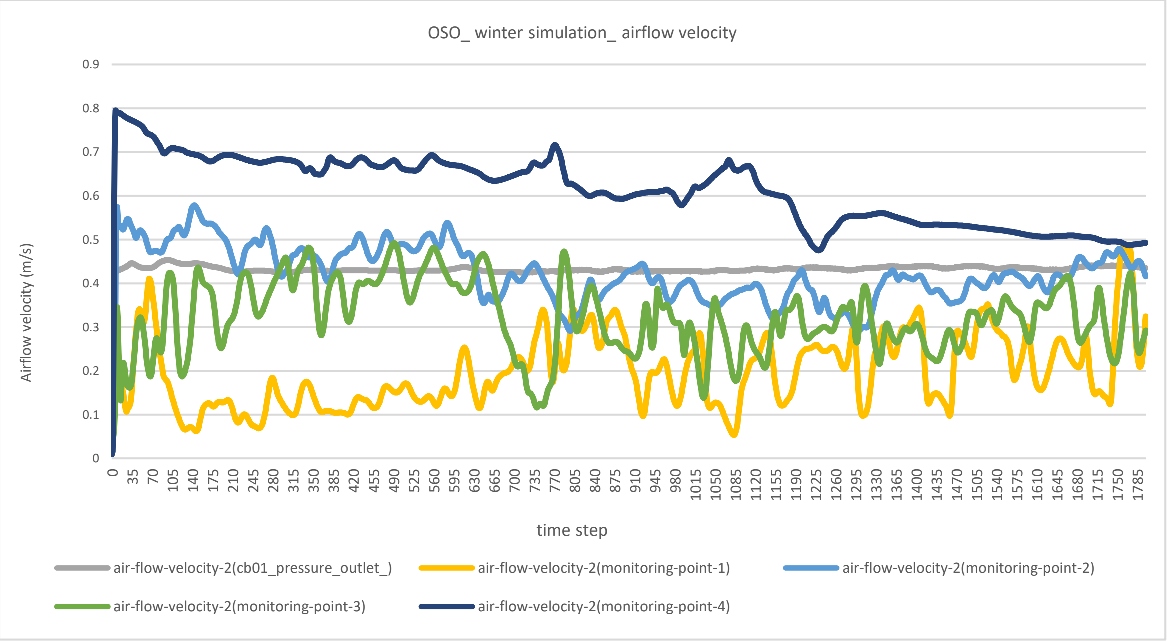


Figure 5-14 OSO_ Winter simulation_ PM concentration

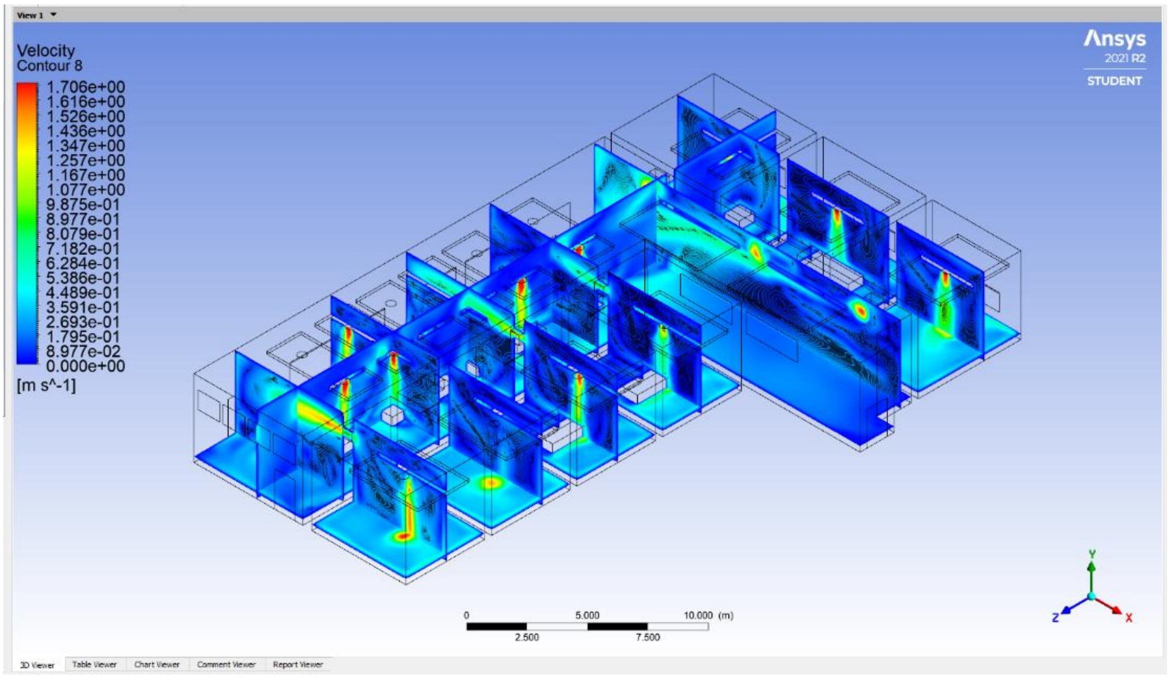


Figure 5-15 OSO 2-D surfaces illustrating the contour of airflow velocity_ winter simulation

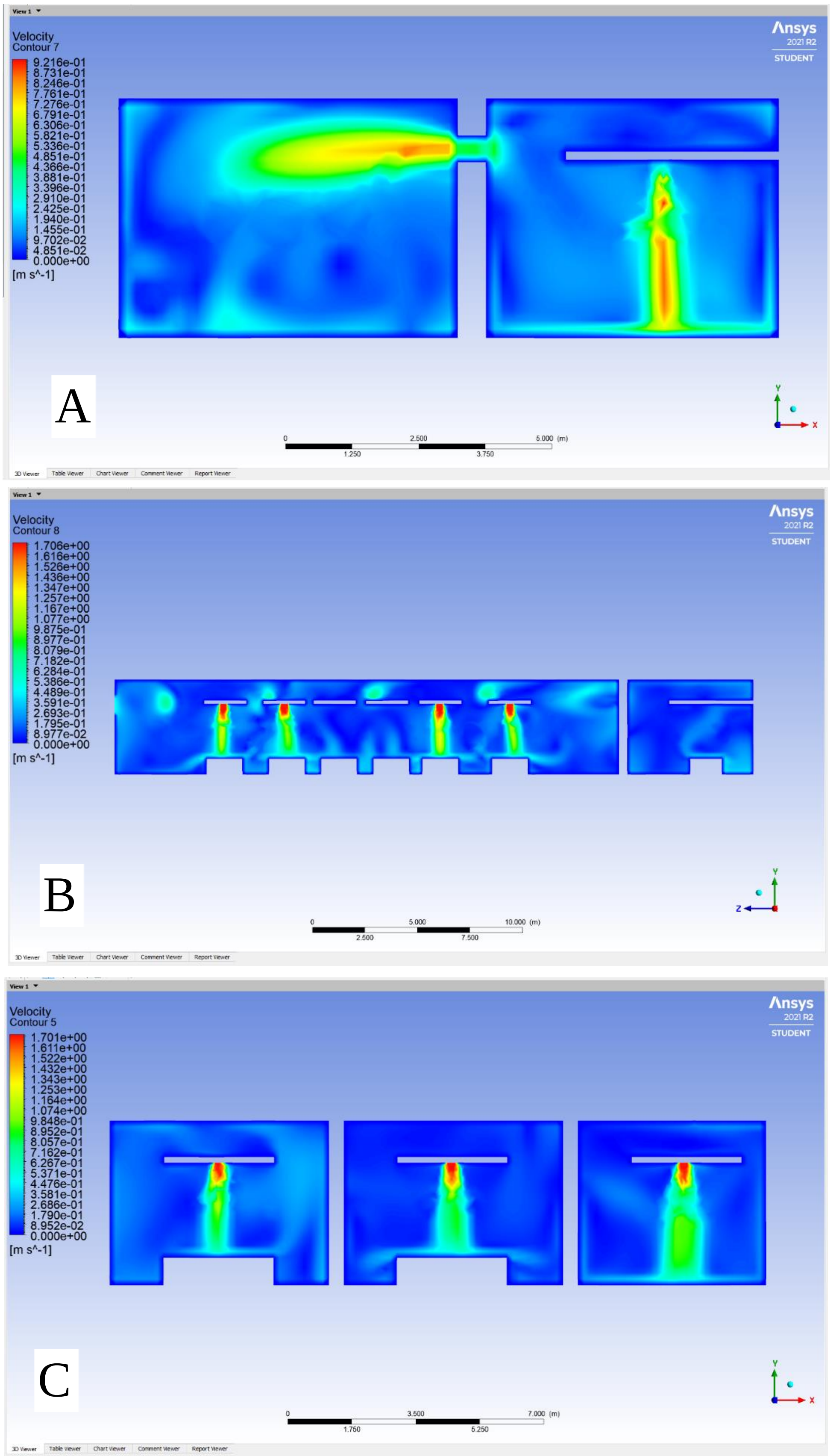


Figure 5-16 OSO 2-D surfaces illustrating the contour of airflow velocity_ winter simulation

Table 5-4 OSO_ Winter simulation_ air flow velocity: average readings

Monitoring point	air-flow-velocity (HVAC inlet)	air-flow-velocity (pressure outlet)	air-flow-velocity-(monitoring-point-1)	air-flow-velocity (monitoring-point-2)	air-flow-velocity (monitoring-point-3)	air-flow-velocity (monitoring-point-4)
Average readings (m/s)	1.700	0.432	0.198	0.423	0.321	0.611

The airflow velocity in the winter scenario is very limited compared to the other scenarios. For example, the windows located on all sides of the OSO is closed almost all the time to preserve the heat inside the indoor space. The doors are also closed most of the time, however, on many occasions the door is opened when students and employees are entering and leaving the OSO. As a result, many pollutants are kept inside the indoor space much longer. As can be seen from table (5-4) the air velocity coming from the MVHR system is fixed at 1.7 m/s. The four-monitoring points have registered very slow air velocity as can be seen from table (5-4). Three of the four monitoring point have registered an average air velocity of 0.3 m/s which is almost unnoticeable by occupants. The pattern of the air movement inside the space is closer to a laminar flow than a turbulent. However, there are few areas where the airflow velocity increases such as the areas that are close to the opening between the opening of the individual offices and the main open space area. The reason being is that the extract fans are pulling out all the air from inside these individual rooms which goes to the open space area then being extracted by the main extract fans figure (5-16).

5.2.4 OSO Winter simualtion_CO_2 concentration

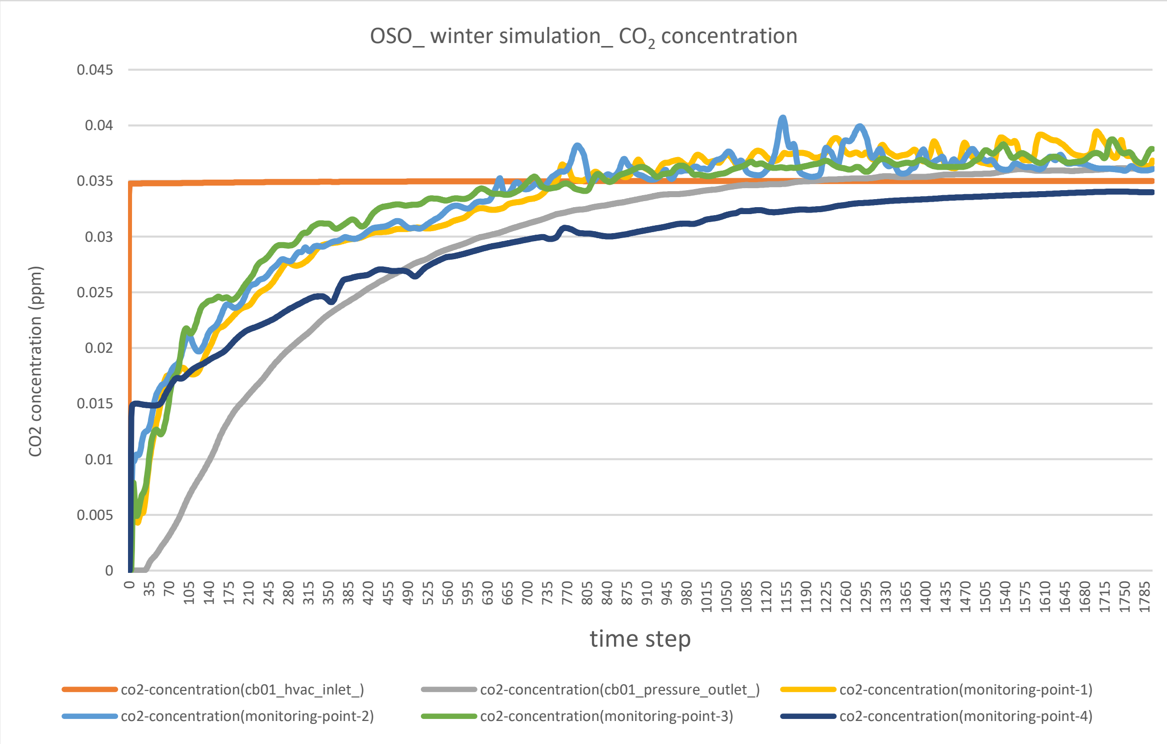


Figure 5-17 OSO_ winter simulation_ CO_2 concentration

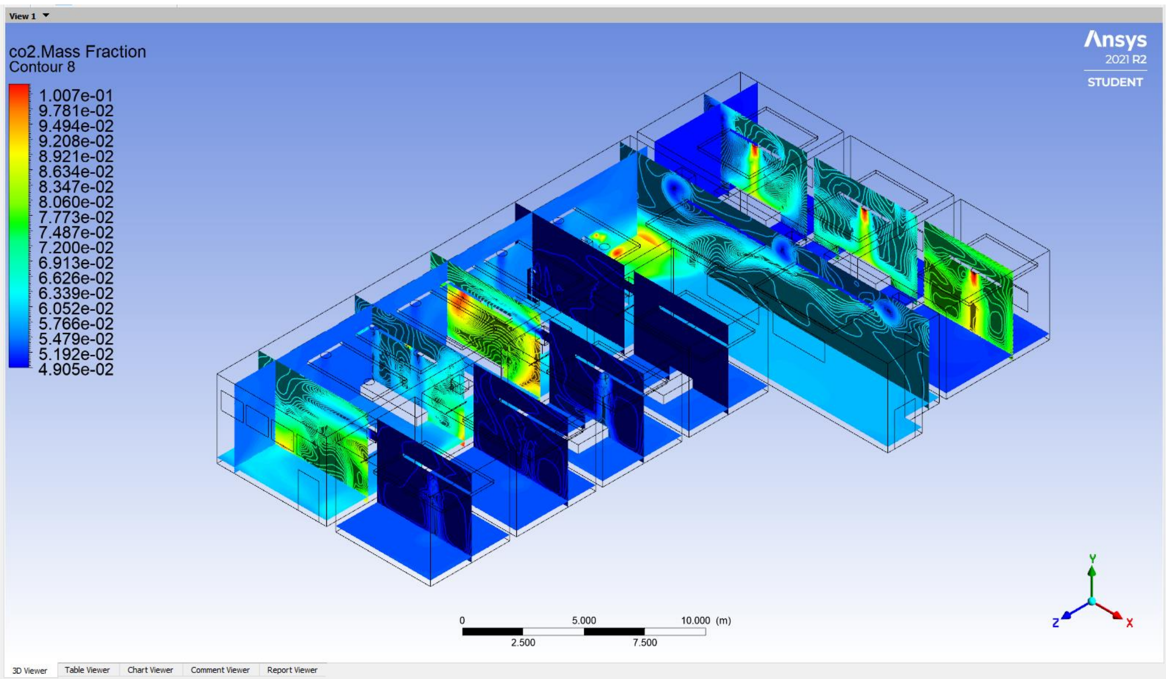


Figure 5-18 OSO 2-D surfaces illustrating the contour of CO_2 concentration_ winter simulation

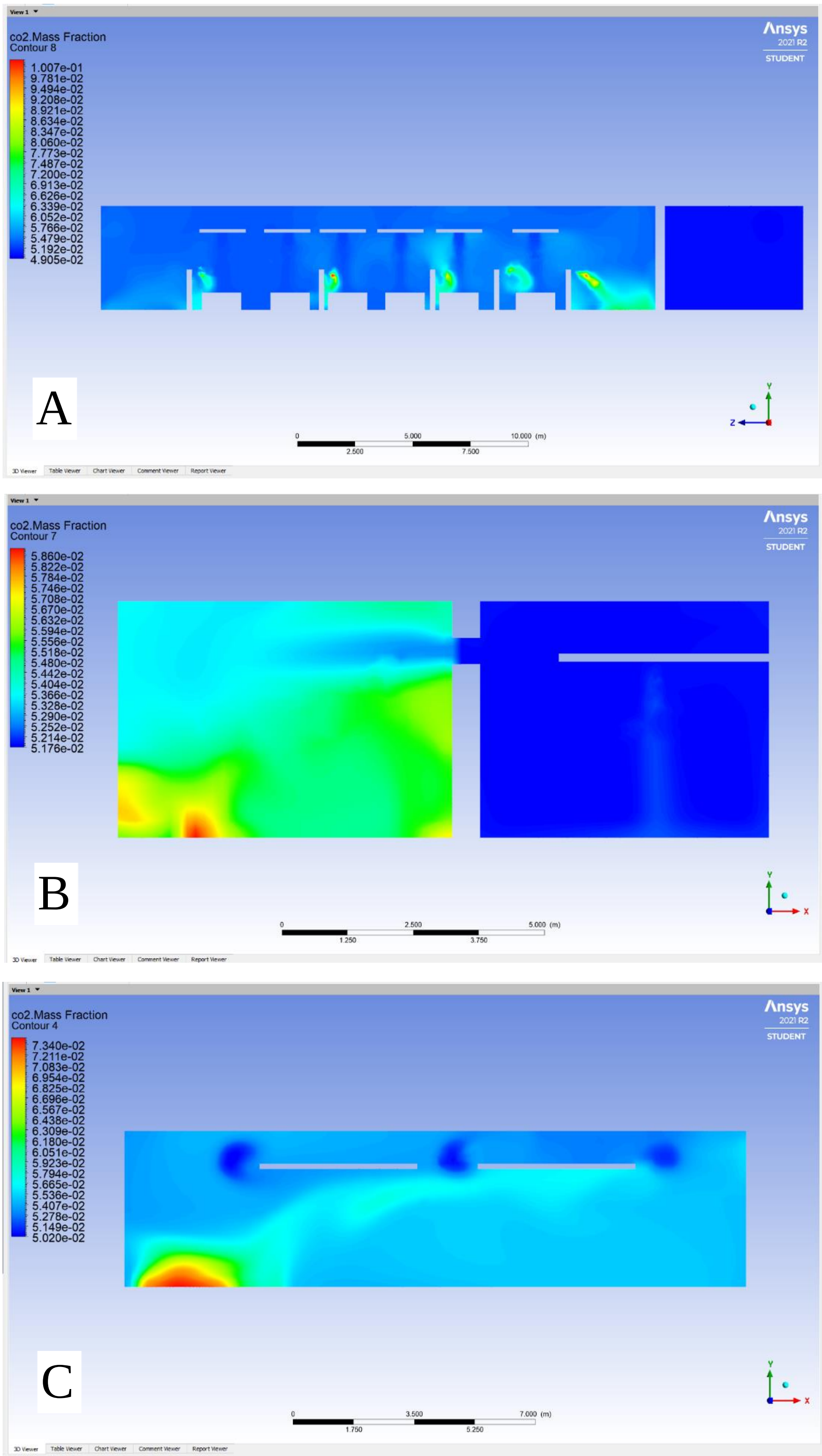


Figure 5-19 OSO multiple 2-D surfaces illustrating the contour of CO2 concentration_ winter simulation

Table 5-5 OSO_ winter simulation_ CO_2 concentration_ Average readings

Monitoring points	CO_2 concentration (HVAC Inlet)	CO_2 Concentration (Pressure outlet)	CO_2- concentration (monitoring-point-1)	CO_2- concentration (monitoring-point-2)	CO_2- concentration (monitoring-point-3)	CO_2- concentration (monitoring-point-4)
Average readings (ppm)	0.0349	0.0289	0.0326	0.0327	0.0329	0.0290

When analyzing the chart in figure (5.17) it is clear that the value of CO_2 is highest at monitoring point 2. This monitoring point is located in the middle of the OSO main open area. That is because there are two sources of CO_2 near that monitoring point. The lowest value was registered at monitoring point 4 as shown in table (5-5). Monitoring point 4 was installed inside an individual office that is separate from the rest of the main open office area. The reason why the levels of CO_2 is lowest at that there was no human model inserted inside the office and this shows the value of CO_2 inside the room without the presence of people. When looking at figure (5.19) it is clear that the CO_2 is residing close to the ground. Two of the images in figure (5.19) shows that the concentration of CO_2 is higher at the ground level when compared to the concentration of CO_2 at the ceiling level. In fact, in one of the images in figure (5.19), the concentration has reached 734 ppm. This simulation shows how much the presence of people could have a significant impact on the concentration of CO_2 on indoor air quality. By comparing monitoring point 2 and monitoring point 4 it is clear there is at least an average 37 ppm difference between the monitoring point and of course, the more people present inside the pace the higher levels of CO_2 will be. However, in general, the levels of CO_2 inside the space is relatively low as compared to the SIBCE standards previously mentioned in chapter 2 which is around 500 ppm maximum level allowed for long term exposure.

5.3 OSO Summer simulations

5.3.1 OSO_Summer simulations_(PM) concentration

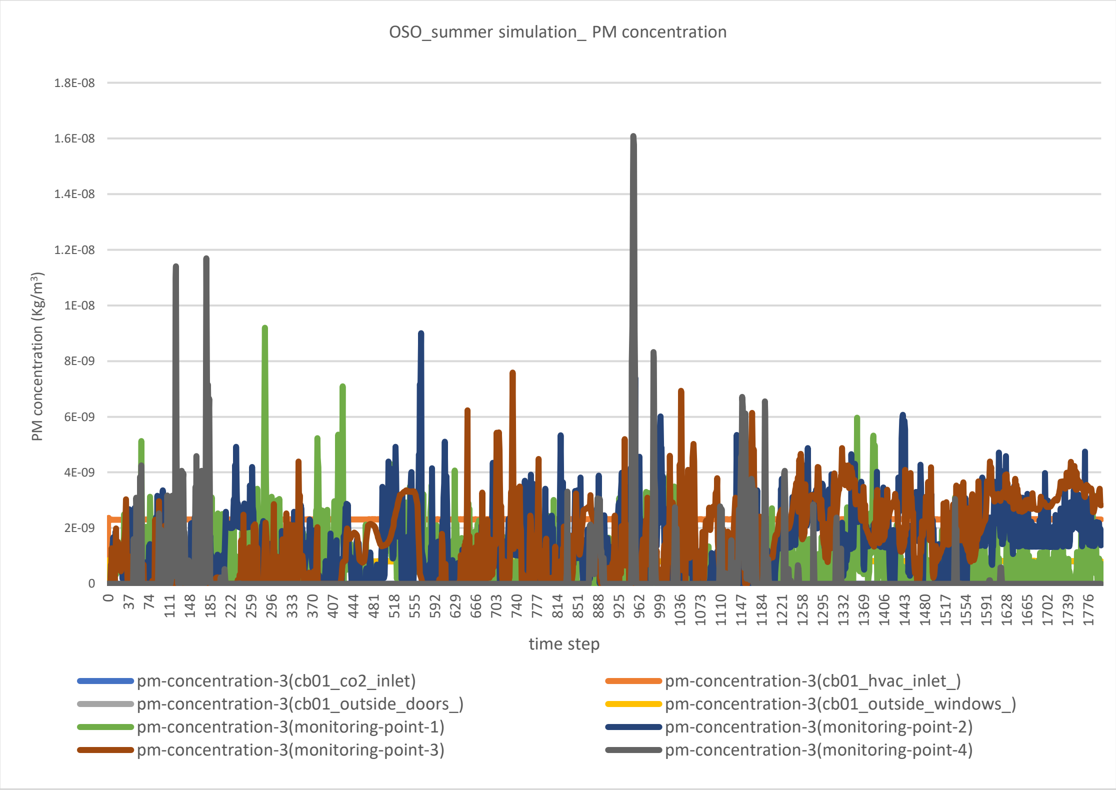


Figure 5-20 OSO_summer simulation_ PM concentration

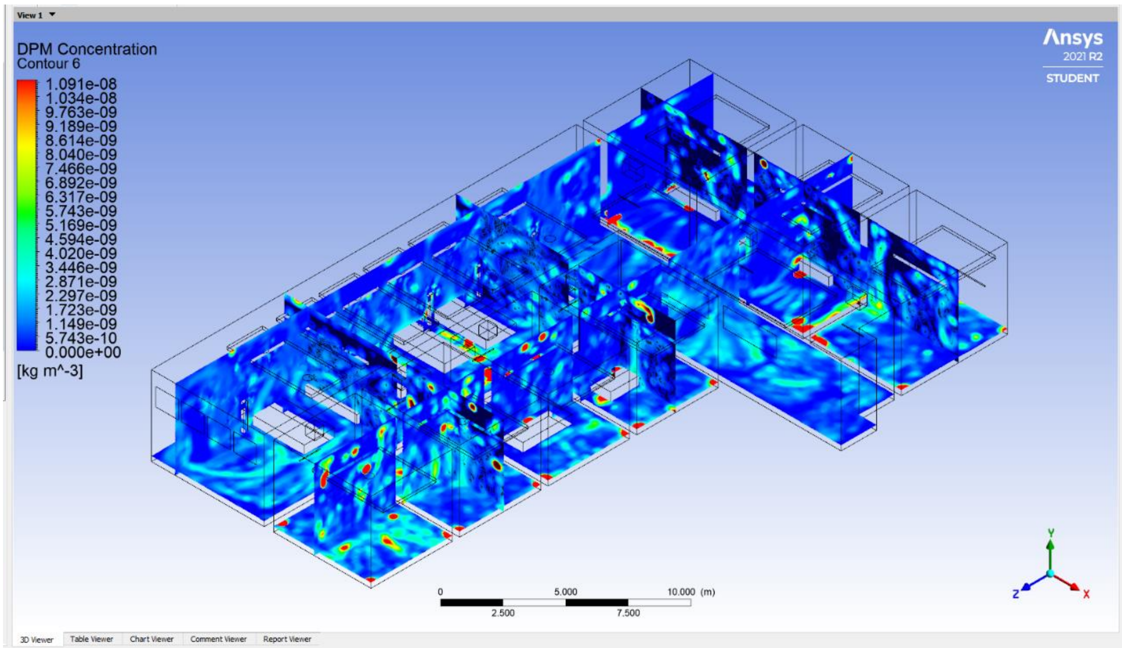


Figure 5-21 OSO 2-D surfaces illustrating the contour of (PM) concentration_ summer simulation

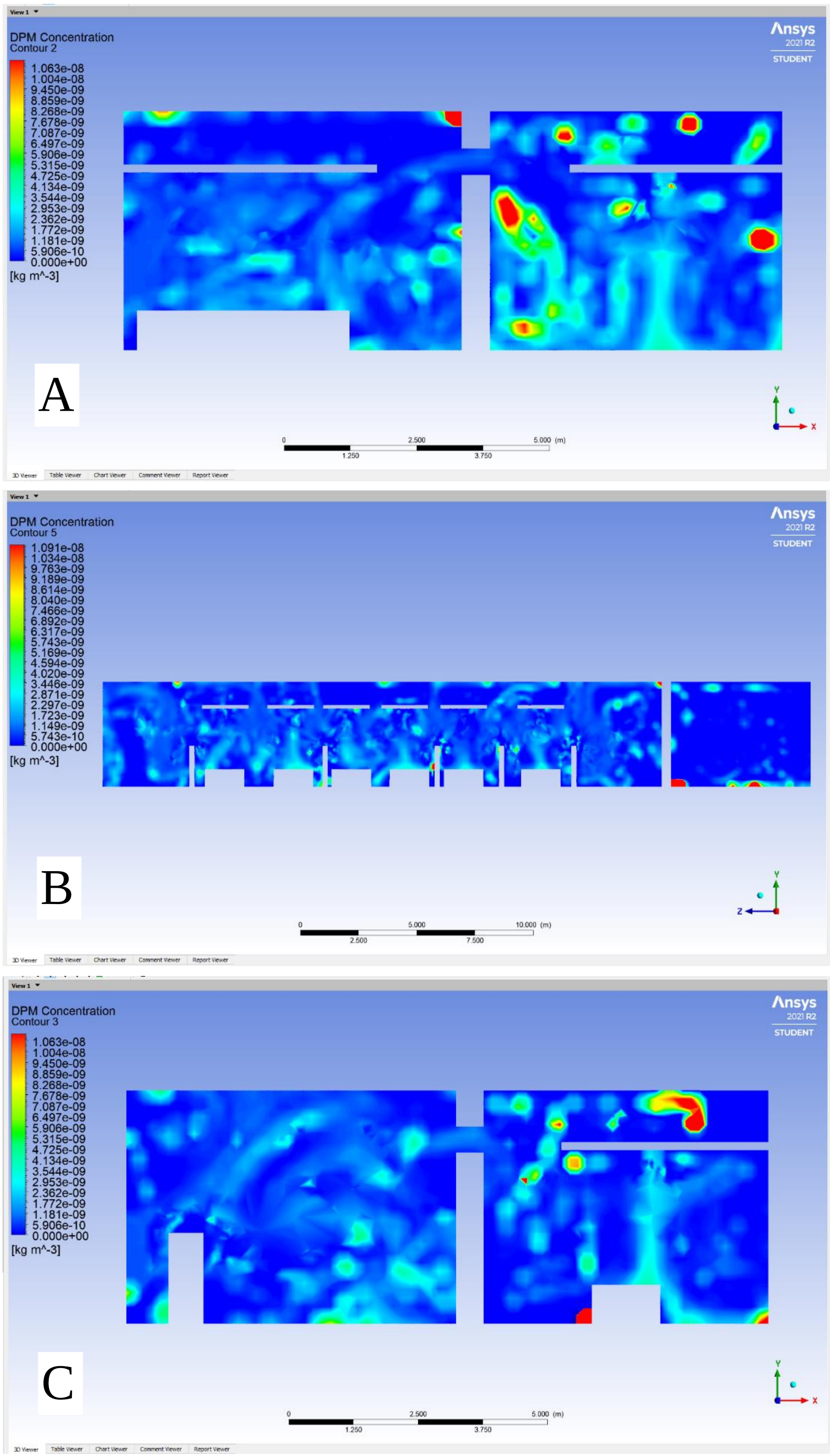


Figure 5-22 OSO multiple 2-D surfaces illustrating the contour of (PM) concentration_ summer simulation

Table 5-6 OSO_ summer simulation_ PM concentration

Monitoring point	PM concentration (HVAC inlet)	PM concentration (pressure outlet)	PM concentration (monitoring-point-1)	PM concentration (monitoring-point-2)	PM concentration (monitoring-point-3)	PM concentration (monitoring-point-4)
Average readings (Kg/m^3)	2.312E-09	1.406E-09	7.542E-10	1.384E-09	1.510E-09	2.645E-10

The summer scenario is almost the complete opposite of the winter scenario. In the summer scenario, the airflow, as well as the temperature entering the interior space, is very different. One of the major differences between the summer scenario and the winter is the opening of windows and doors during the summer period. Therefore, when simulating the summer scenario, the windows and door adjacent to the winter garden are kept open throughout the entire time of the simulation. These opening have introduced a new source f (PM) into the interior space. However, when comparing the concentration of (PM) from both the winter simulation and the winter simulation, the result shows that the concentration of (PM) in the winter simulation is greater than the concentration of (PM) from the summer simulation. For example, monitoring 1 from the winter simulation has an average (PM) concentration of 2.2 $\mu g/m^3$ while the average concentration of (PM) from the same monitoring point in the summer simulation is around 0.75 $\mu g/m^3$ which is very different between the two scenarios. The difference is even greater when comparing the reading from monitoring point 4 which shows that the average concentration from the winter scenario to be around 1.2 $\mu g/m^3$ while the summer scenario from the same monitoring showed an average (PM) concentration of 0.26 $\mu g/m^3$ which is a 46% reduction in the (PM) concentration. Despite that, some readings closer to each other between the winter scenario and the summer scenario. Like for instance in monitoring point 3 it shows that the two-readings are close but there is still differences between them where in the winter scenario at monitoring 3 point has an average (PM) concentration of 2.1 $\mu g/m^3$ whereas the same monitoring in the summer scenario registered an average of 1.5 $\mu g/m^3$. This phenomenon could be explained by the fact that monitoring point 3 is located close to multiple sources of (PM) the first is the particles coming from the separate office located close to that monitoring point, second the introduction of an additional source of (PM) from the door which is also located near the monitoring point 3.

5.3.2 OSO Summer simulation_ Ambient temperature

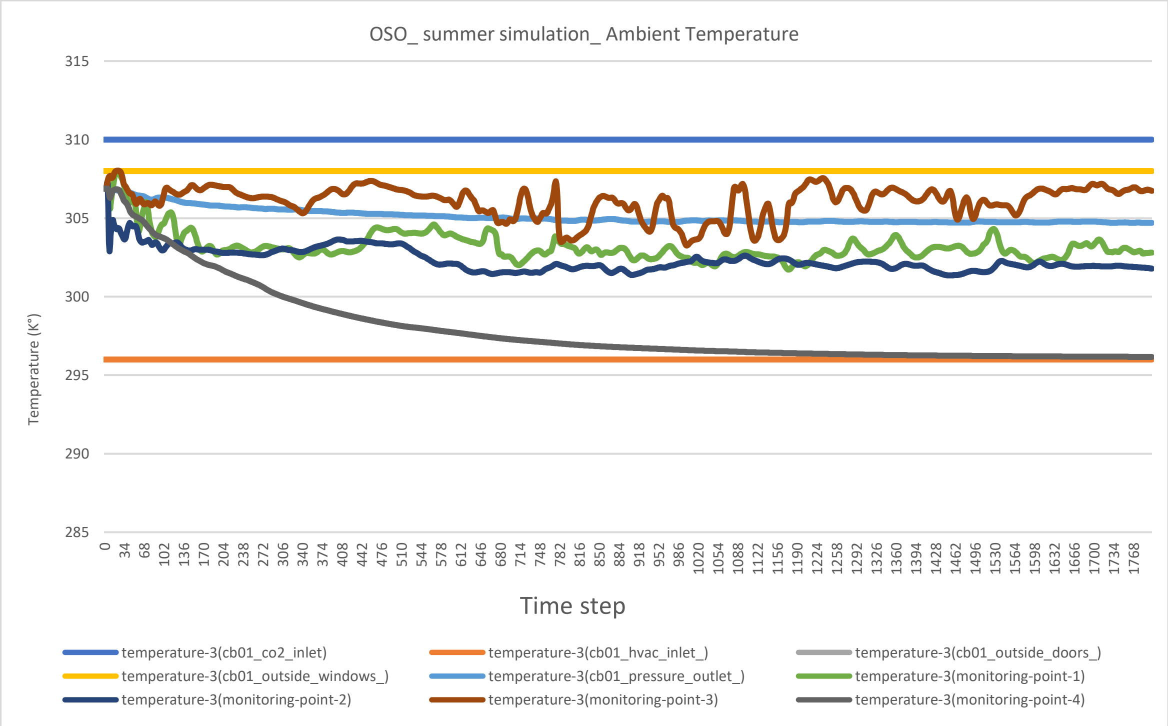


Figure 5-24 OSO_ summer simulation_ Ambient Temperature

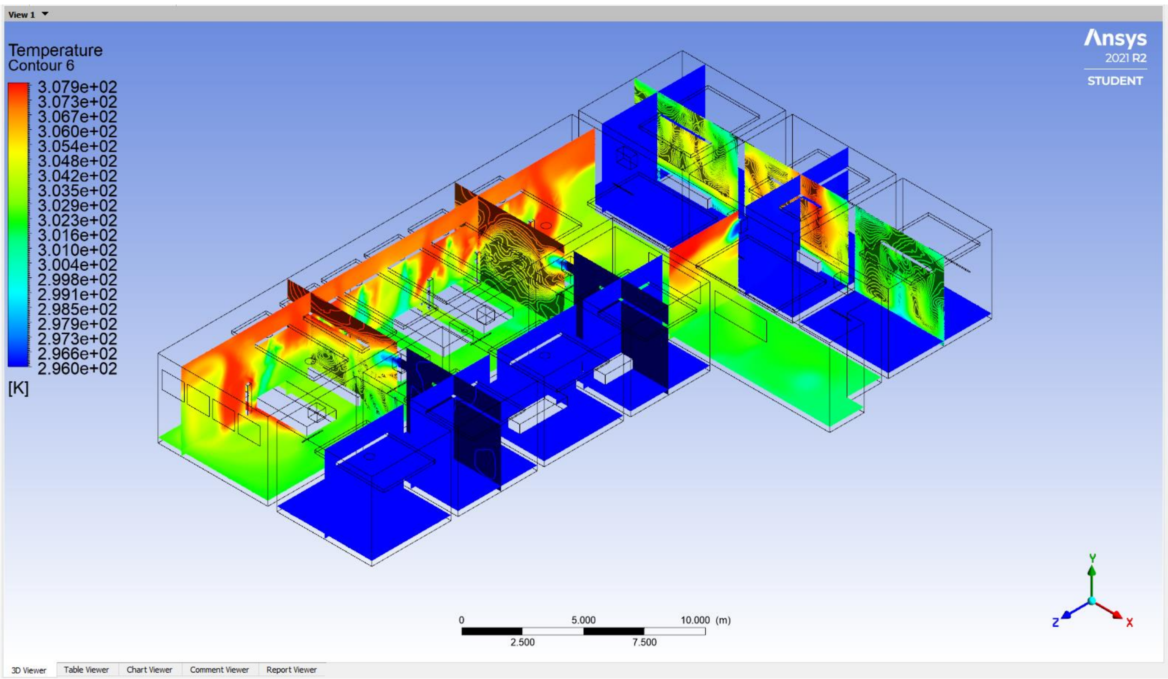


Figure 5-23 OSO 2-D surfaces illustrating the contour of Ambient temperature_ Summer simulation

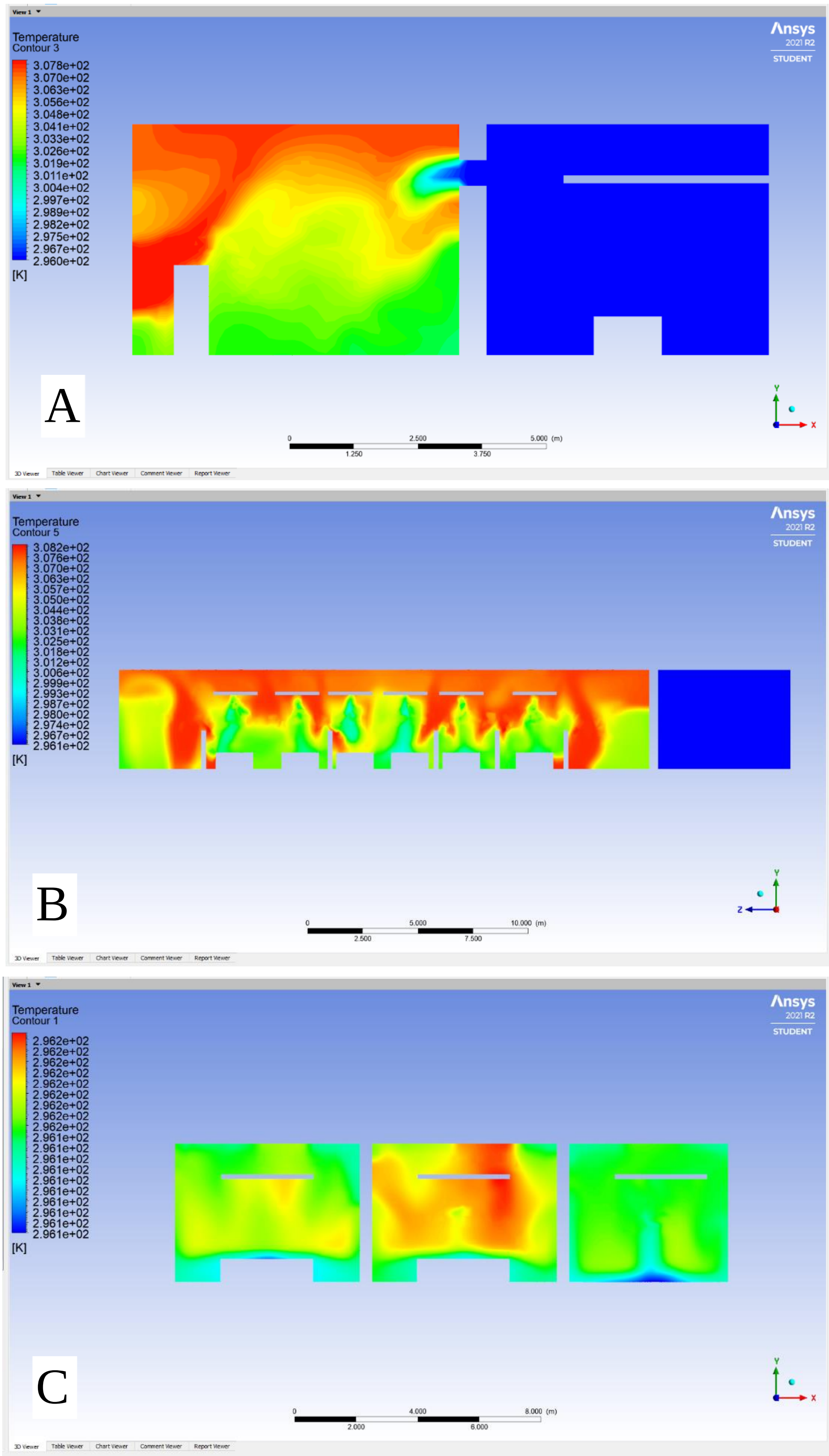


Figure 5-25 OSO multiple 2-D surfaces illustrating the contour of Ambient temperature_ Summer simulation

Table 5-7 OSO_ summer simulation_ Ambient temperature

Monitoring point	Temperature- (HVAC inlet)	Temperature (pressure outlet)	Temperature (monitoring point-1)	Temperature (monitoring-point-2)	Temperature (monitoring-point-3)	Temperature (monitoring-point-4)
Average Reading (kelvin)	296	305.108	303.201	302.343	306.091	297.981

The ambient temperature during the summertime in Nottingham can reach up to 36 °C outdoors. This high temperature will have an impact on the ambient temperature of the indoor space. During the summer period, the windows and doors are kept open almost all the time. Therefore, the external hot air will enter the space and it will mix with the existing indoor air. The result of that can be seen in all of the four monitoring points. There is a slight difference between the first three monitoring point and monitoring point 4 and that is because the fourth monitoring point is located inside an individual office that has no human model present in that space which shows that the average ambient temperature of 297 °K (23 °C). while the other three monitoring points shows an average ambient temperature of around 303 °K (29 °C). In fact monitoring point 3 have reached an average temperature of 306 °K (32 °C). the laterally mention temperature is much higher than the recommended temperature by CIBSE standards which dictates that during summer periods the temperature should be between 22-24 °C. The result of the summer scenario simulation shows that the ambient temperature is higher than the indoor air ambient temperature recommended by the local UK government authority and that could lead to thermal discomfort by the occupants. the presence of people can also have an impact on the ambient temperature that is because humans exhale air that is hot and moist which is around 310 °K (37 °C).

5.3.3 OSO Summer simulation _ Airflow velocity

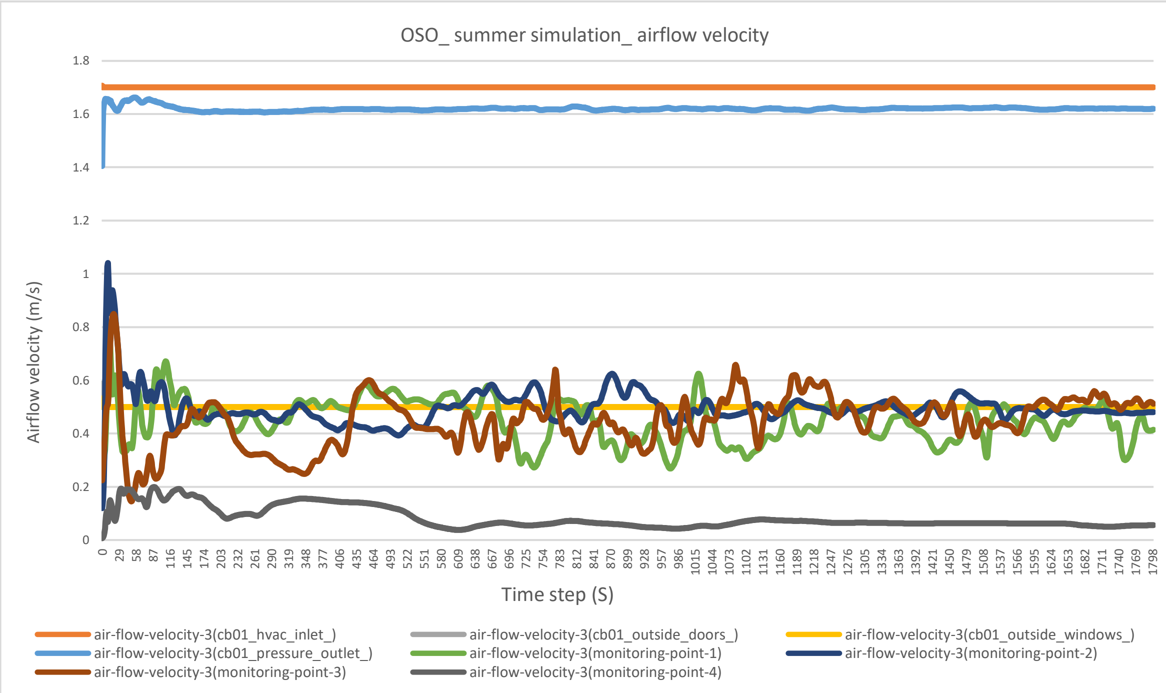


Figure 5-26 OSO_ summer simulation_ airflow velocity

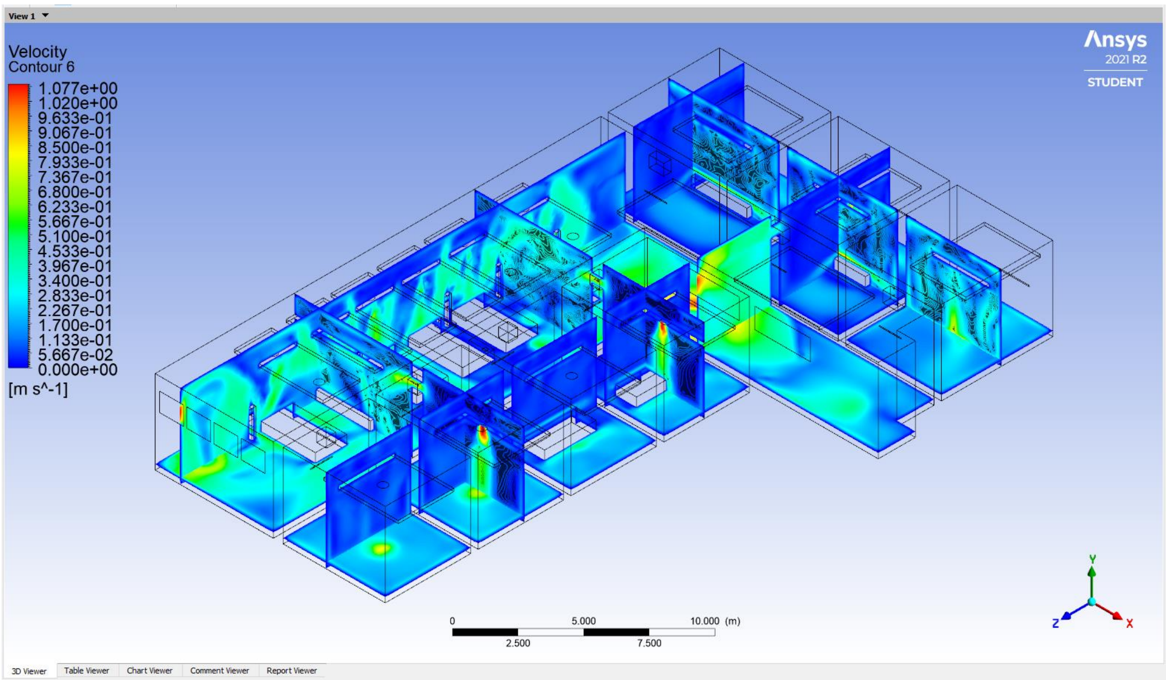


Figure 5-27 OSO 2-D surfaces illustrating the contour of airflow velocity_ summer simulation

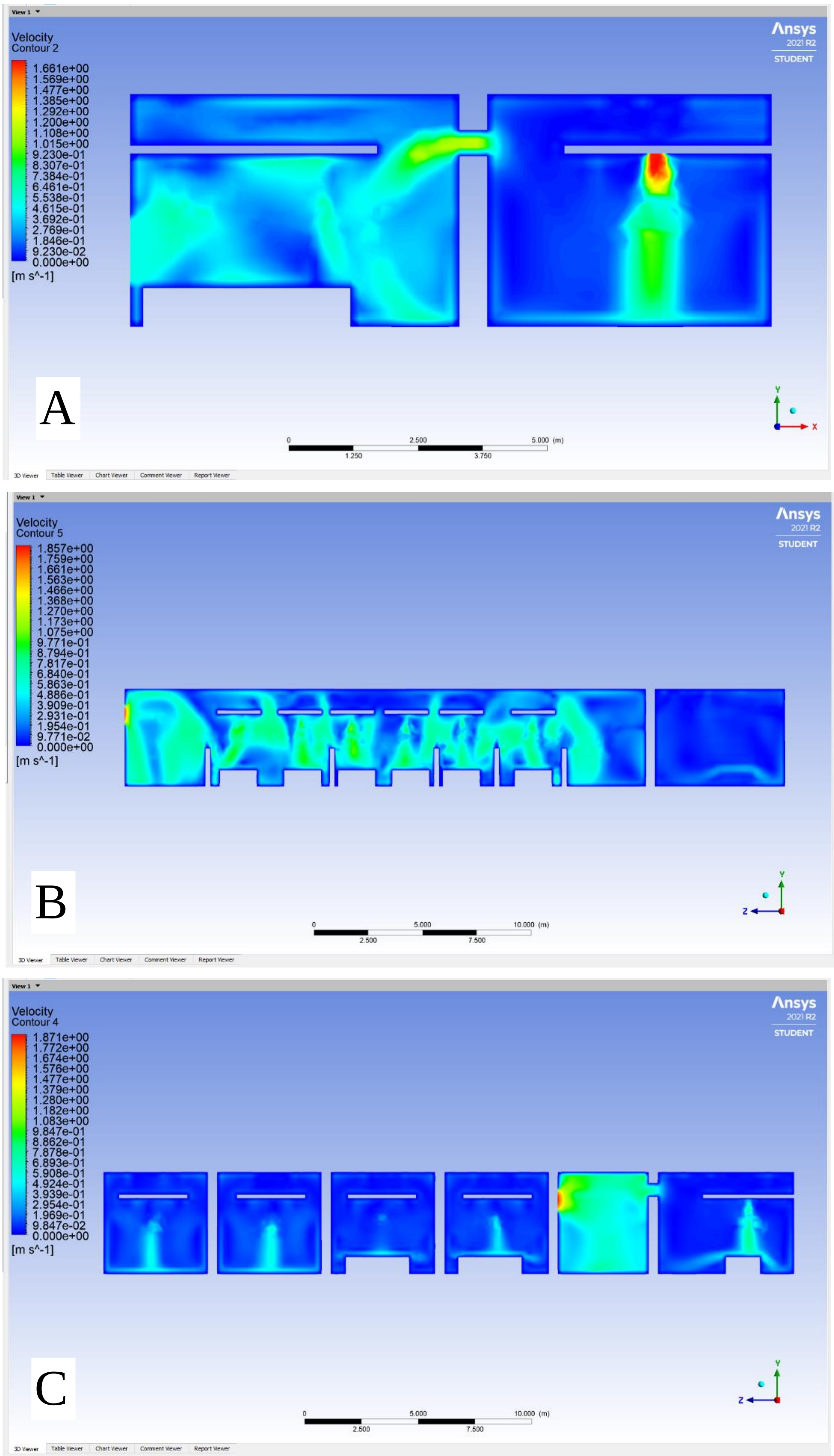


Figure 5-28 OSO multiple 2-D surfaces illustrating the contour of airflow velocity_ summer simulation

Table 5-8 OSO_ summer simulation_ airflow velocity

Monitoring point	air-flow-velocity (HVAC inlet_)	air-flow-velocity (pressure outlet)	air-flow-velocity (monitoring-point-1)	air-flow-velocity (monitoring-point-2)	air-flow-velocity-3(monitoring-point-3)	air-flow-velocity-3(monitoring-point-4)
Average Readings (m/s)	1.70	1.619	0.449	0.495	0.446	0.0827

As mentioned earlier, the airflow in the summer is distinctly different from the airflow in the winter period. And it can be seen in the result depicted in table (5-8). When comparing the airflow velocity between the winter scenario and the summer scenario it will be clear that the average air velocity in the summer scenario is higher than the air velocity in the winter. The reason for that is the opening of the windows and doors in the summer period. Opening the windows and door allowed more air to enter the space. Another point of comparison is the difference in airflow speed between different monitoring point and especially between the separated offices and the main open space office. When looking at monitoring point 1, it shows an average airflow velocity of 0.457 m/s while monitoring point 4 has registered an average air velocity average of 0.082 m/s. As stated earlier, monitoring point 4 is a sensor located inside an individual office that is separated from the rest of the main open space area. the windows located inside these were not allowed to be opened, therefore, the airflow inside these offices is restricted to the MVHR alone. Another thing to note is that the temperature of the airflow coming from the open windows is much higher than the existing air inside the interior space. This could be seen in figure (5.28) where it shows the airflow rising to the ceiling due to its higher temperature. According to the CIBSE standards in the UK, the appropriate airflow velocity inside the space should be between 0.1 and 0.4 m/s and any airflow higher than that would not be well perceived by the occupants. When examining the airflow velocity in the summer period it shows that airflow velocity is very close to the recommended levels of CIBSE.

5.3.4 OSO_Summer simulation_ CO_2 concentration:

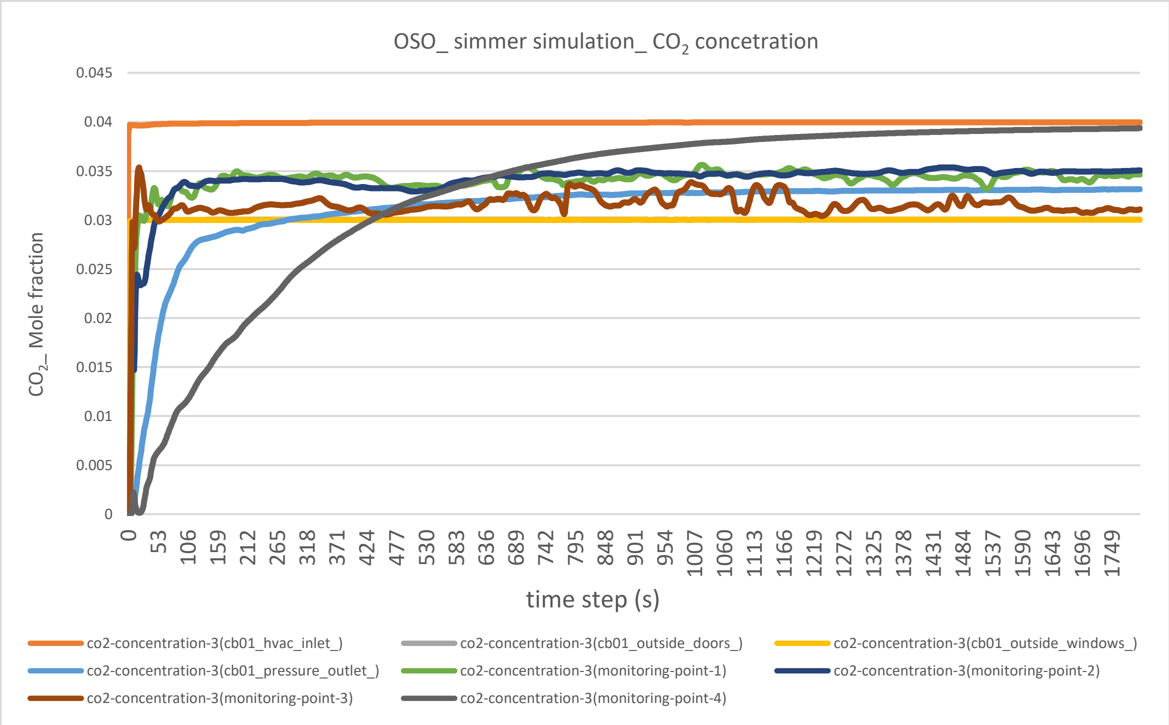


Figure 5-29 OSO_ simmer simulation_ CO_2 concertation

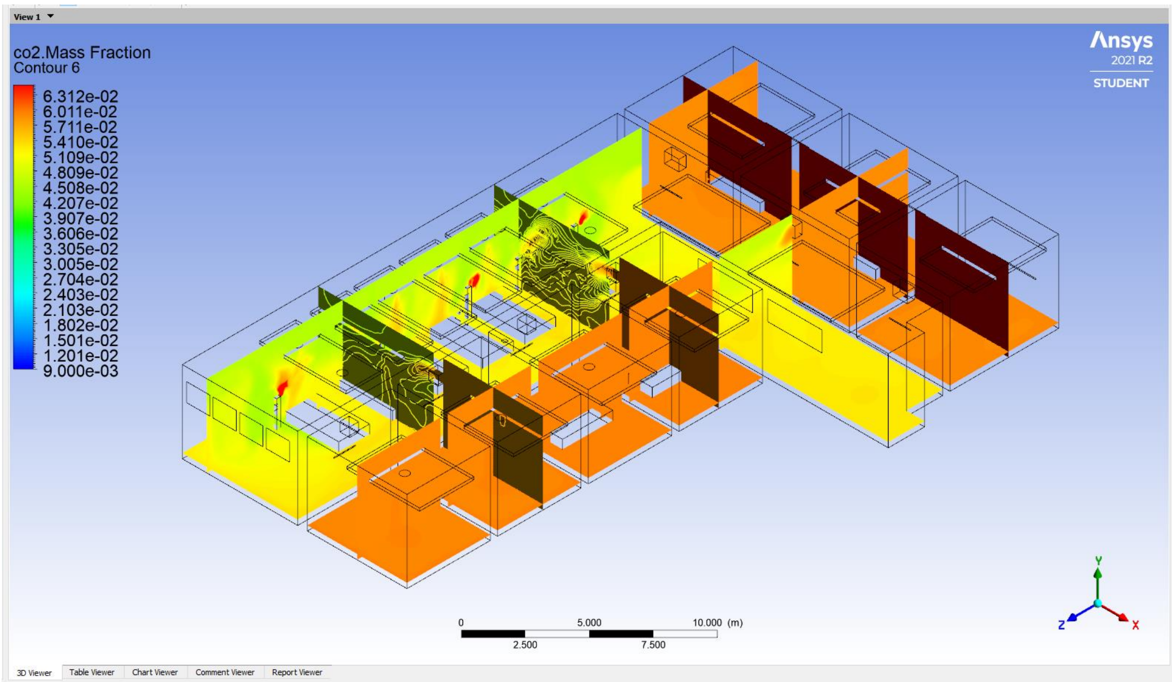


Figure 5-30 OSO 2-D surfaces illustrating the contour of CO_2 concentration_ summer simulation

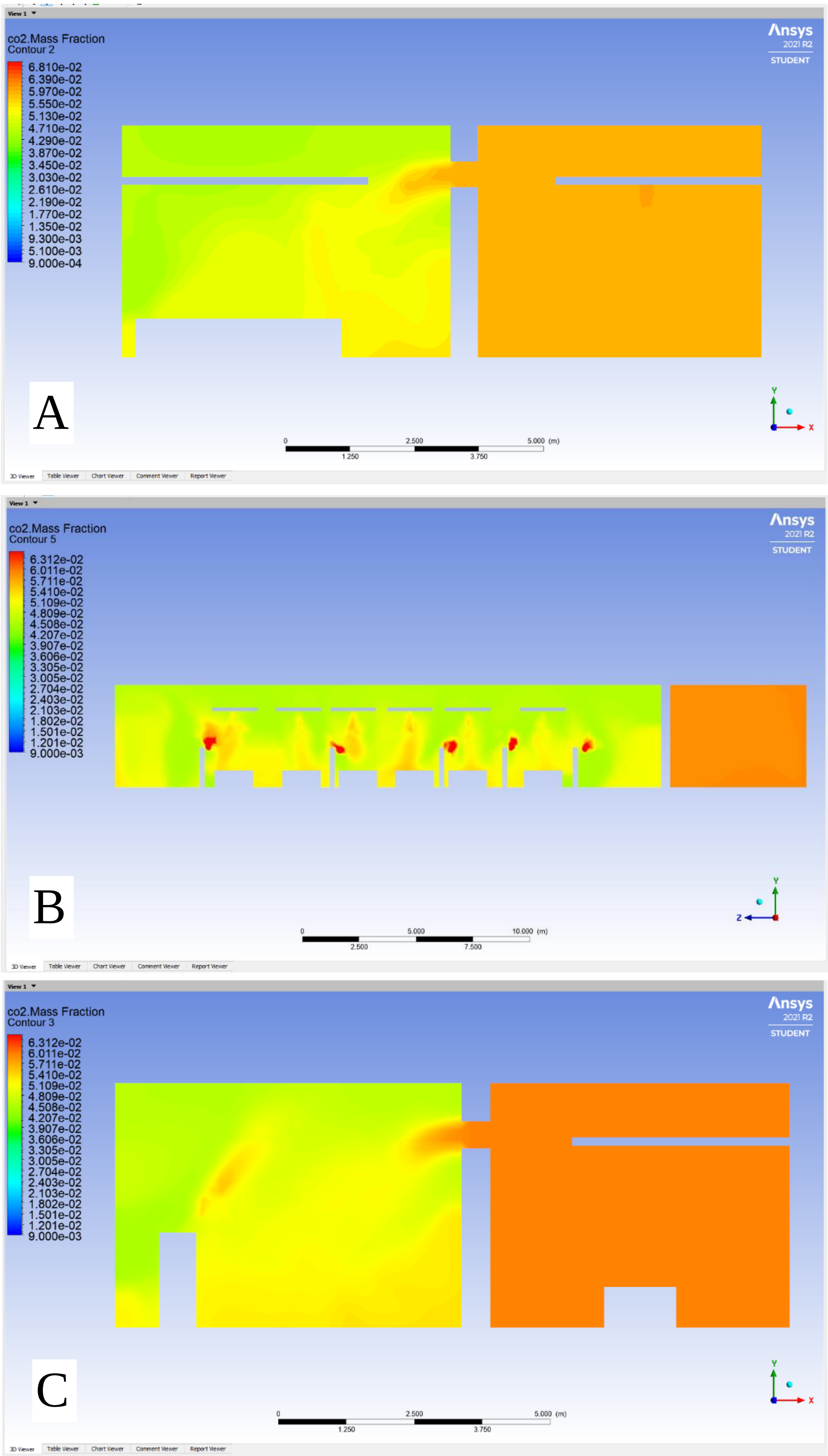


Figure 5-31 OSO multiple 2-D surfaces illustrating the contour of CO2 concentration_ summer simulation

Table 5-9 OSO_ summer simulation_ CO2 Concentration

Monitoring point	co2-concentration (co2 inlet)	co2-concentration (HVAC inlet)	co2-concentration (pressure outlet)	co2-concentration (monitoring-point-1)	co2-concentration (monitoring-point-2)	co2-concentration (monitoring-point-3)	co2-concentration (monitoring-point-4)
Average Readings (ppm)	0.346	0.0399	0.0310	0.0339	0.0340	0.0314	0.0326

The introduction of outside air from the Winter-Garden has influenced the overall CO_2 concentration inside the interior space and especially the main open space area. when looking at the chart in figure (5.22) illustrates that the first three monitoring point (1,2, and 3) follow almost the same pattern of CO_2 concentration. These three sensors are showing that the concentration of CO_2 is not increasing over time. When comparing these sensor readings to the readings taken from monitoring point 4, it will show that the concentration of CO_2 recorded in that sensor is gradually increasing. This could be explained by the fact that because the first three sensors are located very close to the window area, therefore, the air coming from outside the interior space is passing by these sensors. At the same time, these sensors are also close to the human models which emit CO_2 into the interior space. When the air from the outside of the interior space enters the room it dilutes the concentration of CO_2 existing inside the space. Not only that but also carries that air upward toward the ceiling because the incoming air is hotter than the residing air inside the space. This airlift can be seen in figure (5.31) where some of the 2-D contour surfaces are displaying the lift effect of the hot air towards the ceiling. However, the concentration of CO_2 in the summer scenario is still not too concerning considering that the levels of CO_2 concentration did not exceed 342 ppm which is much lower than the recommended level by the CIBSE.

5.4 OSO_ Autumn/spring simulation

5.4.1 OSO_ Autumn/spring simulation _(PM)_simulation

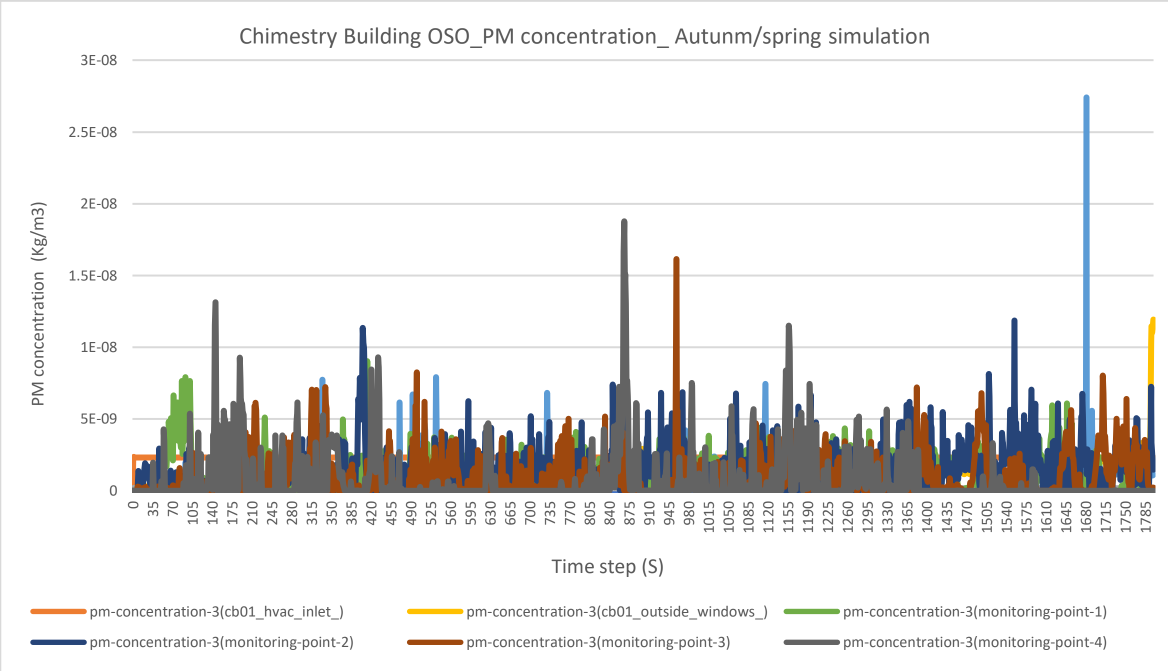


Figure 5-32 Chemistry Building OSO_PM concentration_ Autumn/spring simulation

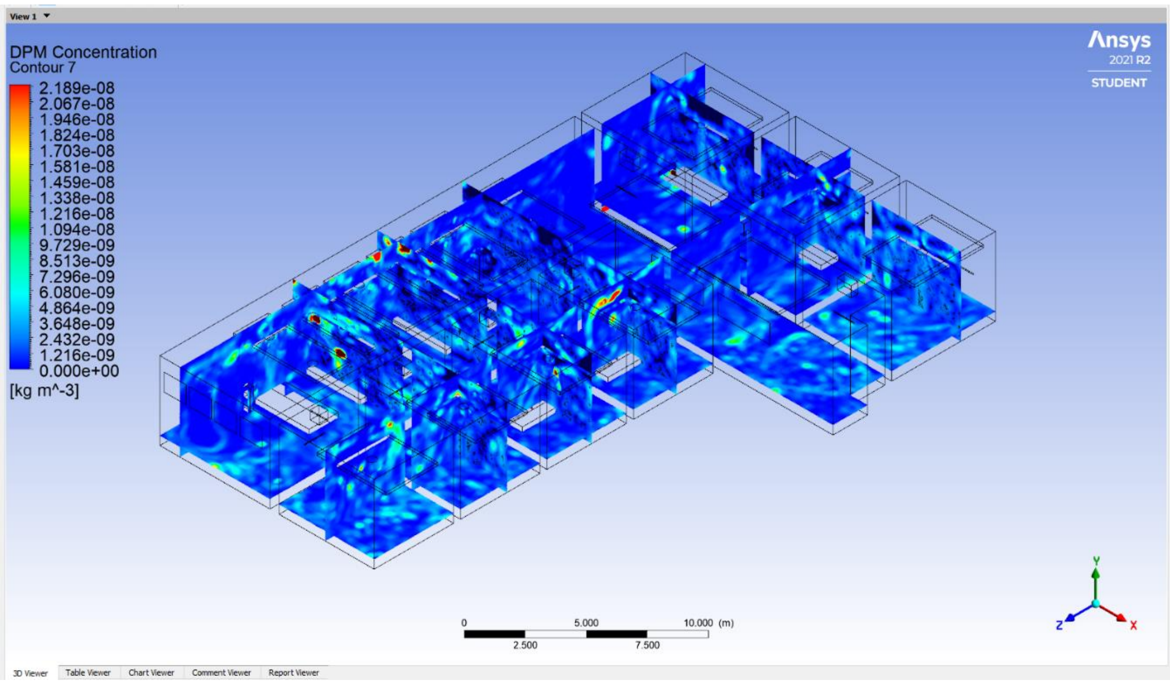


Figure 5-33 OSO 2-D surfaces illustrating the contour of (PM) concentration_ autumn/spring simulation

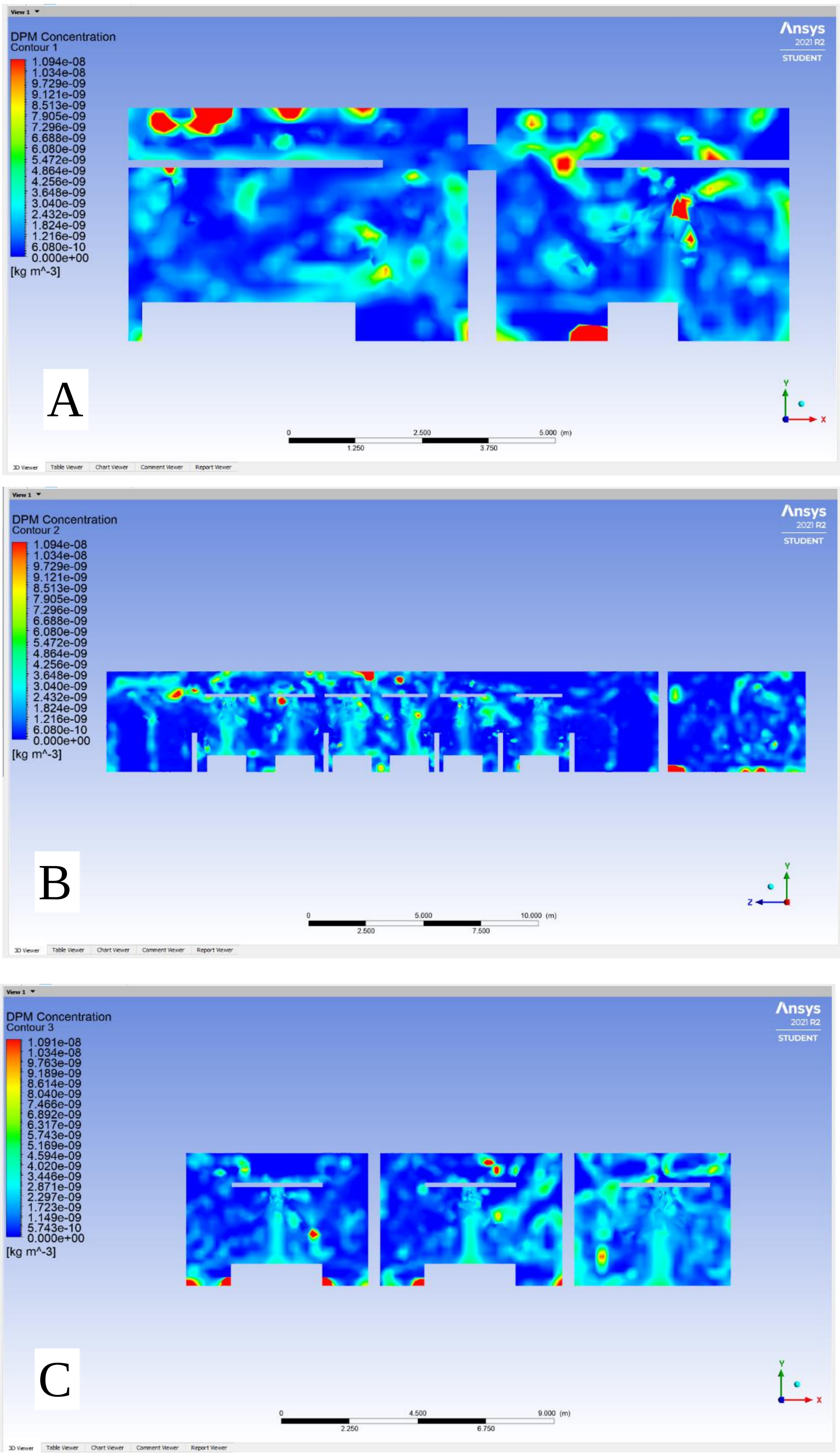


Figure 5-34 OSO multiple 2-D surfaces illustrating the contour of (PM) concentration_ autumn/spring simulation

Table 5-10 Chemistry Building OSO_PM concentration_ Autumn/Spring simulation

Monitoring point	pm-concentration (HVAC inlet_)	pm-concentration-(pressure outlet)	pm-concentration (monitoring-point-1)	pm-concentration (monitoring-point-2)	pm-concentration (monitoring-point-3)	pm-concentration (monitoring-point-4)
Average Readings (Kg/m^3)	2.311E-09	1.157E-09	1.067E-09	1.292E-09	9.292E-10	6.863E-10

The winter and summer conditions are vastly different. That is because in the winter the windows and doors are closed all the time and in the summer the opposite of that happens. Autumn and spring are considered an intermediary period between summer and winter. In those periods, windows and doors are partially opened to allow for some of the outside breeze to enter the building. Because of that, the concentration of pollutants inside the building during spring and autumn are very similar to each other, therefore both of them have been simulated within the same scenario. By looking at the result of the autumn /spring simulation it shows that the concentration of PM is relatively low. When looking at monitoring point 1 the level of PM concentration is 1.06 $\mu g/m^3$ and compared to the winter simulation it reveals that the concentration of the same monitoring point is around 2.2 $\mu g/m^3$ which is around half the concentration in the same location. In addition, when comparing the autumn/spring simulation and the summer simulation, they reveal that the concentration of PM in the autumn/spring simulation is even less than the PM concentration in the summer simulation. This could be attributed to the fact that during the summer period more windows are open in the main OSO that would allow for more air to enter the building, consequently, allowing more PM particles to enter the main open space area. in general, the concentration of PM in the autumn/spring simulation shows that the levels of PM are very low and very much acceptable according to the CIBSE standards.

5.4.2 OSO_Autumn/Spring simulation_ Ambient temperature

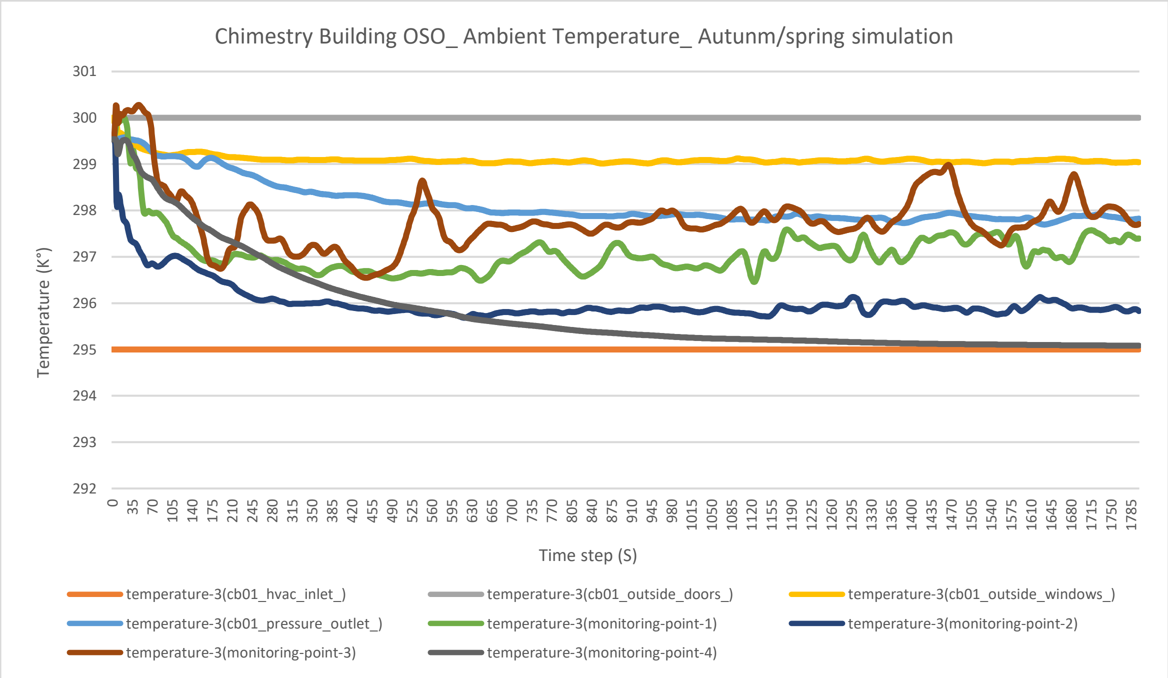


Figure 5-36 Chemistry Building OSO_ Ambient Temperature_ Autumn/spring simulation

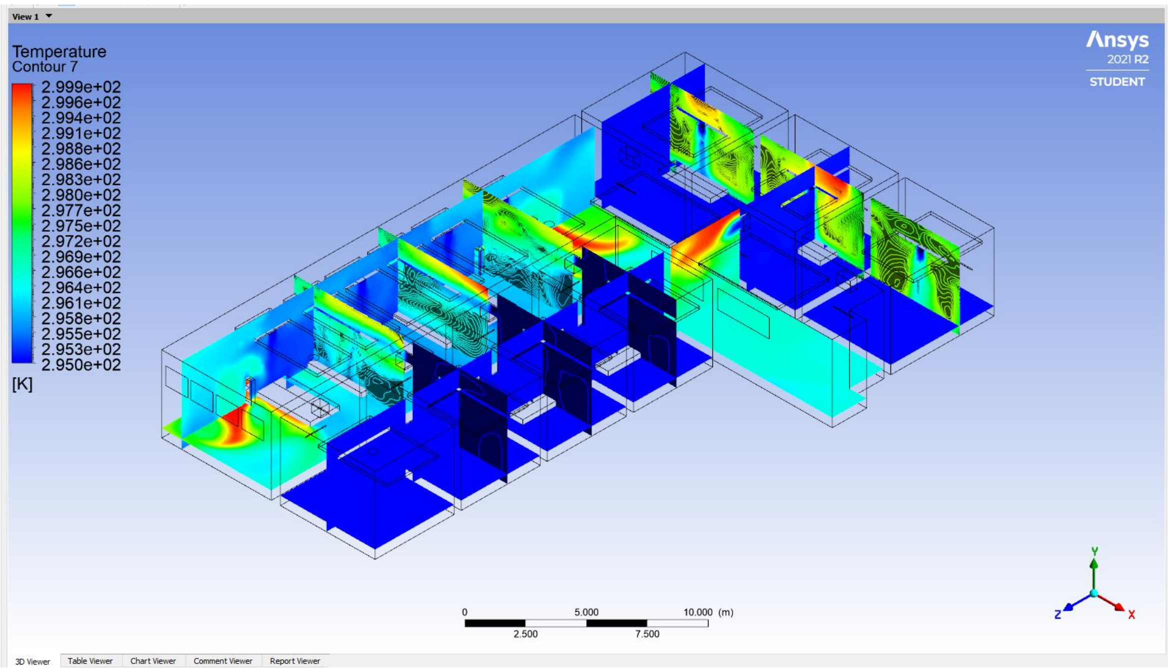


Figure 5-35 Chemistry Building OSO_ Ambient Temperature_ Autumn/spring simulation

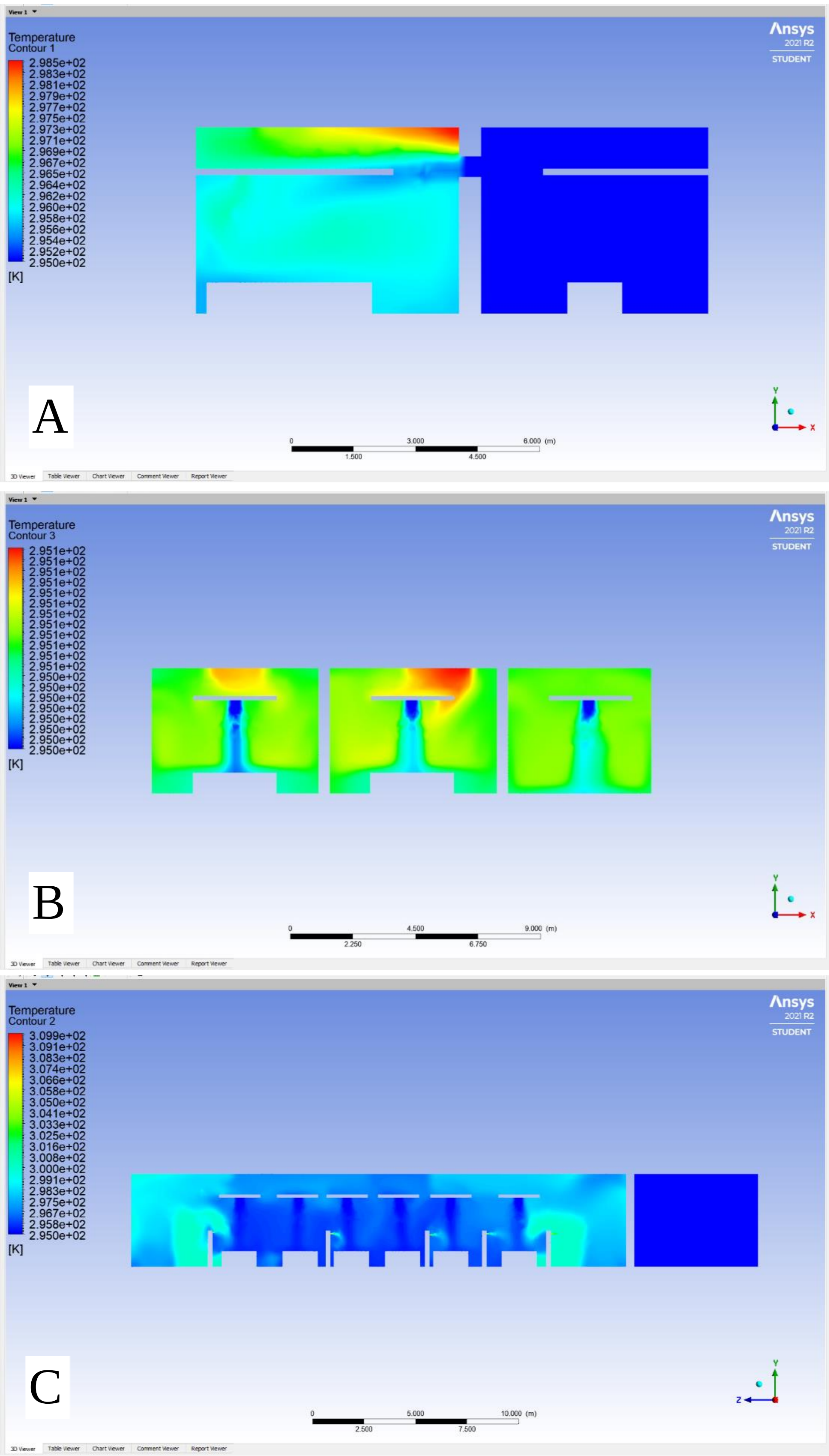


Figure 5-37 Chemistry Building OSO_ Ambient Temperature_ Autumn/spring simulation

Table 5-11 Chemistry Building OSO_ Ambient temperature_ Autumn/spring simulation

Monitoring point	Temperature (HVAC inlet)	Temperature (Pressure outlet)	Temperature (monitoring-point-1)	Temperature (monitoring-point-2)	Temperature (monitoring-point-3)	Temperature (monitoring-point-4)
Average Readings (Kelvin)	295	298.135	297.103	296.021	297.803	295.845

The result of the autumn/spring ambient temperature simulation shows that the average temperature inside the space is around 297.533 °K (24 °C). there is however a slight difference between monitoring point 1 and monitoring point 2. It seems that the ambient temperature in monitoring point 1 is higher than monitoring point 2. The reason is that monitoring point 1 is located very close to one of the doors that are open the entire time of the simulation. The air that enters through this door has a slightly hotter ambient temperature than the existing air inside the OSO. On the other hand, monitoring point 2 is located in the middle between the two open doors, therefore the effect of the hotter air entering the building is not significant in the area where the sensor is located. The same could be said about monitoring point 4 which has an average ambient temperature of 295.845 °K (22.5 °C). This sensor is located inside the individual office and there is no effect of outside hot air entering the office, thus not affecting the ambient temperature in the area surrounding that sensor.

5.4.3 OSO_ Autumn/Spring simulation_ Airflow velocity

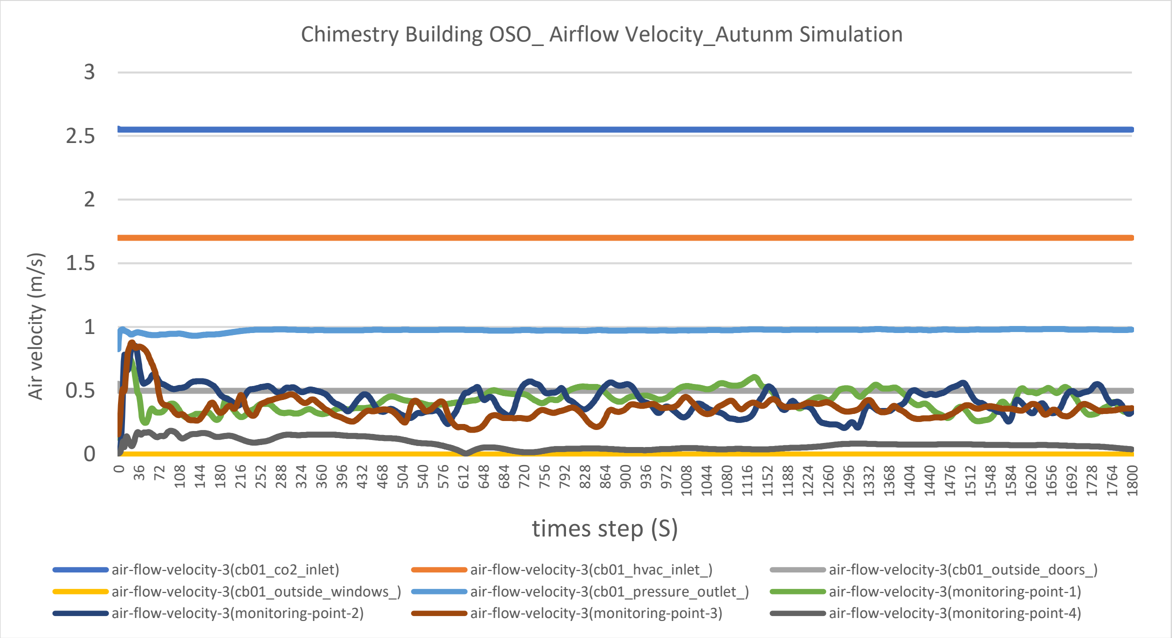


Figure 5-38 Chemistry Building OSO_ Airflow Velocity_ Autumn/spring Simulation

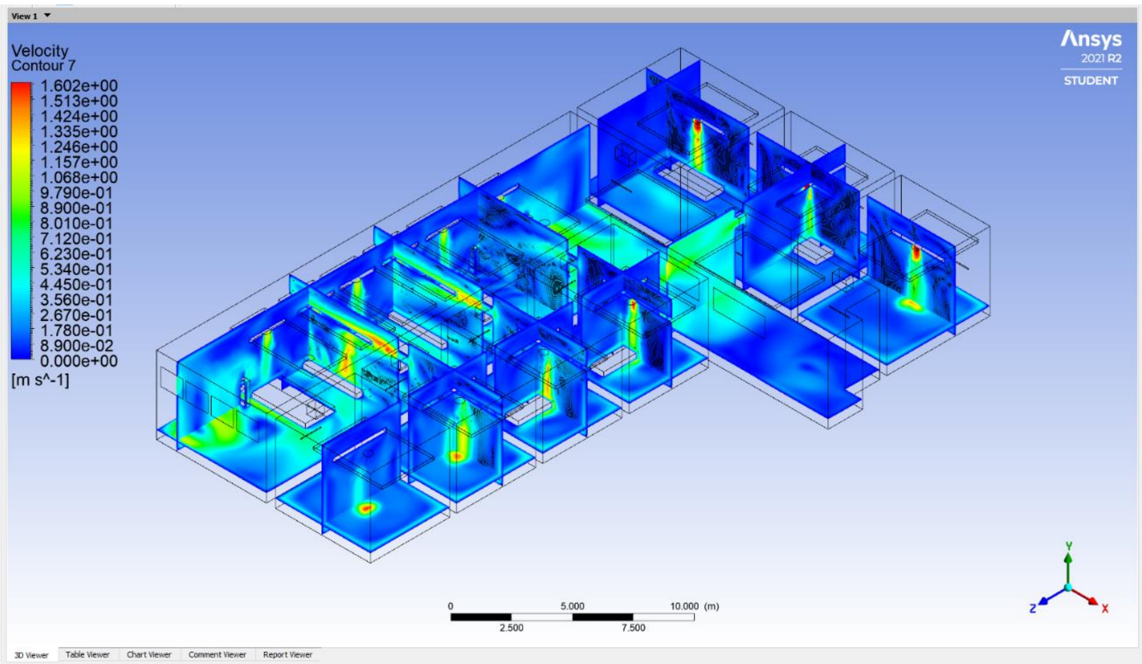


Figure 5-39 OSO 2-D surfaces illustrating the contour of airflow velocity_ Autumn/Spring simulation

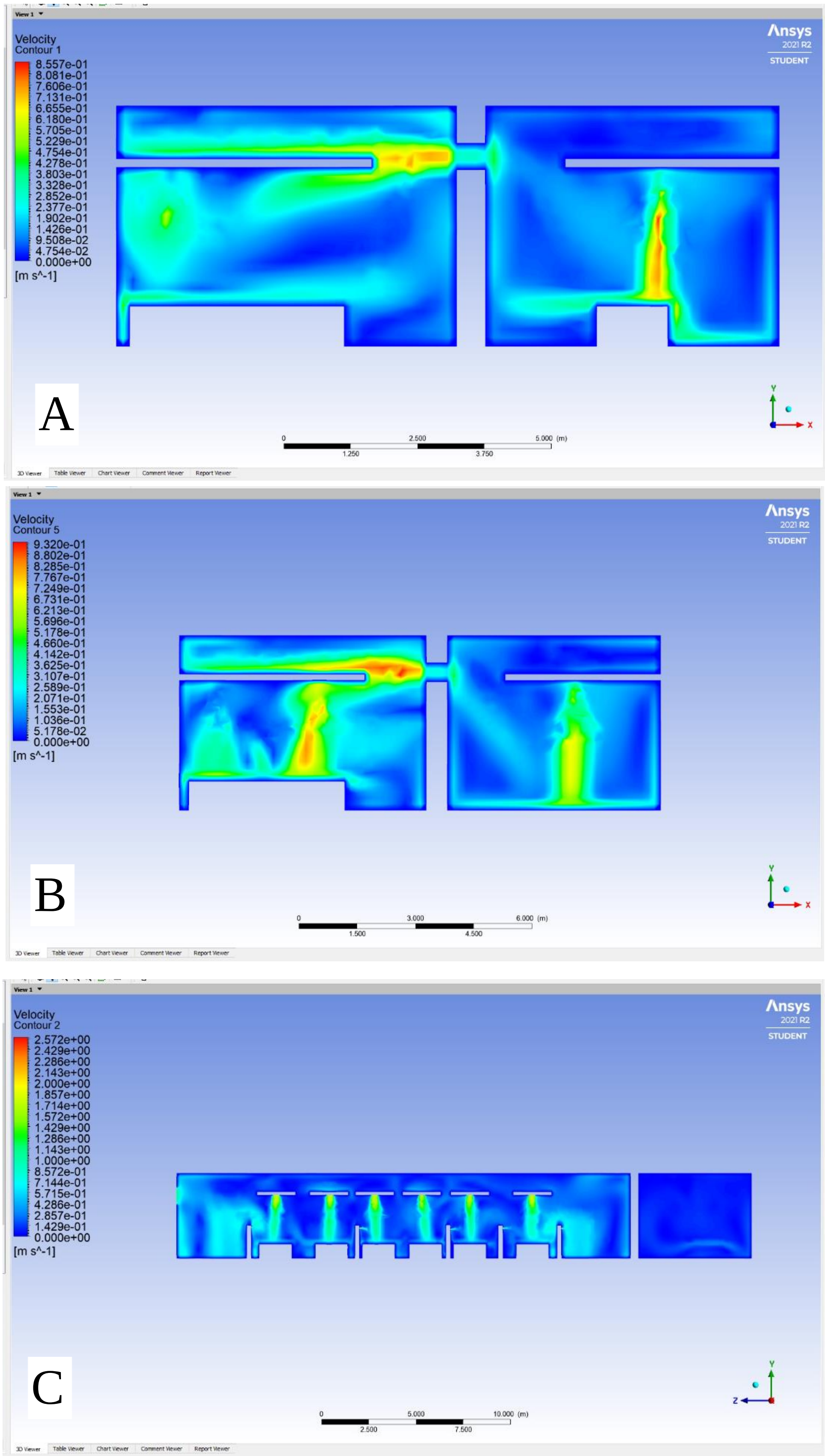


Figure 5-40 OSO multiple 2-D surfaces illustrating the contour of airflow velocity_ Autumn/Spring simulation

Table 5-12 Chemistry Building_ OSO_ airflow velocity_ Autumn simulation

(Time)	air-flow-velocity (HVAC inlet_)	air-flow-velocity (pressure outlet)	air-flow-velocity (monitoring-point-1)	air-flow-velocity monitoring-point-2)	air-flow-velocity (monitoring-point-3)	air-flow-velocity (monitoring-point-4)
Average Readings (m/s)	1.700	0.973	0.423	0.423	0.362	0.080

The result of the airflow velocity simulation within the autumn/spring scenario shows that the airflow velocity is very stable. Monitoring point 2 sensor is located in the middle of the room and there are two doors that are open on each side of the sensor. It seems that when the air passes through the doors and enters the room there is an air mixing in the middle of the room, thus creating small turbulence near the area of monitoring point 2 sensor. Monitoring point 3 shows a lower air velocity recording in the autumn/spring scenario. This sensor is located near the door that is left open for the entire period of the simulation. The lowest air velocity recorded was inside the individual office located at monitoring point 4. The air inside the room relies solely on the MVHR inlet coming from the ceiling of the room and there is no mixing of air with other parts of the OSO.

5.4.4 OSO_ Autumn/Spring simulation_ CO_2 concentration

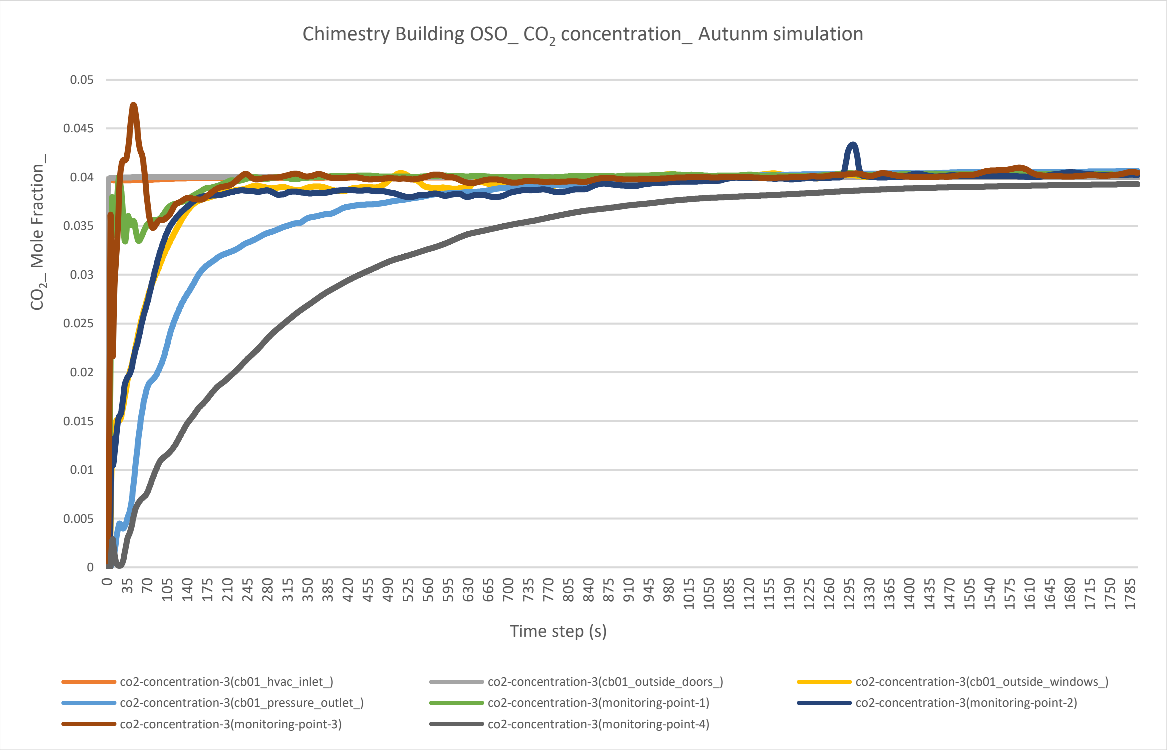


Figure 5-41 Chemistry Building OSO_ CO_2 concentration_ Autumn/spring simulation

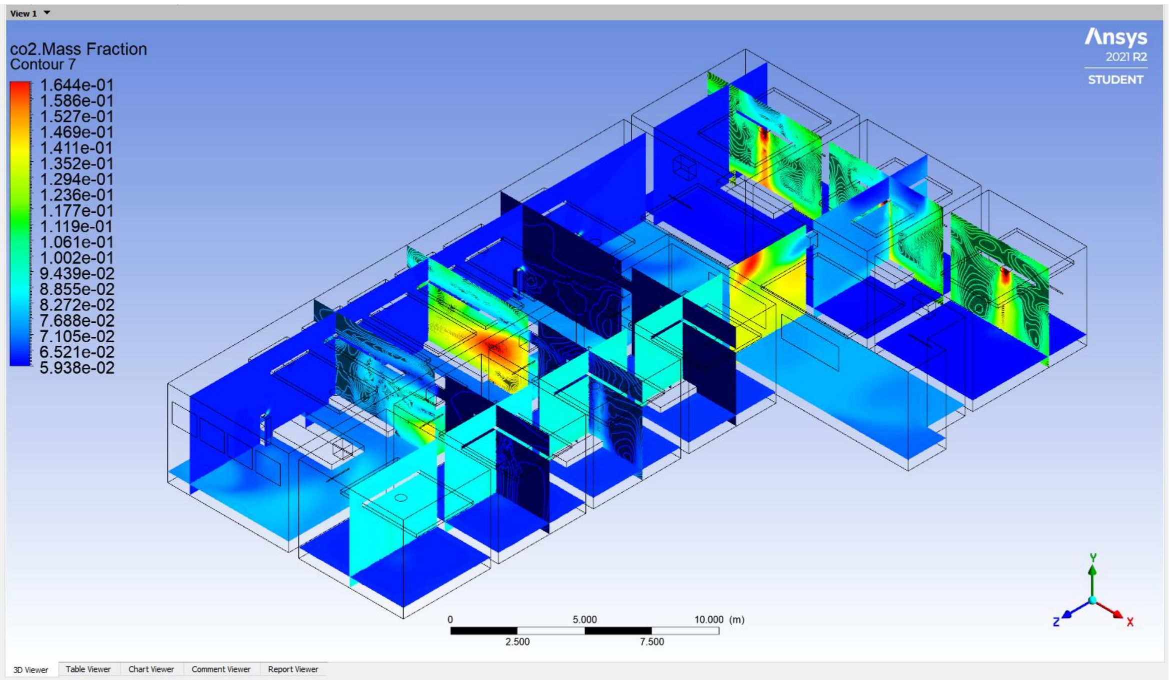


Figure 5-42 OSO 2-D surfaces illustrating the contour of CO_2 concentration_ Autumn/Spring simulation

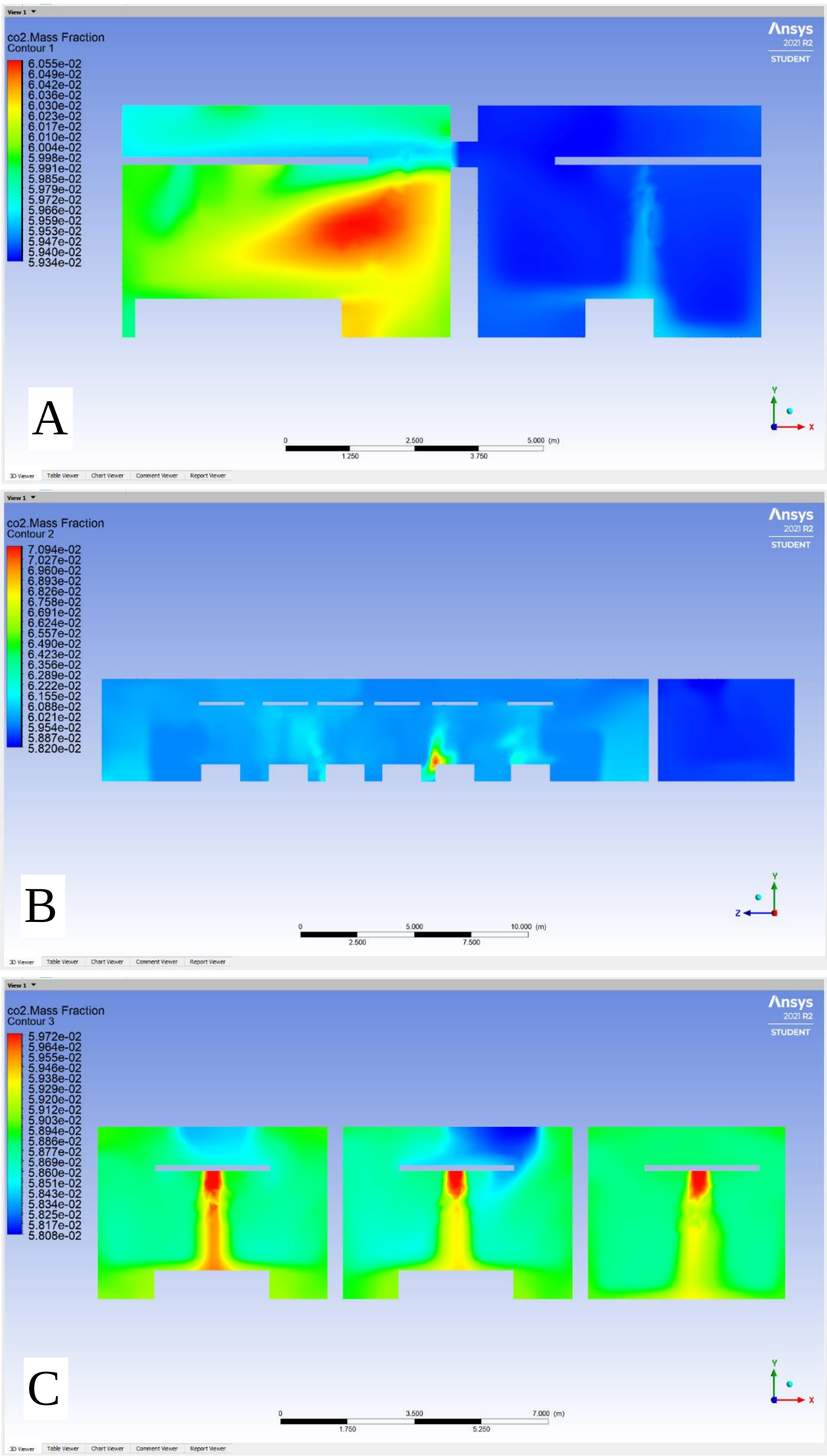


Figure 5-43 OSO multiple 2-D surfaces illustrating the contour of CO2 concentration_ Autumn/Spring simulation

Table 5-13 Chemistry Building_ OSO_ CO_2 concentration_ Autumn/Spring simulation

Monitoring point	co2-concentration (HVAC inlet)	co2-concentration (pressure outlet)	co2-concentration (monitoring-point-1)	co2-concentration (monitoring-point-2)	co2-concentration (monitoring-point-3)	co2-concentration (monitoring-point-4)
Average Readings (ppm)	0.0399	0.0368	0.0396	0.0381	0.0396	0.0324

The same pattern that occurred in all of the aforementioned simulation results takes place also in the CO_2 concentration simulation result in the autumn and spring scenario. When examining the first three monitoring points, it is clear that these monitoring points follow that same pattern in which the CO_2 concentration in these three monitoring points has an average concentration of 380 ppm. With monitoring 1, and 3 having a higher level of CO_2 concentration and monitoring point 2 having a lower concentration. Monitoring point 4 has the lowest value which of course shows that the absence of people being the main contributor to the increasing levels of CO_2. Keeping in mind that human presence is not the only factor of CO_2 concentration levels inside the space.

5.5 The Chemistry Building's First Floor Office

This office is one of many offices located on the first floor of the chemistry building. Each of these offices is situated next to a laboratory which houses all the pieces of equipment that the student and employees use. The office that was chosen for monitoring is located on the southeast corner of the building. The office is around 6 meters in length, and around 7 meters in width and 6 meters in height. It contains 12 office desks that are occupied by postgraduate student and researchers. The airflow in these offices is controlled by two airflow vents located on the top of the office and an exhaust fan on the wall that separates the office from the laboratory figure (5.32). the exhaust system drags the air from the office and from the laboratory to the outdoor atmosphere.

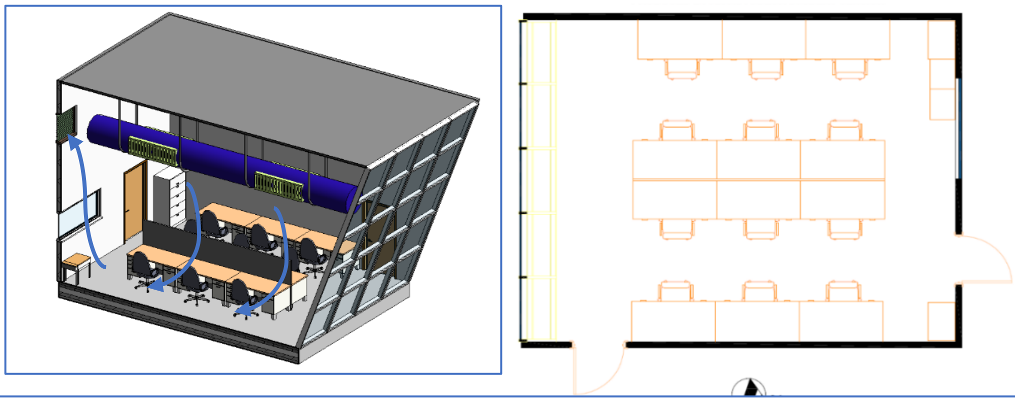


Figure 5-44 on the left is a 3d-section view of the FFO and on the right is the floor plan of the FFO

The mesh model is comprised of 50687 tetrahedral cells with an aspect ratio of 1.17. the average element size is 11 centimeters. The main inlet is from the two airflow vents located at the long tube near the ceiling of the FFO. And the outlet is located at the back of the room (table 14). The four sensors are located very close to the floor at a height of 0.8 meters figure (5.45)

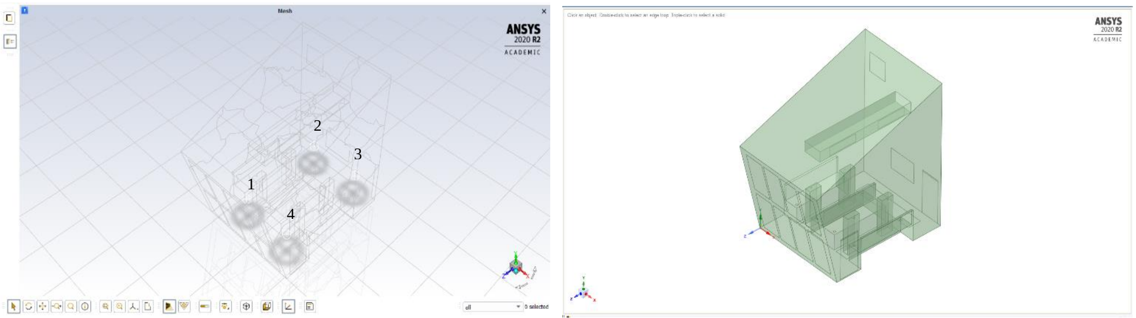
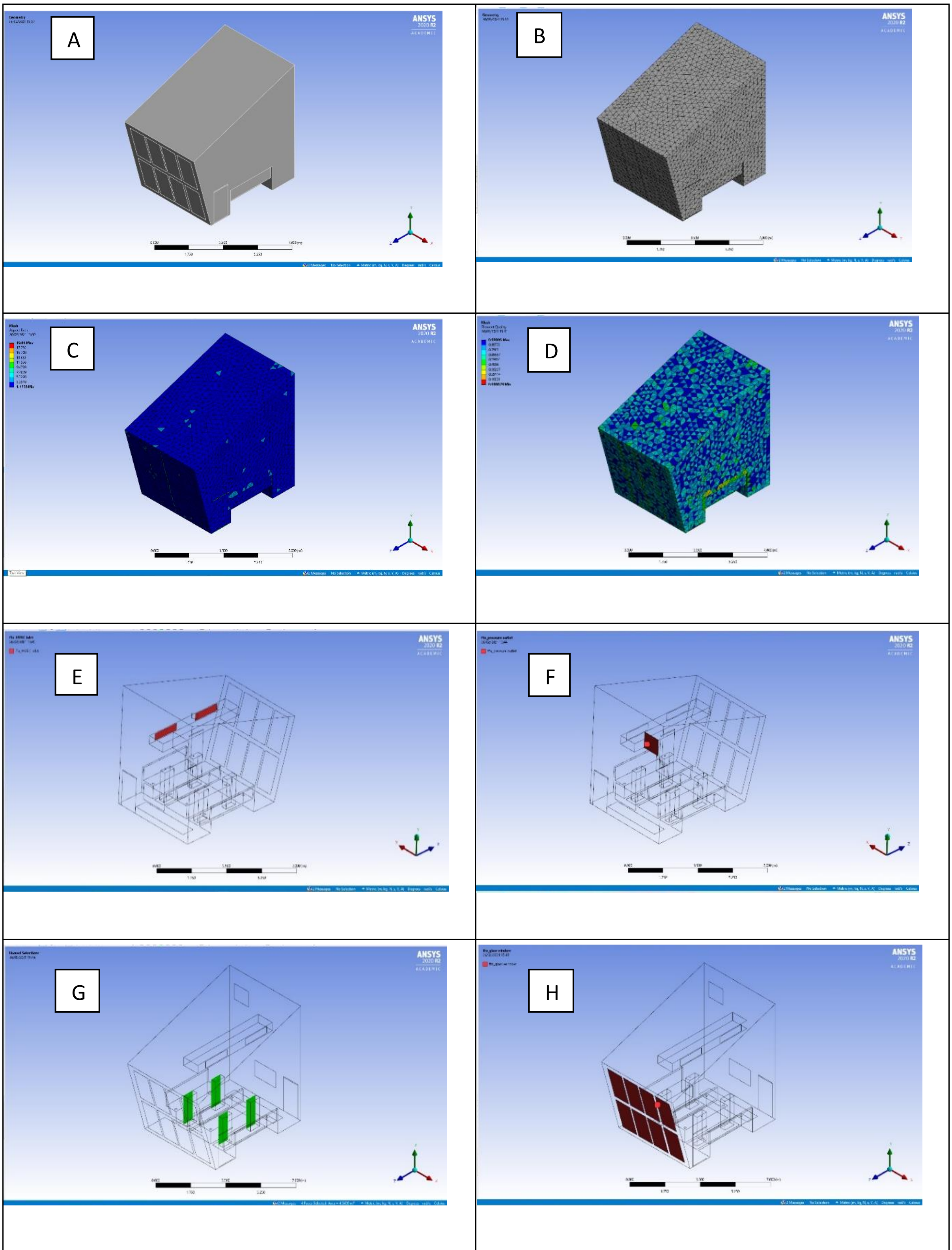


Figure 5-45 on the left illustrate the location of the four sensors , on the right is the geometry of the model

Table 5-14 FFO_ 3d model and boundary condition



These images represent the following: **A)** shows the 3-D geometry of the OSO, **B)** shows the mesh structure of the simulation model, **C)** shows the aspect ratio, **D)** mesh quality, **E)** shows the HVAC inlet, **F)** shows the outlet exhaust, **G)** CO2 inlet location, **H)** border windows.

5.6 FFO_ Winter simulation

5.6.1 FFO_Winter simulation_(PM) concentration

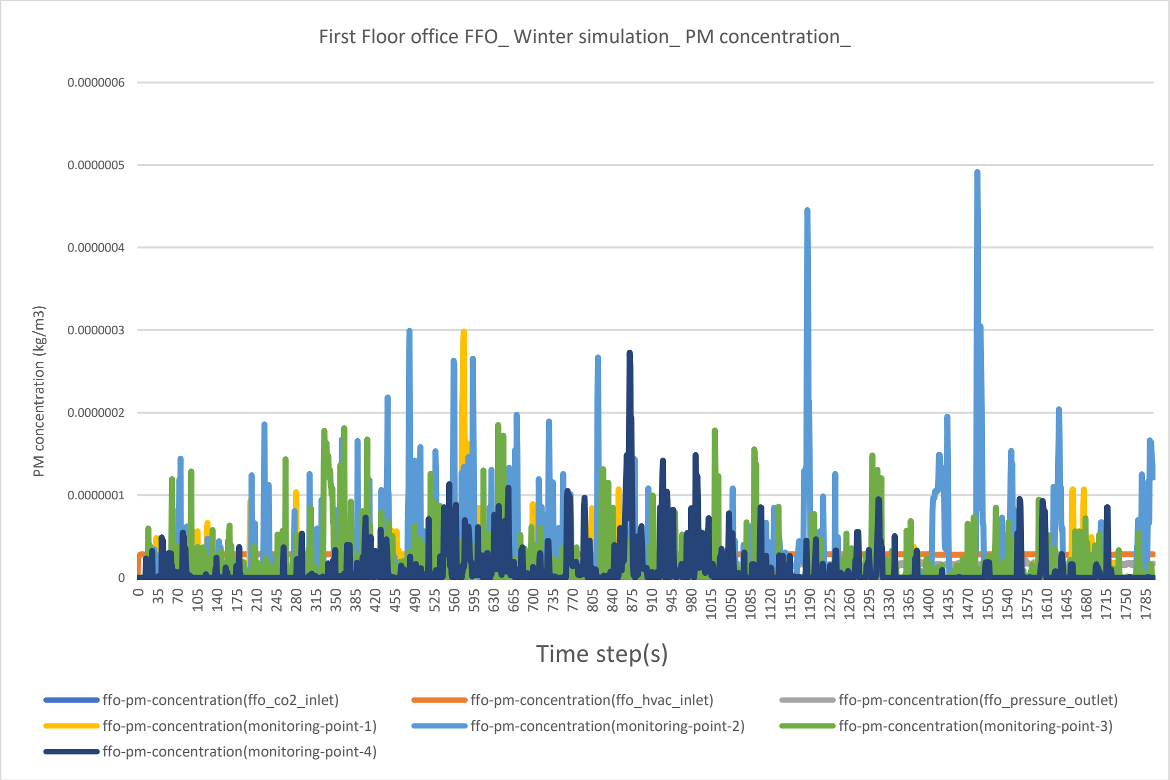


*Figure 5-47 First Floor office FFO_ Winter simulation_ PM concentration_*

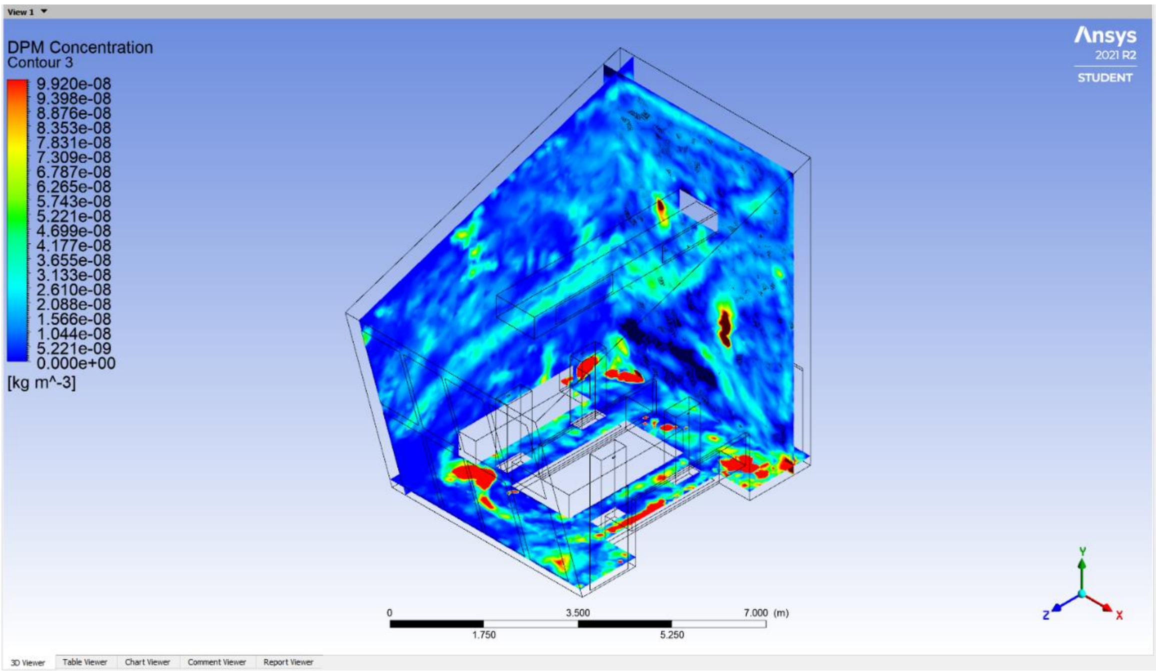


Figure 5-46 FFO 2-D surfaces illustrating the contour of PM concentration_ winter simulation

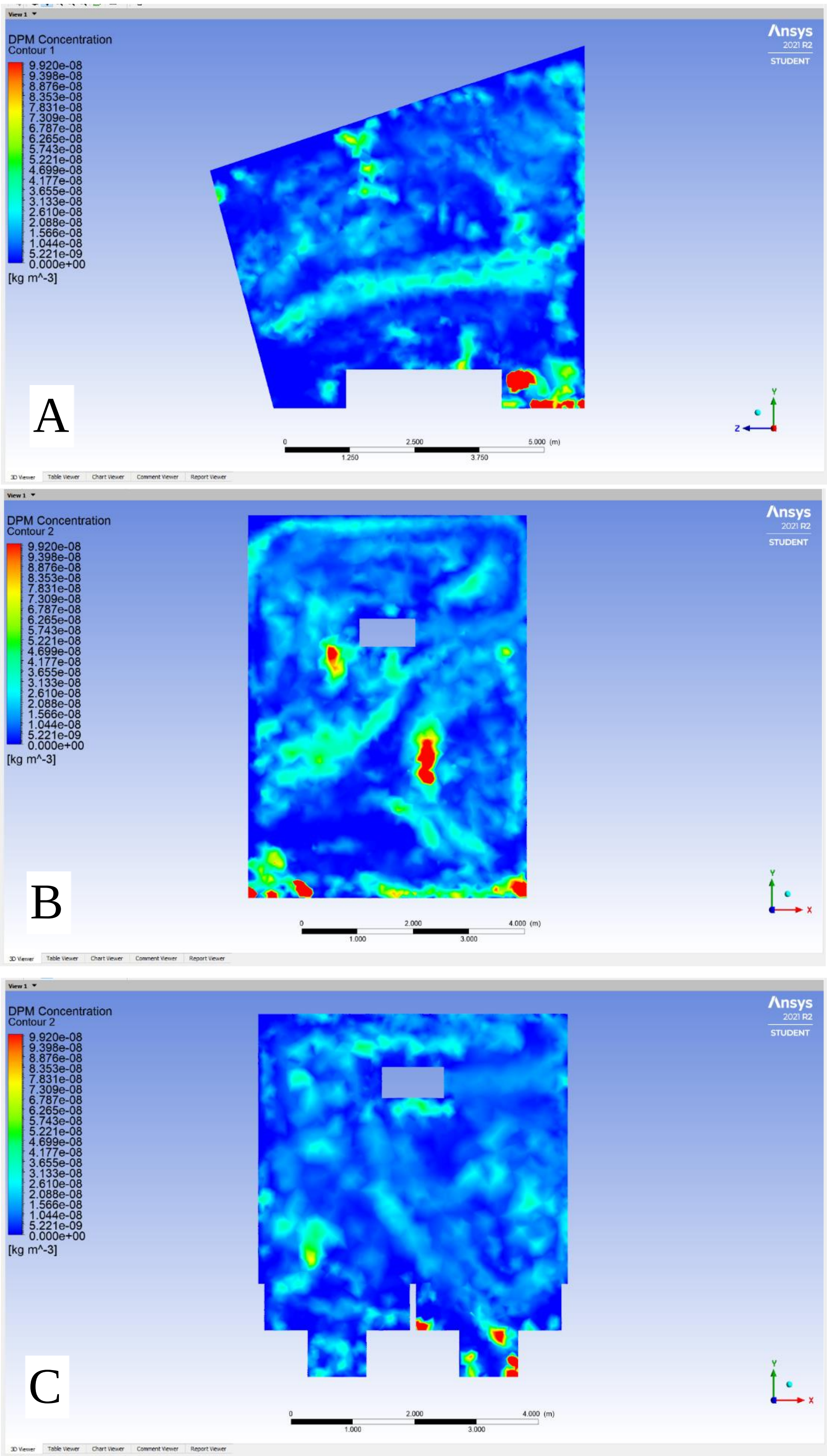


Figure 5-48 FFO multiple 2-D surfaces illustrating the contour of PM concentration_ winter simulation

Table 5-15 FFO_ Winter simulation_ PM concentration

Monitoring points	PM concentration (HVAC inlet)	PM concentration (pressure outlet)	PM concentration (monitoring-point-1)	PM concentration (monitoring-point-2)	PM concentration (monitoring-point-3)	PM concentration (monitoring-point-4)
Average readings (Kg/m^3)	2.830E-08	1.504E-08	4.949E-09	2.039E-08	1.058E-08	9.680E-09

The introduction of PM was set at the MVHR inlet located in the tube near the ceiling of the FFO table (14). Other sources of PM are considered are the resuspension of particles from the ground. The difference between the two sources of PM is that the first is a continuous stream of particles entering the building. While the other source of PM is intermittent with multiple periods of injection during the 1800 second of simulation. The floor of the FFO is covered in carpet, therefore, the condition of the floor was set as trap. The trap boundary condition will allow the particles to stick to the ground as soon as the particle landed on the floor. The two doors of the FFO are kept closed throughout the entire time of the simulation, leaving only the extract fan and the MVHR as the two openings of the system. The average concentration of PM in the FFO is much higher than the concentration found in the OSO. Among the four monitoring points, monitoring point 3, and 4 records the high concentration of 10.5 and 9.6 $\mu g/m^3$. The location of these two sensors shows that the highest concentration PM was near the main entrance which is opposite to the extract fan. In addition, by looking at figure (5.48), it is clear that most of the PM particles are moving upwards toward the extract fan, clearing the area underneath the extract fan from the accumulation of Particulate matter. That is why when looking at the other two monitoring point 1 the concentration of PM near this monitoring points is very low. In fact, monitoring point 1 has an average concentration of 4.9 $\mu g/m^3$. However, Monitoring point 2 shows that the average concentration of PM is around 20 $\mu g/m^3$ due to the fact that the air is carring large quantity of PM towards the extract fan. Not only that, but even the other monitoring point (3, and 4) records a high value of concentration at the beginning of the simulation, figure (5.48).

5.6.2 FFO_Winter simulation_ Ambient temperature

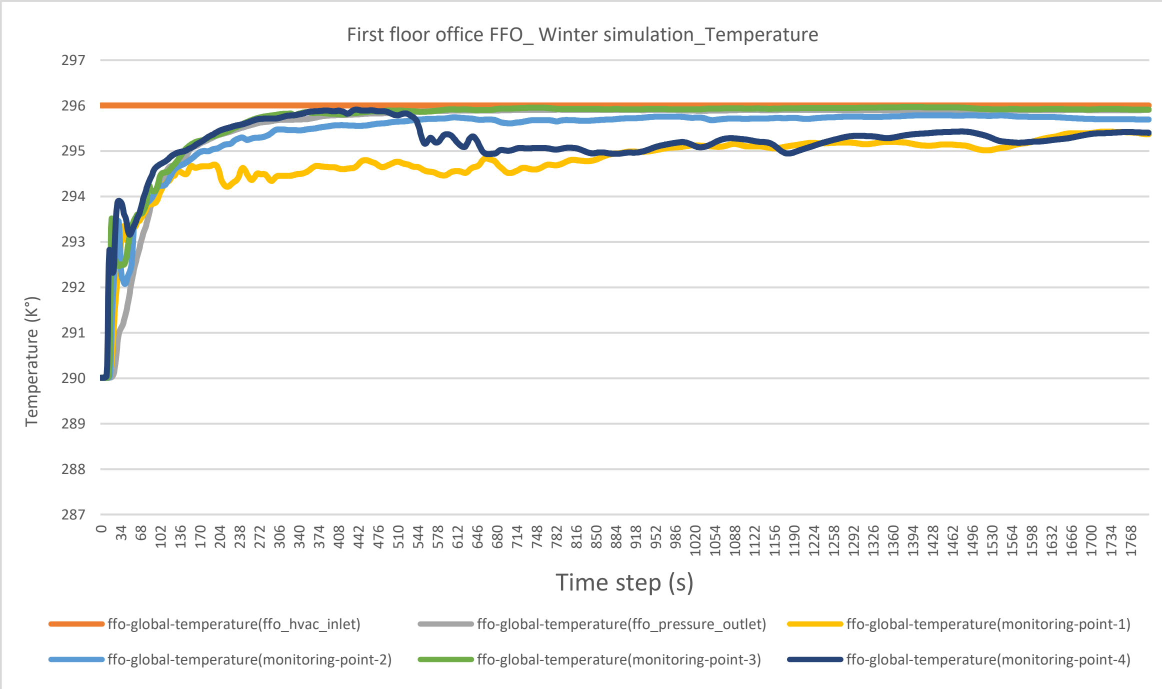


Figure 5-50 FFO_ Winter simulation_ Ambient Temperature

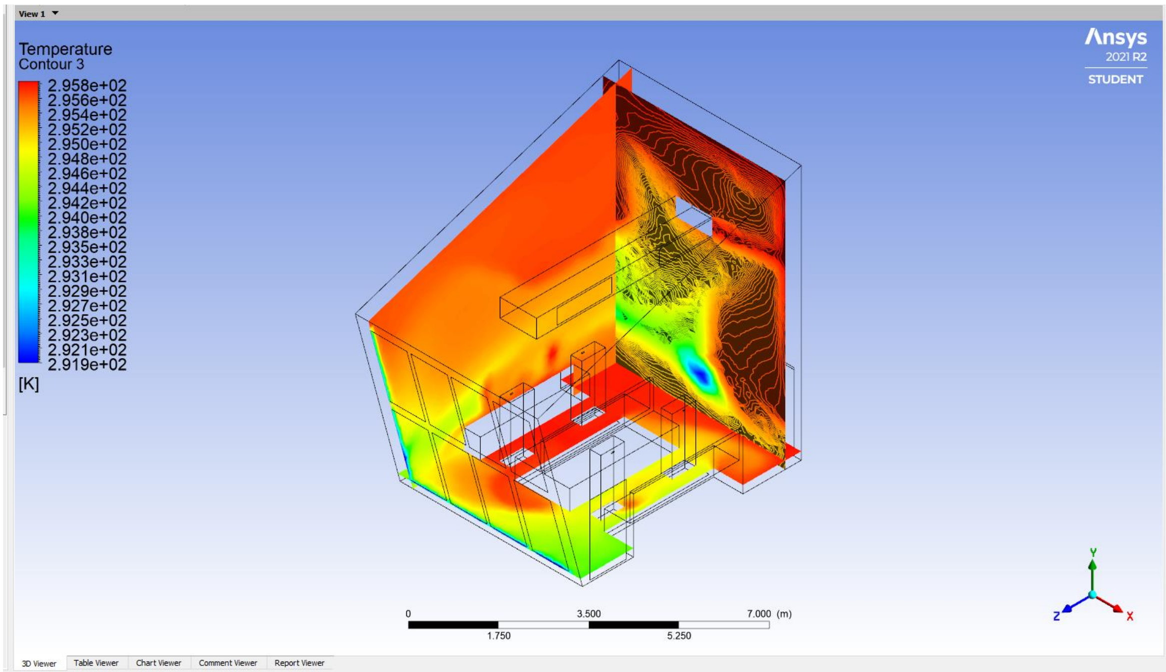


*Figure 5-49 FFO 2-D surfaces illustrating the contour of ambient temperature_ Winter simulation_*

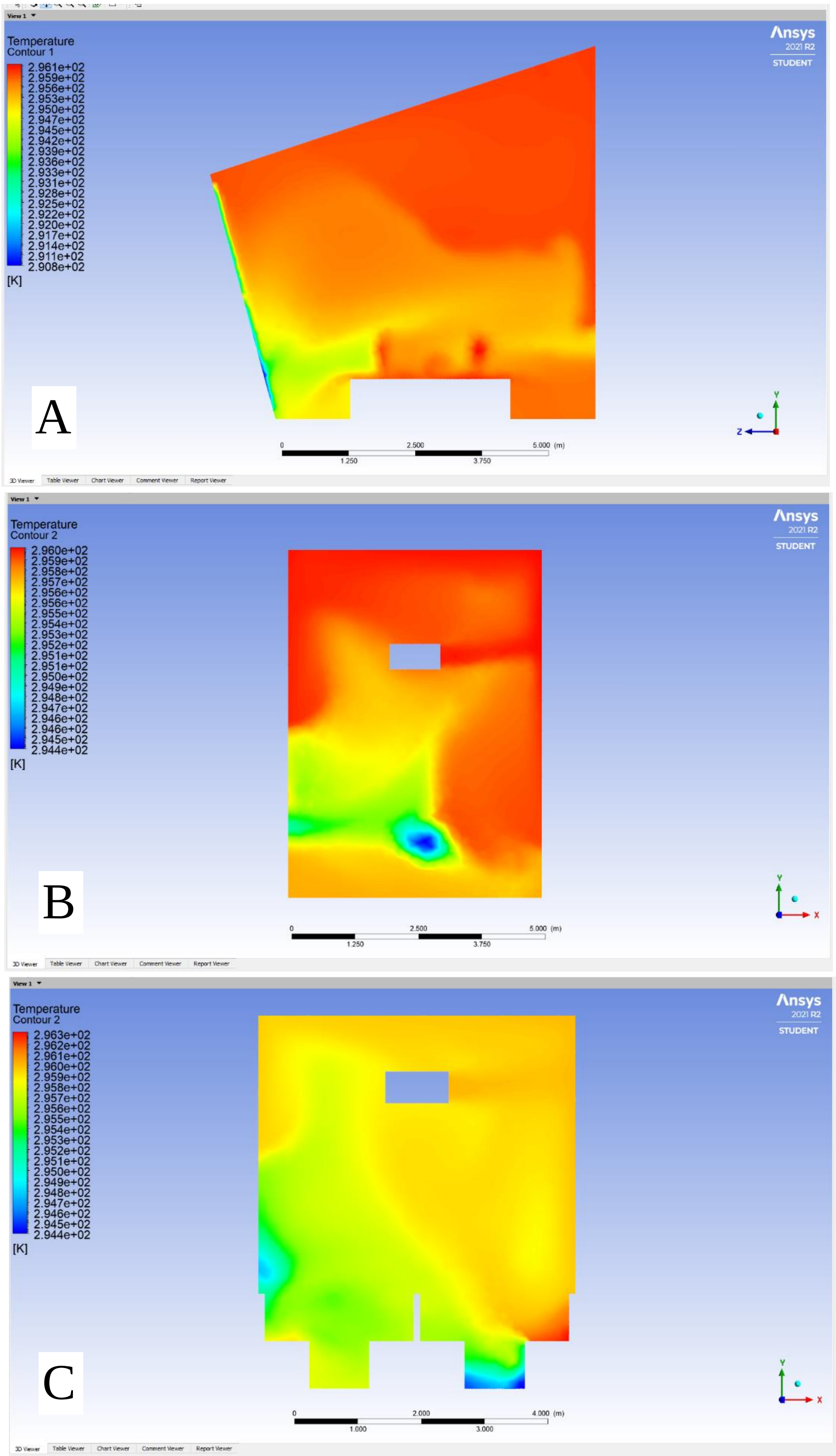


*Figure 5-51 FFO_ multiple 2-D surfaces illustrating the contour of ambient temperature_ Winter simulation_*

Table 5-16 FFO_ Winter simulation - Ambient temperature

Monitoring points	Ambient Temperature HVAC inlet)	Ambient Temperature (pressure outlet)	Ambient Temperature (monitoring-point-1)	Ambient Temperature (monitoring-point-2)	Ambient Temperature (monitoring-point-3)	Ambient Temperature (monitoring-point-4)
Average readings (Kelvin)	296	295.582	294.779	295.445	295.674	295.191

The temperature condition during the winter scenario shows that there is a great source of cold air coming from the border window. This is evident by looking at figure (5.51), in one of the 2-D surface contours, the gradient of temperature change can be from the border window all the way to the rest of the room. There are two sources of hot air that could counteract the cold air caused by the border window. The first is the MVHR which emits hot air at 296 °K (22 °C). the second source of hot air is the emission of exhaled air by the human model that introduces hot air into the model at 310 °K (37 °C). The air mixing is showing to be on the lower side of the room while the upper side of the room is kept relatively warm. Throughout the entire time of the simulation, however, the recorded temperature in the four monitoring point did not show any drastic changes in the average ambient temperature close to these sensors. All of the monitoring points have a very close range of temperature as can be seen in figure (5.51). When comparing the effect of the MVHR to the effect of the human model on the ambient air temperature inside the room, it appears to be that the effect of the MVHR is much more prominent than the effect of the human model as evident by the average temperature recorded by the four monitoring points which all of them had an average ambient temperature of 295 °K (21.85 °C).

5.6.1 FFO_Winter simulation_Airflow velocity

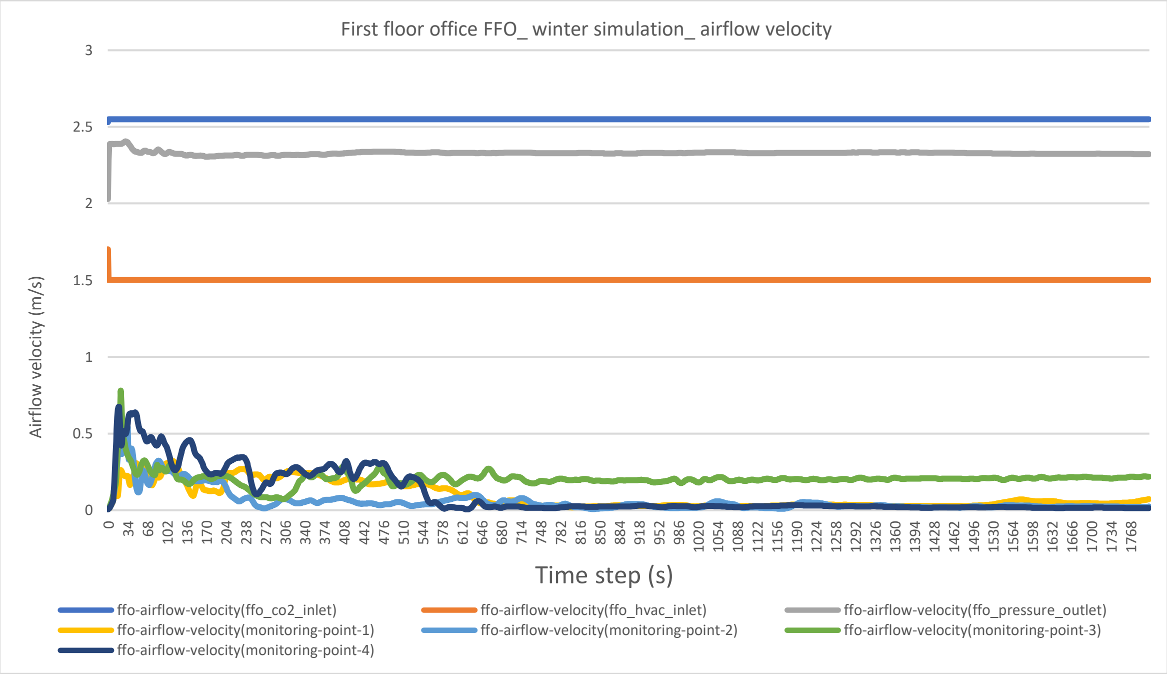


Figure 5-53 FFO_ winter simulation_ airflow velocity

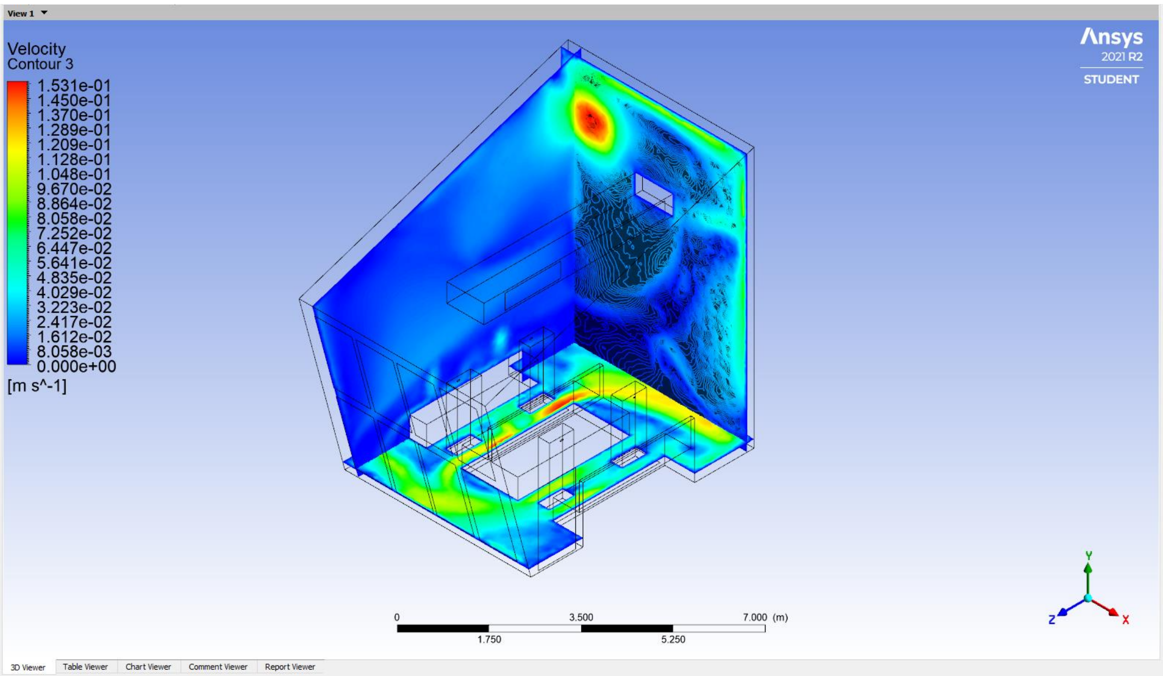


*Figure 5-52 FFO 2-D surfaces illustrating the contour of airflow velocity_ Winter simulation_*

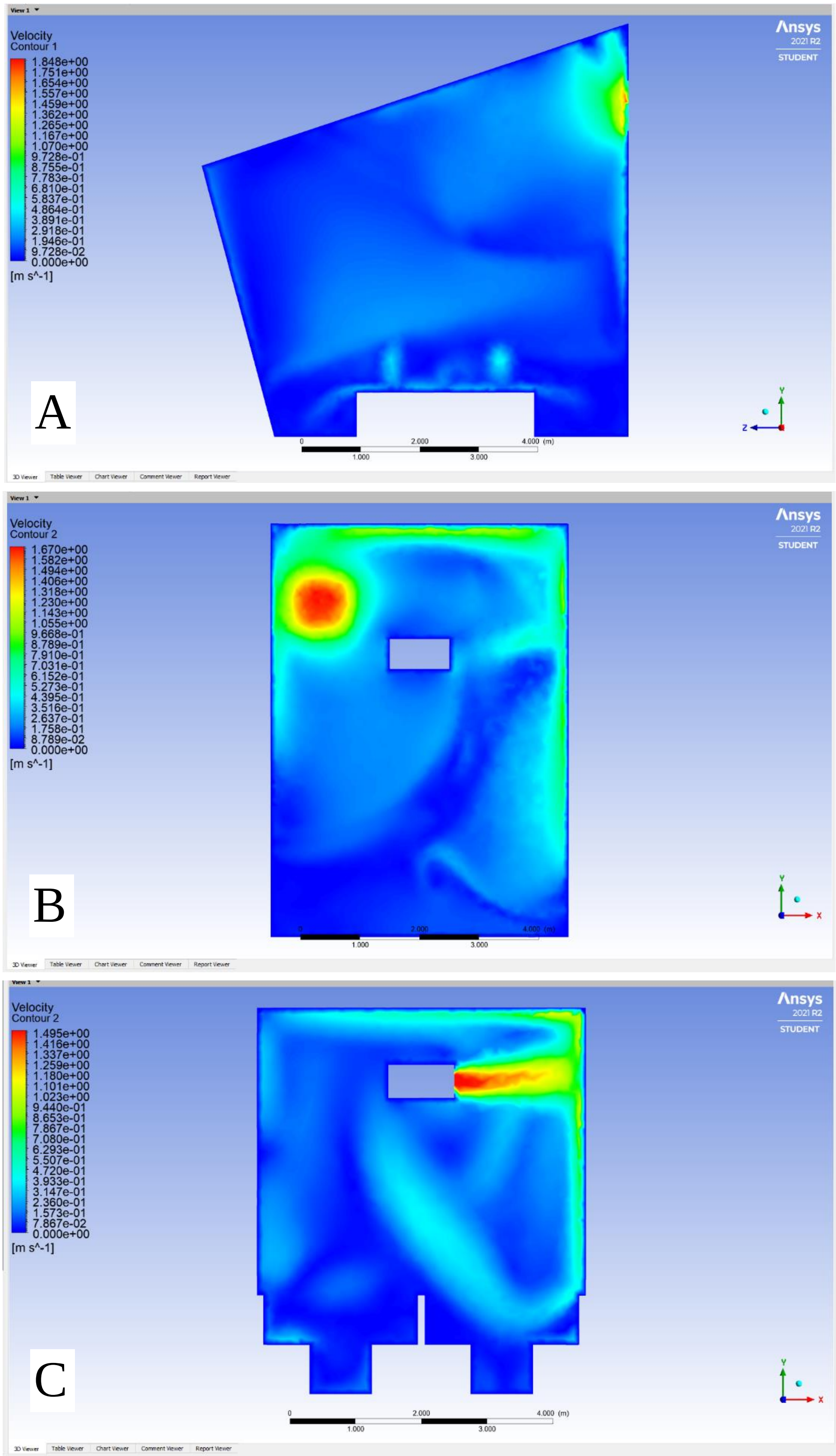


*Figure 5-54 FFO_ multiple 2-D surfaces illustrating the contour of airflow velocity_ Winter simulation_*

Table 5-17 FFO_ winter simulation_ Airflow velocity

Monitoring points	Airflow-velocity (HVAC airflow inlet)	Airflow-velocity (pressure outlet)	Airflow-velocity (monitoring-point-1)	Airflow-velocity (monitoring-point-2)	Airflow-velocity (monitoring-point-3)	Airflow-velocity (monitoring-point-4)
Average readings (m/s)	1.500	2.328	0.0918	0.0588	0.204	0.107

The main source of airflow in the FFO is the MVHR at 1.5 m/s. the air is pushed forward from the MVHR opening toward the opposite wall then falls down to the floor. The air is then lifted upwards toward the extract fan creating a full loop of air mixing that mixes with the existing air in the FFO. The second source of airflow is from the human model located next to the desks. The human model was set to simulate the exhalation of people at a velocity of 2.55 m/s. When examining the airflow inside the model, the area near monitoring point 3, and 4 has a higher average airflow velocity as can be seen in table (5-1t). That could be because these monitoring sensors are located underneath the air registers. The reduction in airflow velocity from the air register to the monitoring points is from 1.5 m/s to 0.2 m/s. The airflow then is lifted toward the extract fan where it passes over the other two monitoring point (1, and 2) with very little impact on the air velocity near this region of the room. This could be also verified from table (5-17) where the average air velocity in monitoring point 1, and 2 is 0.091 and 0.058 m/s respectively. While the average air velocity in monitoring point 3, and 4 is 0.204 and 0.107 m/s respectively.

5.6.1 FFO_Winter simulation_CO_2 concentration

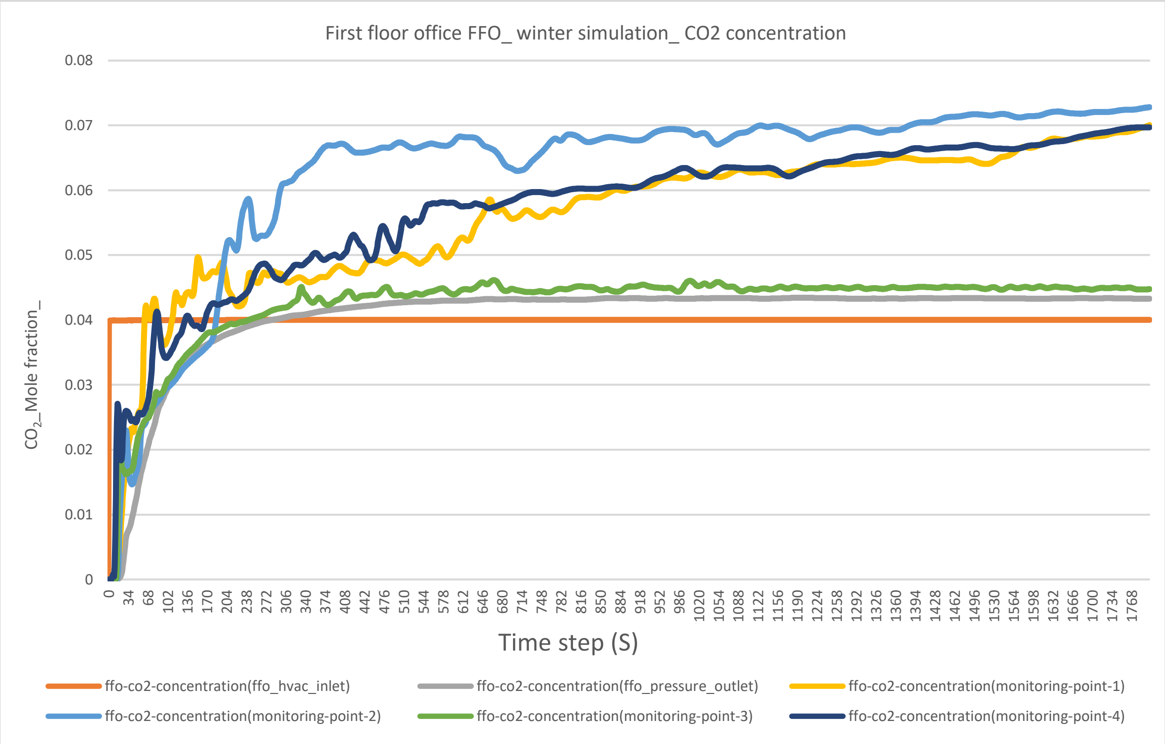


Figure 5-56 FFO_ winter simulation_ CO2 concentration

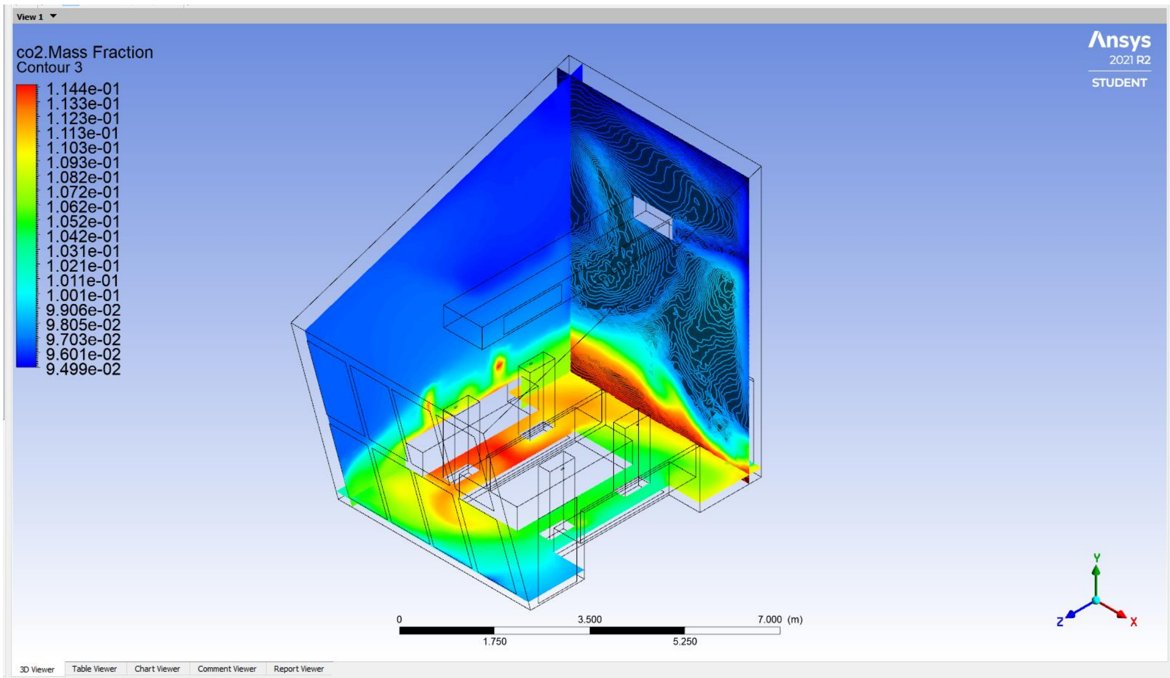


Figure 5-55 FFO 2-D surfaces illustrating the contour of ambient temperature_ winter simulation

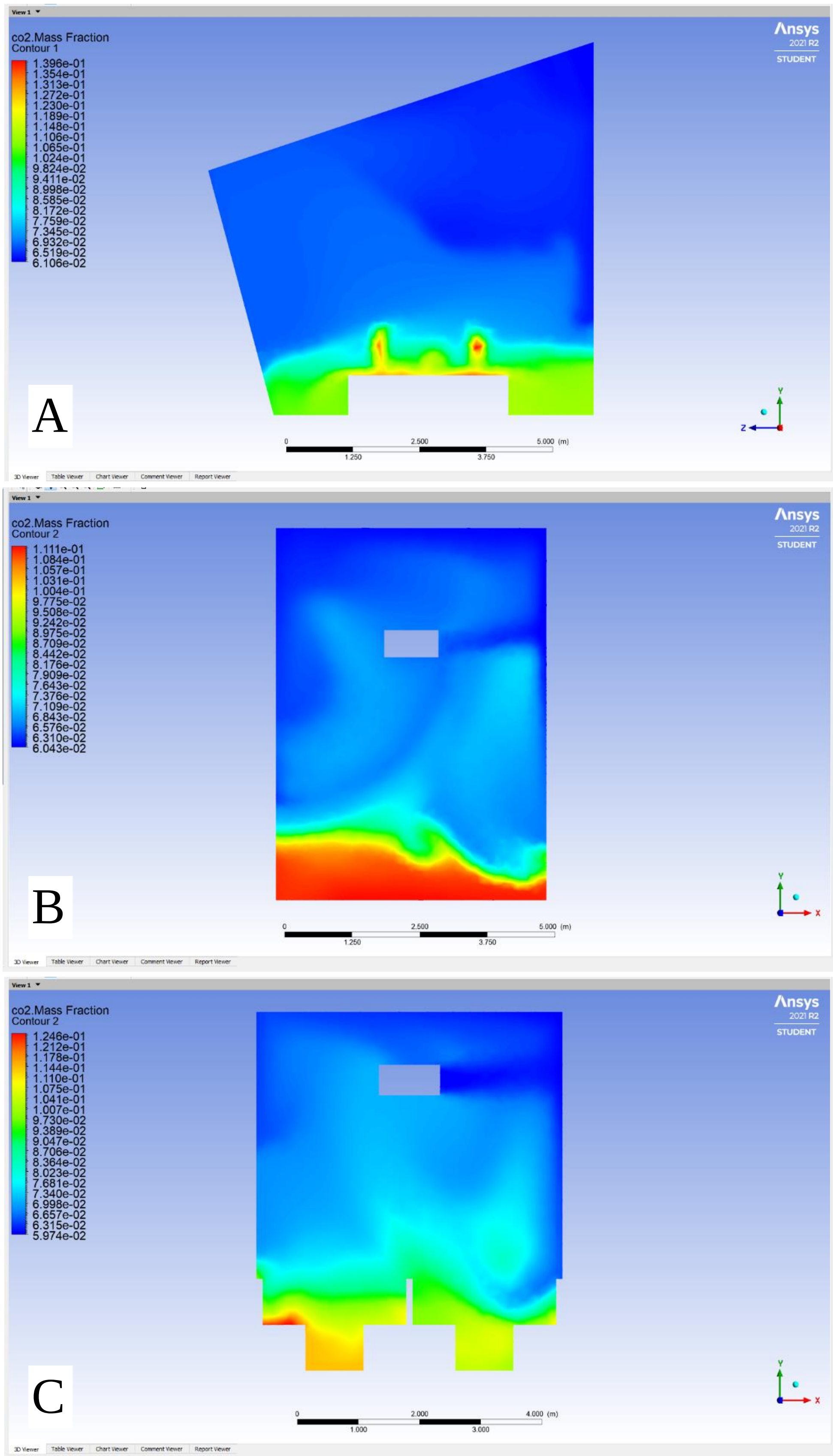


Figure 5-57 FFO multiple 2-D surfaces illustrating the contour of ambient temperature_ winter simulation

Table 5-18 FFO_ winter simulation_ CO_2 Concentration

Monitoring points	CO_2 concentration (HVAC Airflow inlet)	CO_2 concentration (co2 inlet)	CO_2 concentration (Pressure outlet)	CO_2 concentration (monitoring point-1)	CO_2 concentration (monitoring point-2)	CO_2 concentration (monitoring point-3)	CO_2 concentration (monitoring point-4)
Average readings (ppm)	0.0399	0.326	0.0406	0.0397	0.0398	0.0422	0.0542

The sources of CO_2 is mainly from the human occupants inside the model. In the FFO the number of desks placed inside the room is 12. However, the number of people present at the same time is not always the same. In this simulation, four human models were considered to be a close representation of the number of people that are mostly present at the same time. Each model is emitting around 3500 ppm as can be seen in table (5-18). When looking at both table (5-18) and figure (5.57) it can be inferred that the overall concentration of CO_2 is similar in all region of the room close to the ground. On the other hand, the concentration of CO_2 in the upper part of the room is much less in comparison. But when analyzing the four monitoring points. Monitoring 3 and 4 have a slightly higher concentration (422, and 542 ppm respectively) compared to monitoring points 1 and 2 (397 and 398 ppm respectively). The higher concentration of CO_2 around the region of monitoring point 3 and 4 might be explained by the fact that the airflow velocity near, like for example, monitoring point 1 is much higher than monitoring point 3. By looking at the airflow velocity near each of these sensors it can be seen that the airflow velocity near monitoring point 1 is far less than the airflow velocity in monitoring point 3, therefore, the higher CO_2 concentrations could be attributed to the fact that lack of air movement serves as a catalyst for pollution dilution. This could also be shown by looking at the graph in figure (5.56). In this graph, it shows that the concentration of CO_2 in monitoring point 2 can get as high as 700 ppm while the concentration of CO_2 near monitoring remains the same almost the entire time of the stimulation near monitoring point 2 and 3.

5.7 FFO_Summer simulation

5.7.1 FFO_summer simulation_ (PM) concentration

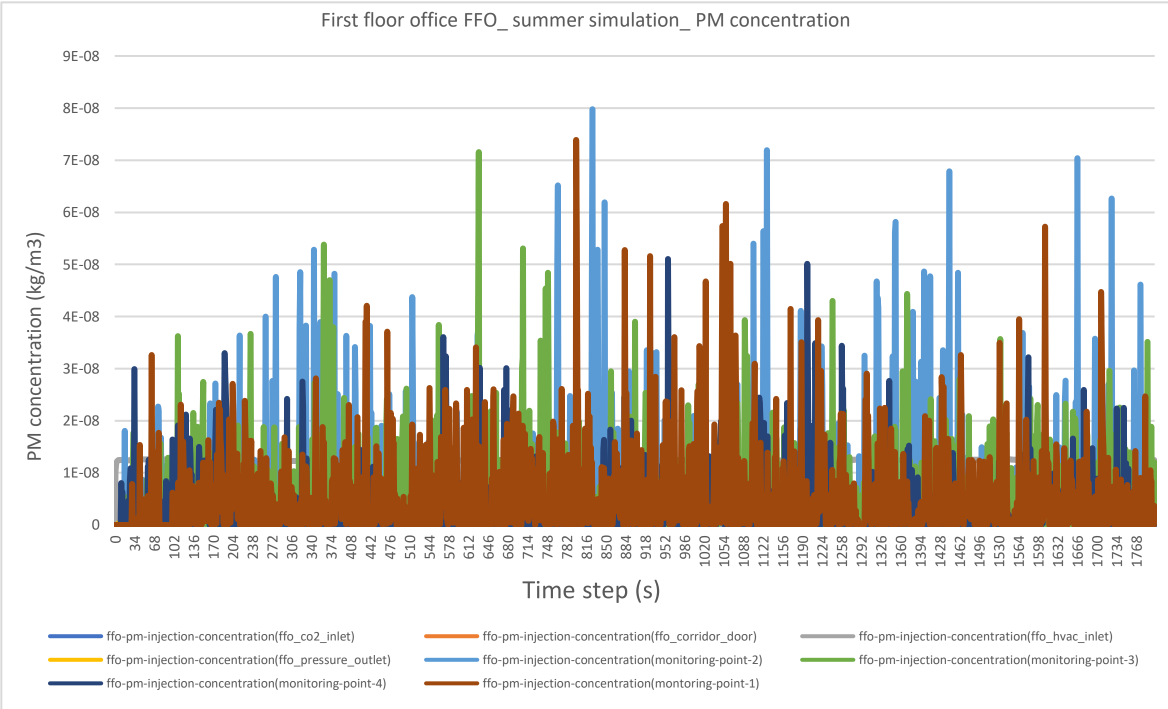


Figure 5-58 FFO_ summer simulation_ PM concentration

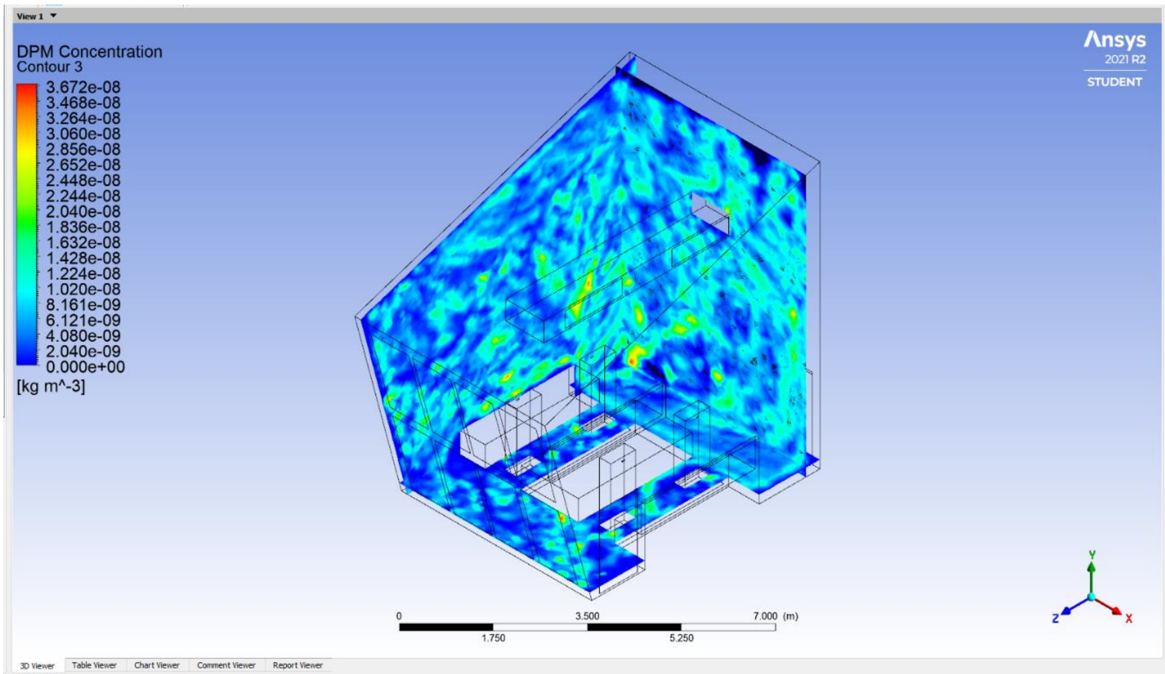


Figure 5-59 FFO 2-D surfaces illustrating the contour of (PM) concentration_ Summer simulation

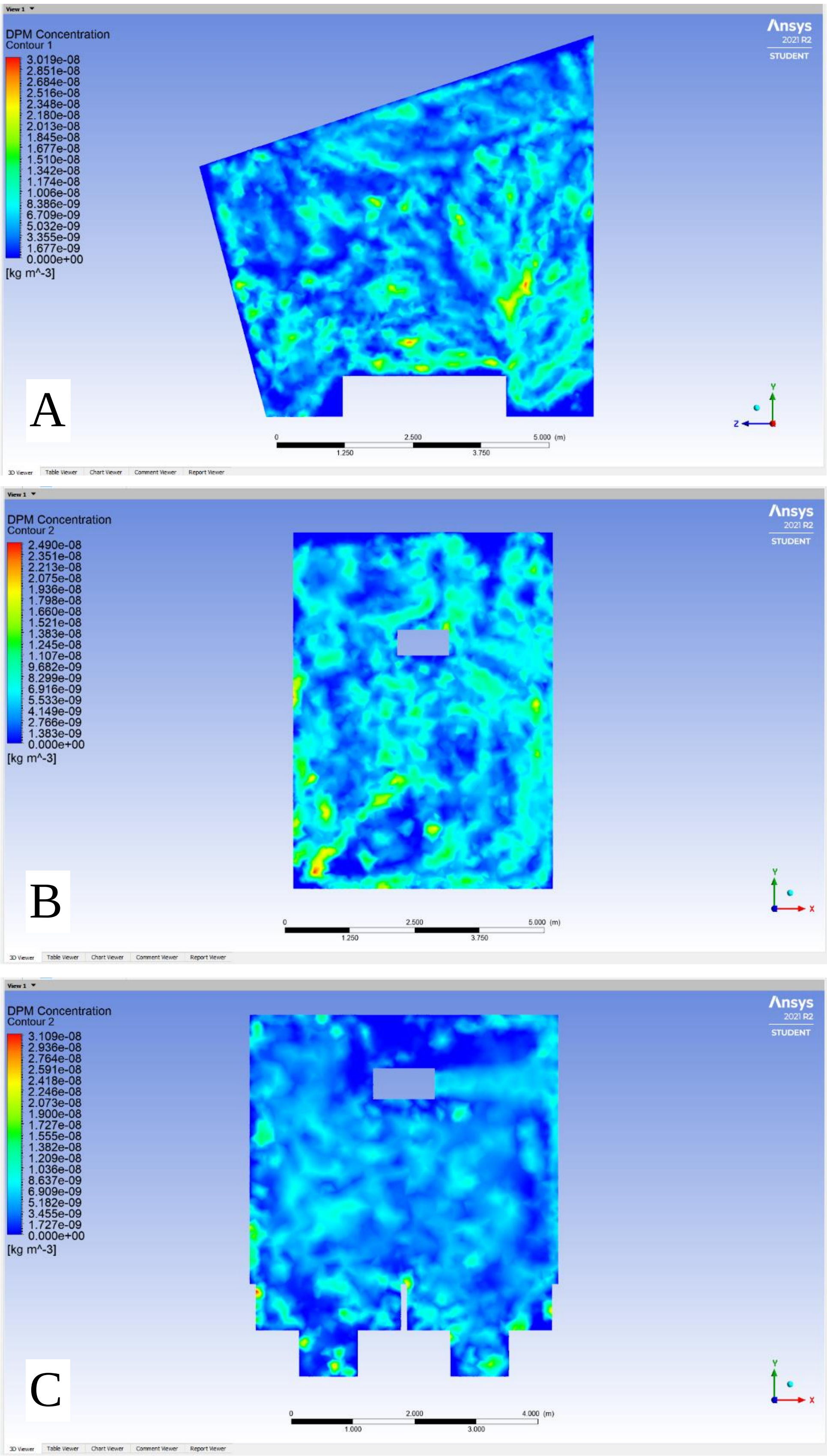


Figure 5-60 FFO_multiple 2-D surfaces illustrating the contour of (PM) concentration_ Summer simulation

Table 5-19 FFO_ summer simulation_ PM concentration

Monitoring points	PM Injection-concentration (HVAC inlet)	PM Injection-concentration (Pressure outlet)	PM Injection-concentration (monitoring-point-2)	PM Injection-concentration (monitoring-point-3)	PM Injection-concentration (monitoring-point-4)	PM Injection-concentration (montoring-point-1)
Average readings (Kg/m^3)	1.247E-08	5.640E-09	4.012E-09	4.678E-09	2.430E-09	4.966E-09

The boundary condition difference between the winter simulation and the summer simulation is in terms of airflow and PM sources is the opening of the entrance door near monitoring point 4. The entrance door allows the air from the inside of the building to escape the model which creates an opportunity for some of the PM particles to leave the room. When looking at figure (5.60) and comparing it to figure (5.48) there is a difference in the way the particles are moving inside the room. In the winter simulation, most of the particles are moving in a circular movement from the MVHR inlet all the way to the extract fans. However, that is not the case in the summer simulation. In the summer simulation, the movement of PM particles is spread evenly in the room. This could be also seen from table (5-19) where it shows the average concentration for (PM) to be less drastic than in the winter simulation. That is not to say that there is no difference between the four monitoring points. The highest concentration of PM is near monitoring point 1 where the concentration of PM reaches an average of 4.9 $\mu g/m^3$, the second-highest recording of PM concentration is near monitoring point 3 where the average PM concentration is near 4.6 $\mu g/m^3$. The third highest concentration is near monitoring point 2 with an average concentration of 4.01 $\mu g/m^3$. And finally, the lowest concentration of PM is near monitoring point 4 with an average concentration of 2.4 $\mu g/m^3$.

5.7.2 FFO_summer simulation_ Ambient temperature

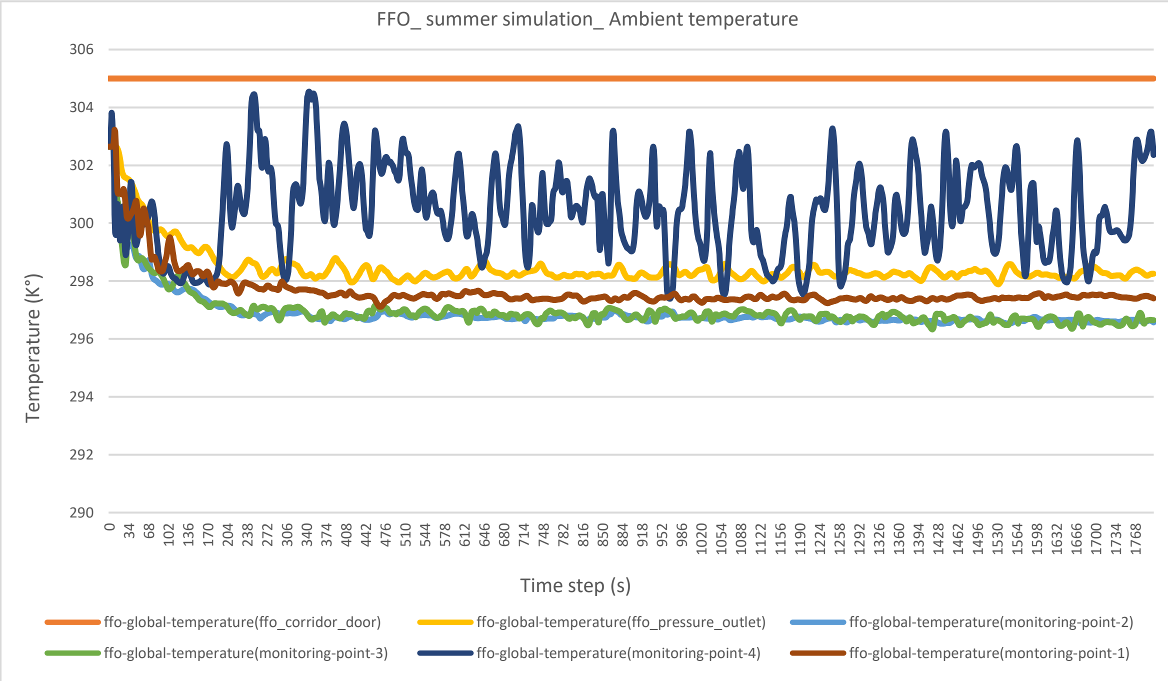


Figure 5-62 FFO_ summer simulation_ Ambient temperature

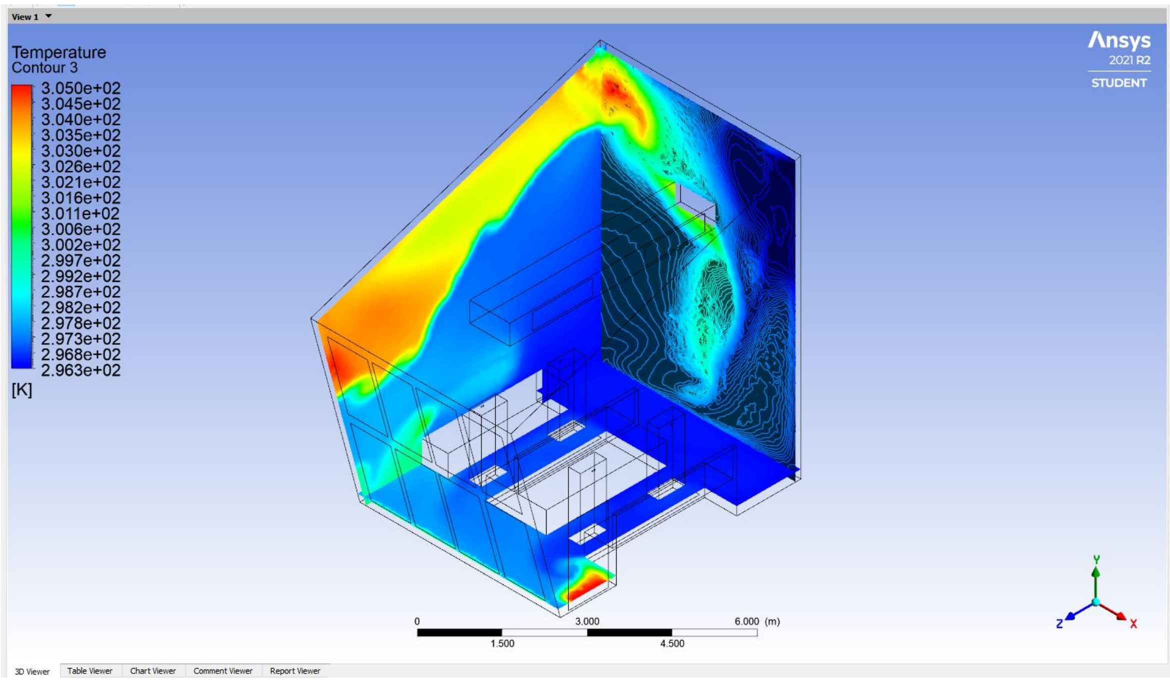


Figure 5-63 FFO 2-D surfaces illustrating the contour of ambient temperature_ Summer simulation

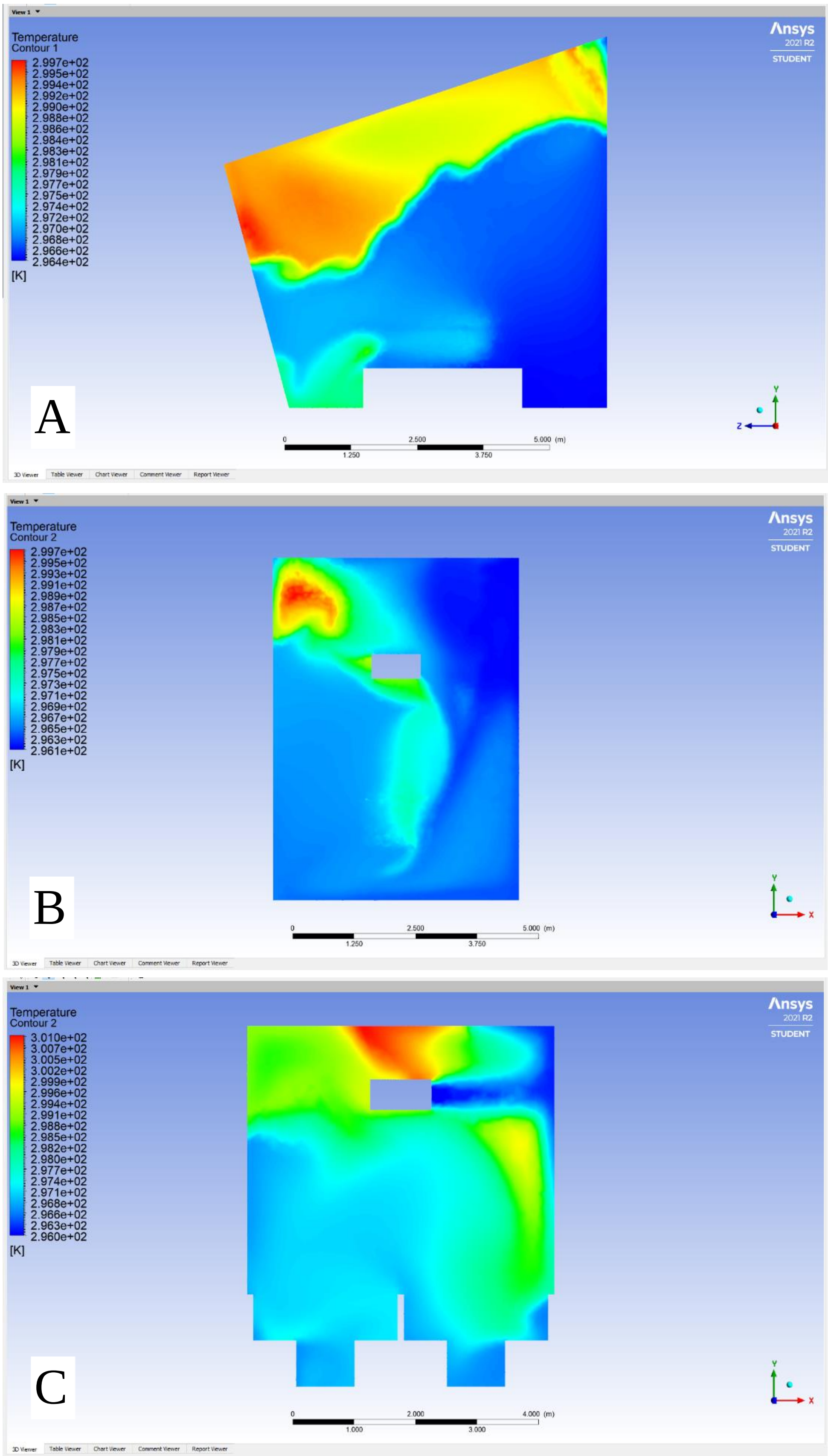


Figure 5-64 FFO_multiple 2-D surfaces illustrating the contour of ambient temperature_ Summer simulation

Table 5-20 FFO_ summer simulation_ Ambient temperature

Monitoring points	Ambient Temperature (HVAC inlet)	Ambient Temperature (Pressure outlet)	Ambient Temperature (monitoring-point-2)	Ambient Temperature (monitoring-point-3)	Ambient Temperature (monitoring-point-4)	Ambient Temperature (monitoring-point-1)
Average readings (Kelvin)	296	298.468	296.909	296.967	300.413	297.6708

The ambient temperature during the summer period is noticeably hot inside the FFO. The regular source of airflow has the same temperature as the previous winter scenario. However, during the summer simulation, the doors are kept open all the time and they would allow an additional source of air to penetrate the room creating a secondary source of airflow. Another prominent source of hot air inside the FFO is the border window. The FFO is situated on the top floor in the corner of the building. The sunrays could hit the room directly causing the air inside the space to heat up considerably. When looking at both figure (5.62) and (5.63) the chart shows that monitoring point 4 has the highest ambient temperature with an average temperature of 301 °K (27 °C). The chart also shows that the range of ambient temperature fluctuation near monitoring point 4 is between 298 to 304 °K (24 to 30 °C) these temperatures are well above the recommended levels suggested by the CIBSE of 22 – 24 °C during the summertime. However, it is important to note the most of the hot air is channeled upwards toward the extract fan as can be depicted in figure (5.64). The reasons why the temperature around monitoring point 4 is considerably high compared to the other sensors is because the sensor is located near two sources of hot air. The first is the border windows whose temperature could reach up to 310 °K (36 °C). the other source of hot air is the entrance door that is located next to the main corridor that brings in hot air from outside of the FFO

5.7.3 FFO_summer simulation_ Airflow simulation

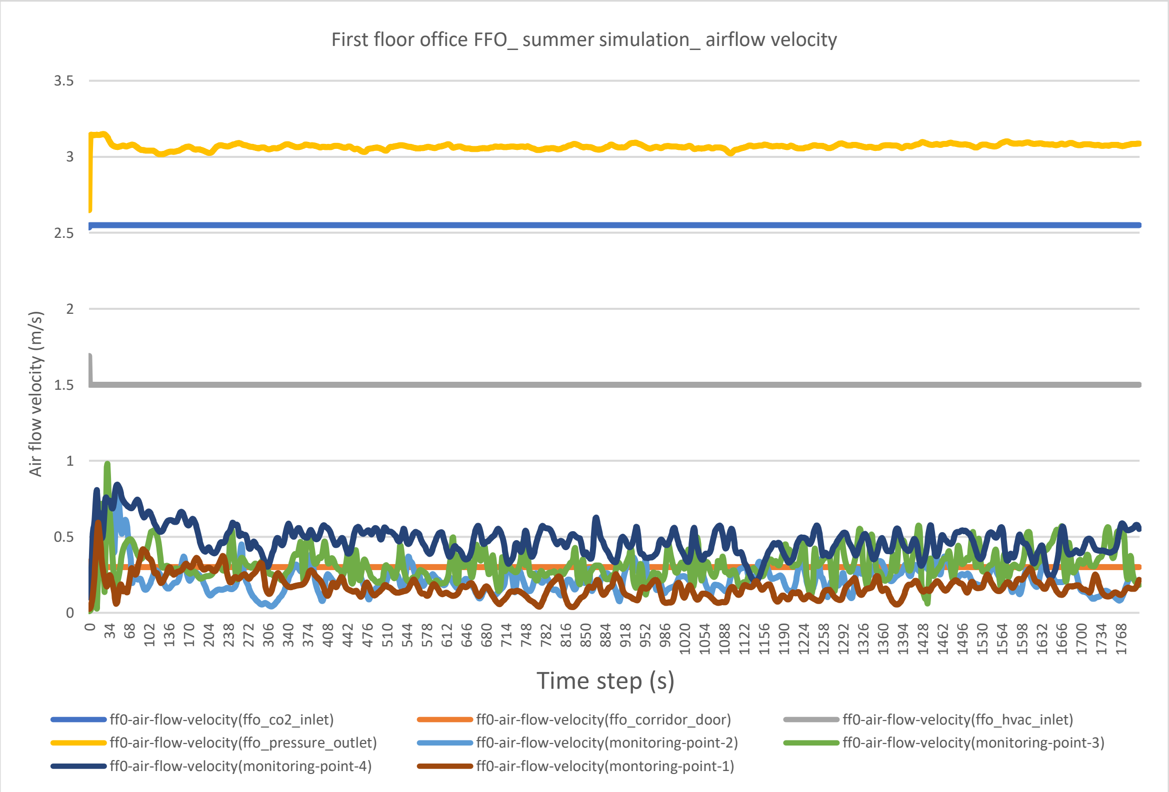


Figure 5-65 FFO_ summer simulation_ airflow velocity

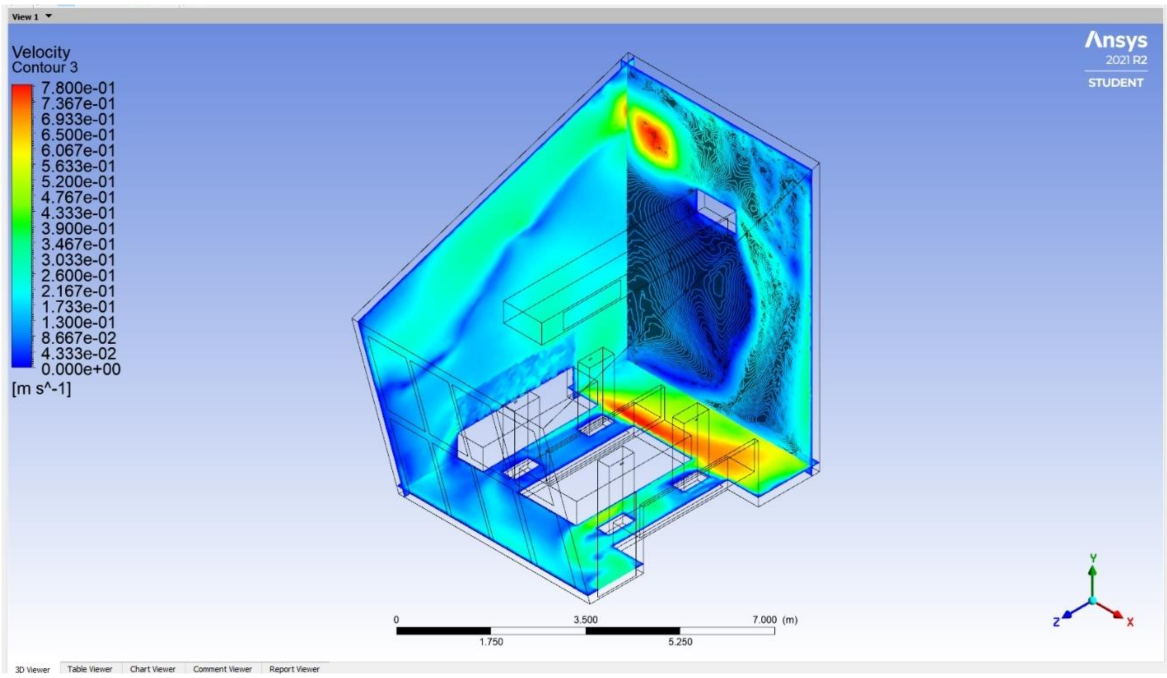


Figure 5-66 FFO 2-D surfaces illustrating the contour of airflow velocity_ Summer simulation

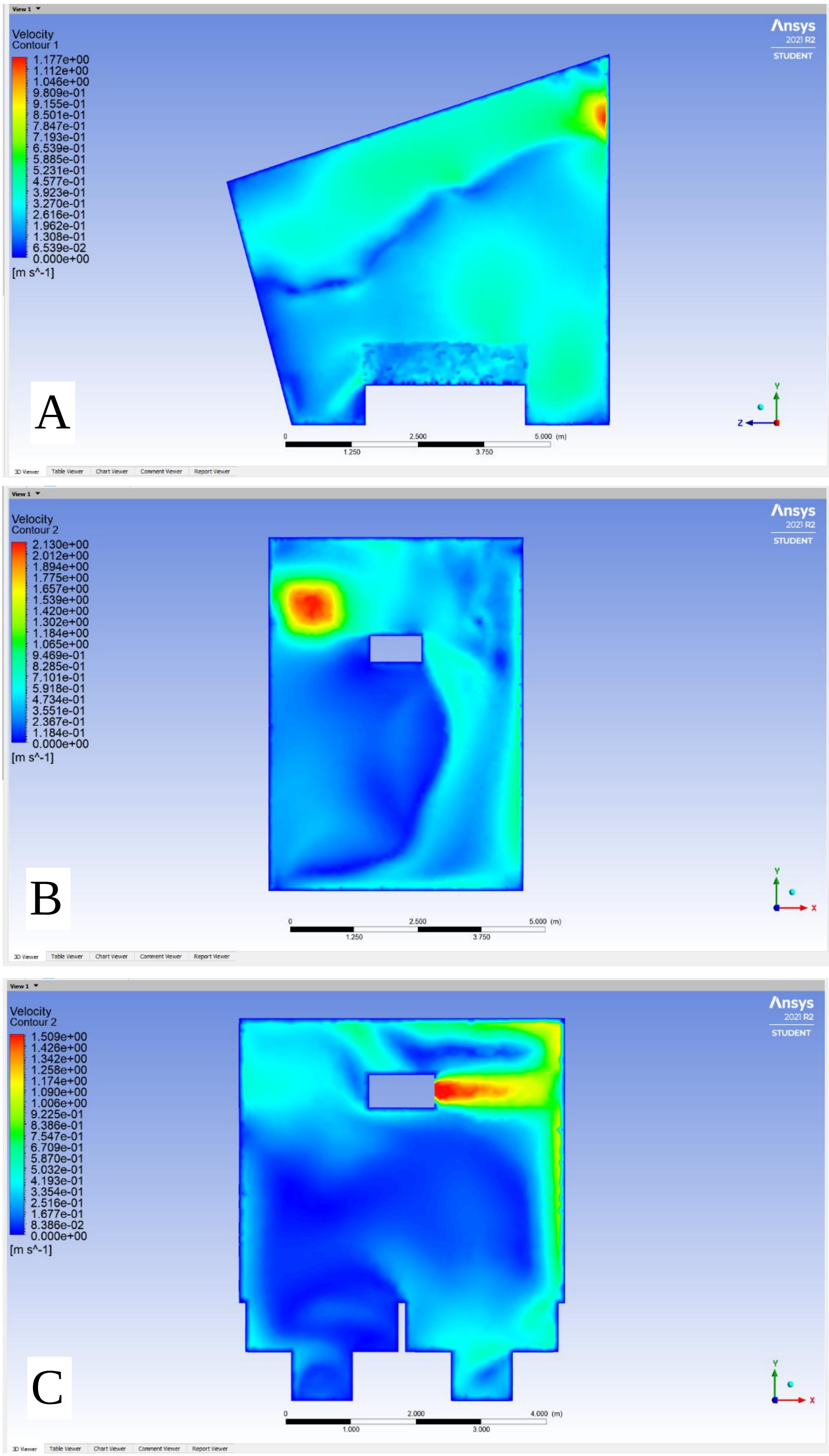


Figure 5-67 FFO 2-D surfaces illustrating the contour of airflow velocity_ Summer simulation

Table 5-21 FFO_ Summer simulation_ Airflow velocity

Monitoring points	Air-flow-velocity (HVAC inlet)	Air-flow-velocity (Pressure outlet)	Air-flow-velocity (monitoring-point-2)	Air-flow-velocity (monitoring-point-3)	Air-flow-velocity (monitoring-point-4)	Air-flow-velocity (monitoring-point-1)
Average readings (m/s)	1.500	3.068	0.223	0.316	0.471	0.171

As stated before, the airflow in the summer period is different from the winter period. The two sources of airflow are the MVHR system and the introduction of natural ventilation coming from the entrance door. When analyzing the difference between the four monitoring points. It is clear that monitoring point 3 and 4 has the highest airflow velocity (0.31 and 0.47 m/s respectively) while the other two sensors, monitoring point 1 and 2 (0.17 and 0.22 m/s respectively) has the lowest airflow velocity. Monitoring point 4 particularly is the highest among all the four sensors. The reason could be that the area near monitoring point 4 is within the crossroad of two-stream of airflow. The first is the downdraft of air coming from the MVHR system from above and the second is the air entering the room through the door which also crosses the area near monitoring point 4. That could explain why monitoring point 4 has the highest value of airflow velocity and that would also explain why the area near monitoring point 1 and 2 has little to no airflow passes near these sensors. The 2-D surface contour plot in figure (5.48) shows how the introduction of outside air coming from the corridor has a major impact on the airflow inside the FFO.

5.7.4 FFO_summer simulation_CO_2 concentration

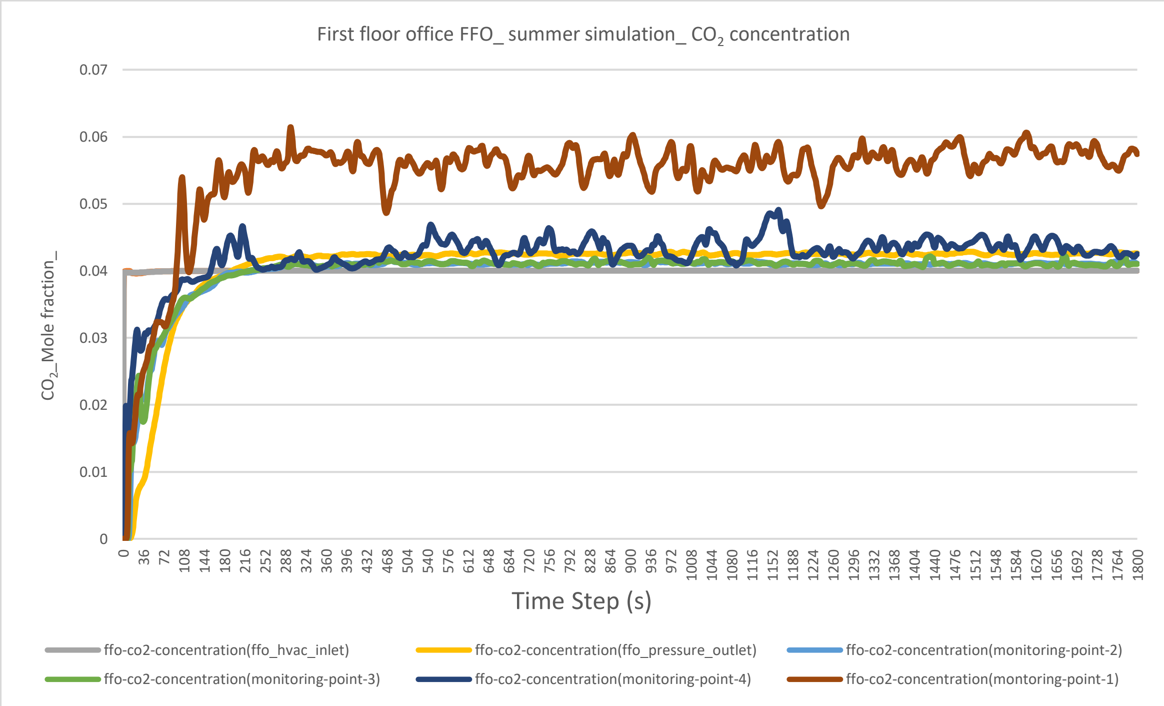


Figure 5-69 FFO_ summer simulation_ CO2 concentration

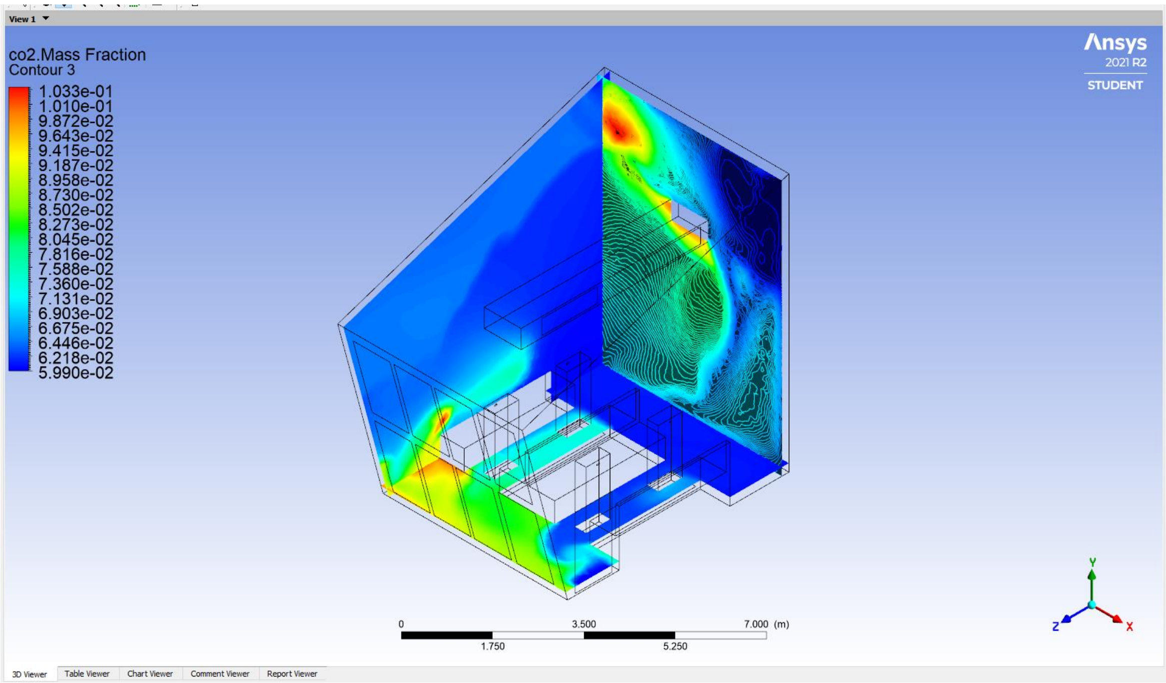


Figure 5-68 FFO 2-D surfaces illustrating the contour of CO_2 concentration_ Summer simulation

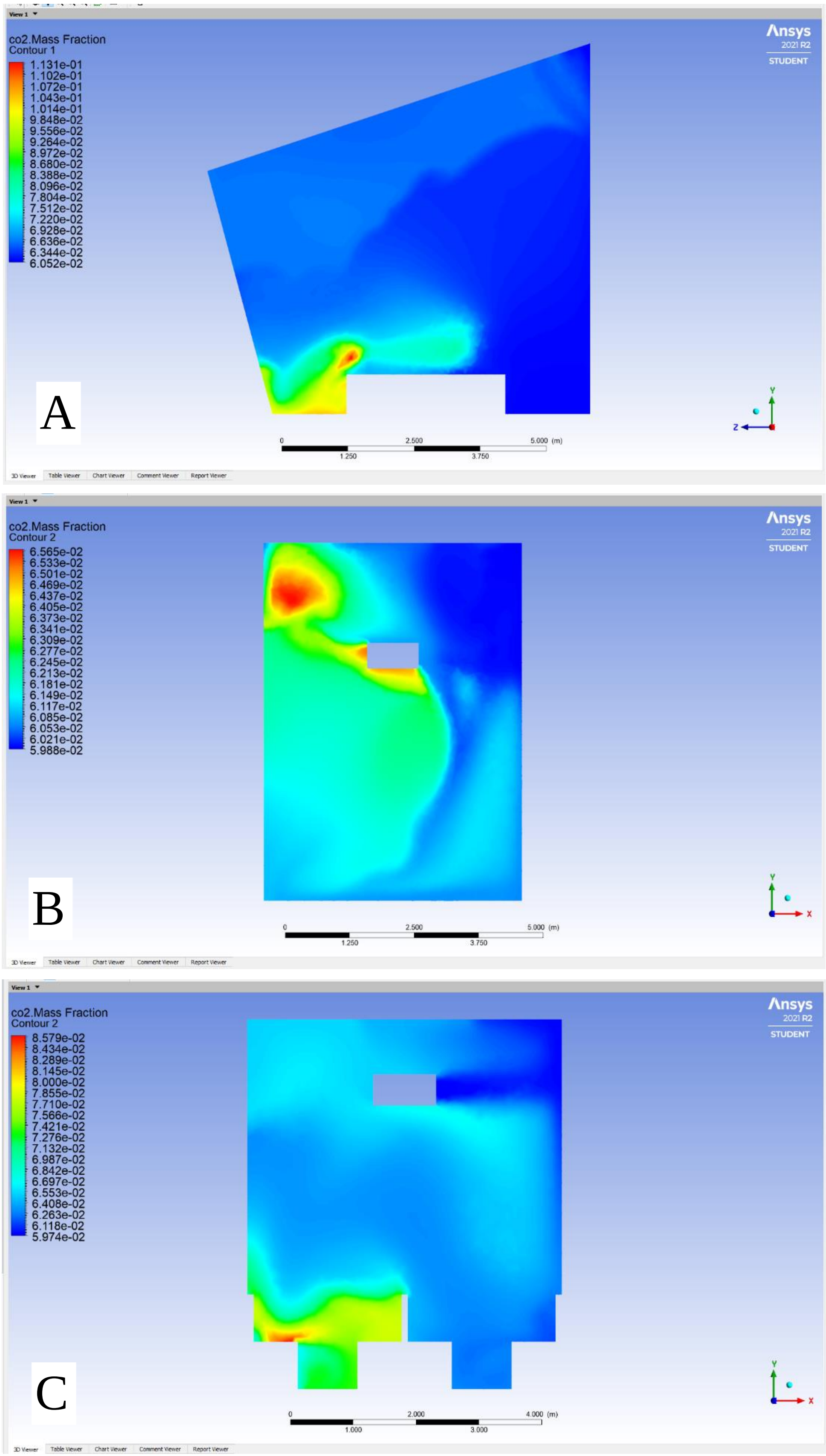


Figure 5-70 FFO_multiple 2-D surfaces illustrating the contour of CO2 concentration_ Summer simulation

Table 5-22 FFO_ summer simulation_ CO_2 concentration

Monitoring points	CO_2-concentration (CO2 inlet)	CO_2-concentration (HVAC inlet)	CO_2-concentration (pressure outlet)	CO_2-concentration (monitoring-point-2)	CO_2-concentration (monitoring-point-3)	CO_2-concentration (monitoring-point-4)	CO_2-concentration (montoring-point-1)
Average readings (ppm)	0.383	0.0399	0.0406	0.0397	0.0398	0.0422	0.0542

CO_2 concentration in the summer period shows a very interesting trend. Some sensors show a higher value of CO_2 compared to the winter period. In particular, monitoring point 1 and 4, table (5-22). These two monitoring points are located in front of the entrance door. These high levels of CO_2 concentration could be explained by the fact that there are additional sources of CO_2 coming from outside of the FFO and it is coupled with the fact that the majority of the CO_2 emitted by the human model is residing near the ground level of the room which would explain why there is a higher concentration of CO_2 skewed very heavily near the far-right corner of the room as can be seen in figure (5.70). The levels of CO_2 recorded in the summer scenario is consistently higher than the CO_2 concentration recorded in the winter simulation, however, even with levels as high as 650 ppm, they still do not reach the limit set by the CIBSE for CO2 indoor exposure.

5.8 FFO_Autumn/Spring simulation

5.8.1 FFO_Autumn/Spring simulation_PM concentration

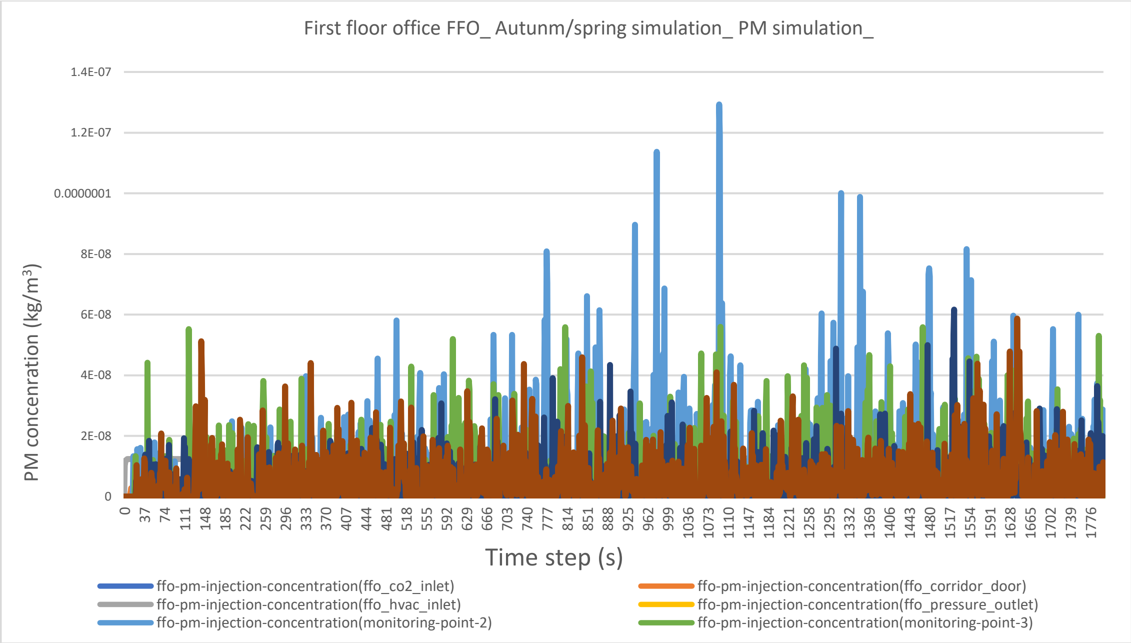


Figure 5-71 FFO_ Autumn/spring simulation_ PM simulation

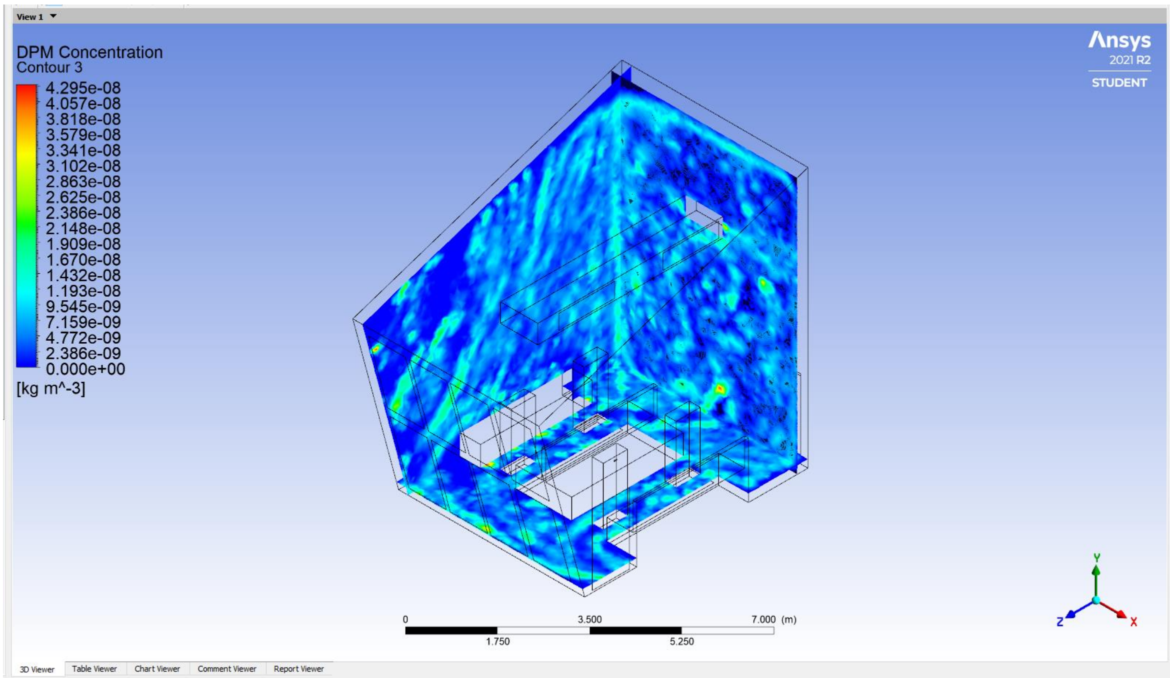


Figure 5-72 FFO 2-D surfaces illustrating the contour of (PM) concentration_ Autumn/spring simulation

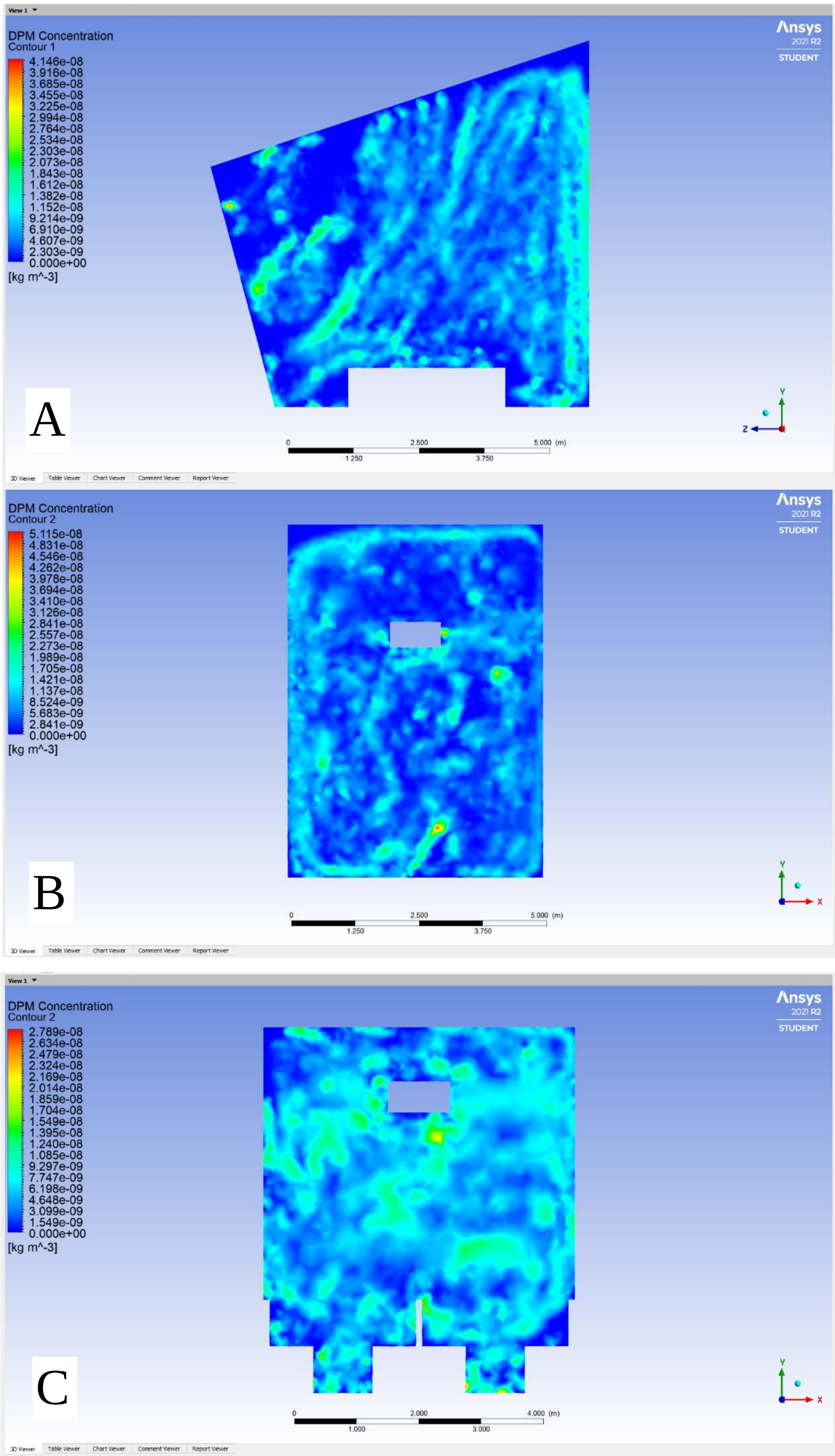


Figure 5-73 FFO_multiple 2-D surfaces illustrating the contour of (PM) concentration_ Autumn/spring simulation

Table 5-23 FFO_ Autumn simulation_ PM simulation

Monitoring points	PM Injection-concentration (HVAC inlet)	PM Injection-concentration (Pressure outlet)	PM Injection-concentration (monitoring-point-2)	PM Injection-concentration (monitoring-point-3)	PM Injection-concentration (monitoring-point-4)	PM Injection-concentration (montoring-point-1)
Average readings (Kg/m^3)	1.249E-08	7.305E-09	6.980E-09	4.809E-09	3.712E-09	5.364E-09

The third simulation represents an intermediary scenario that does not have the same conditions as the summer and winter simulation. The main sources of PM did not change. However, the airflow is slightly different in which the MVHR is the main source of airflow to the interior space, but the door that is open to the corridor is extracting air from the interior space to the corridor instead of having the air being pushed from the corridor to the interior space as in the summer simulation. The reason for this change was because of the changes in the ambient temperature either exists inside the interior space or the ambient temperature that exist outside the interior space. In the summer simulation, for instance, the ambient temperature outside the space is much hotter than the interior space, therefore, the air would move from the outside towards the interior. In some situation in the spring or autumn season, the temperature is sometimes hotter or colder than the interior space but the difference is not great as to have a significant thermal exchange of air between the interior and the exterior. From looking at the figures (5.71 and 5.72) it is clear that the PM is spread evenly all over the interior space. Nevertheless, when looking at table (5-23) it shows that the concentration in monitoring point 2 and 3 are very different than monitoring point 1 and 4. The concentration in monitoring point 1 and 2 (5.3 µg/m^3 and 6.9 µg/m^3 respectively) are higher than the concentration in monitoring point 3 and 4 (3.7 µg/m^3 and 4.8 µg/m^3 respectively). One reason for the higher concentration of PM near monitoring point 1 and 2 is because these two monitoring points are located in the pathway of the extract fan and the exterior door. Monitoring point 1 is in the middle of the pathway of the air coming from the MVHR and then extracted by the main extract fan.

5.8.2 FFO_Autumn/Spring simulation_ Ambient temperature

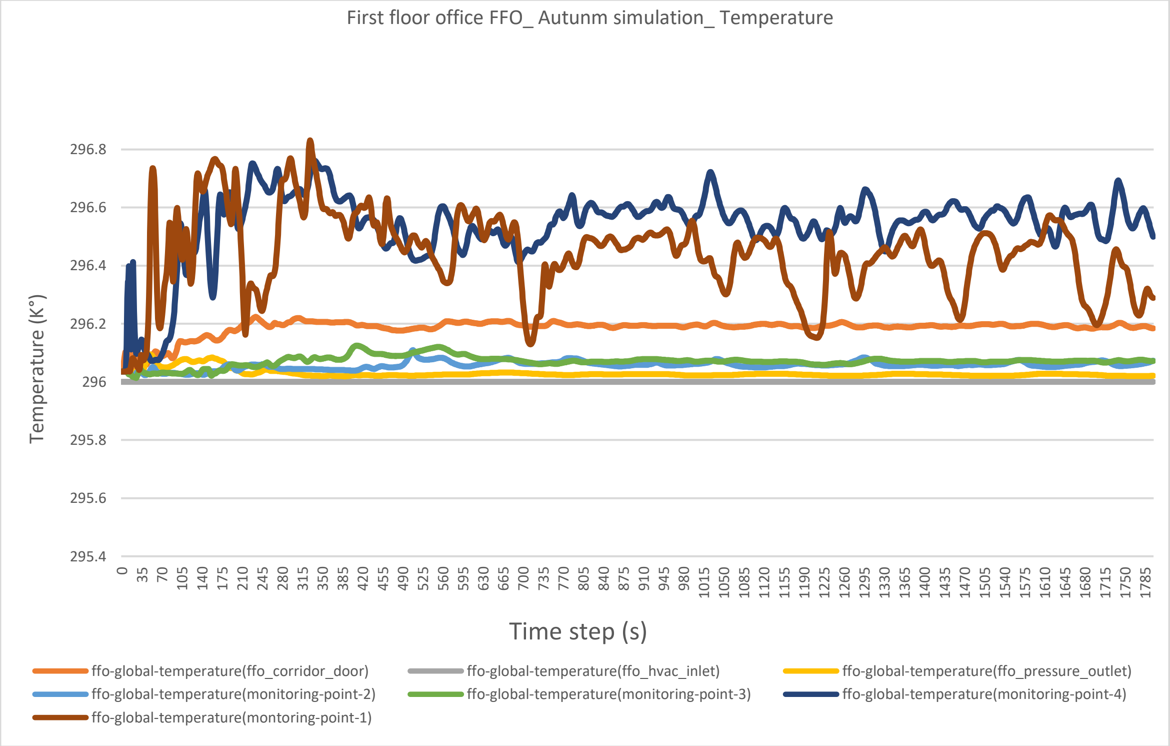


Figure 5-75 FFO_ Autunm/spring simulation_ Ambient temperature

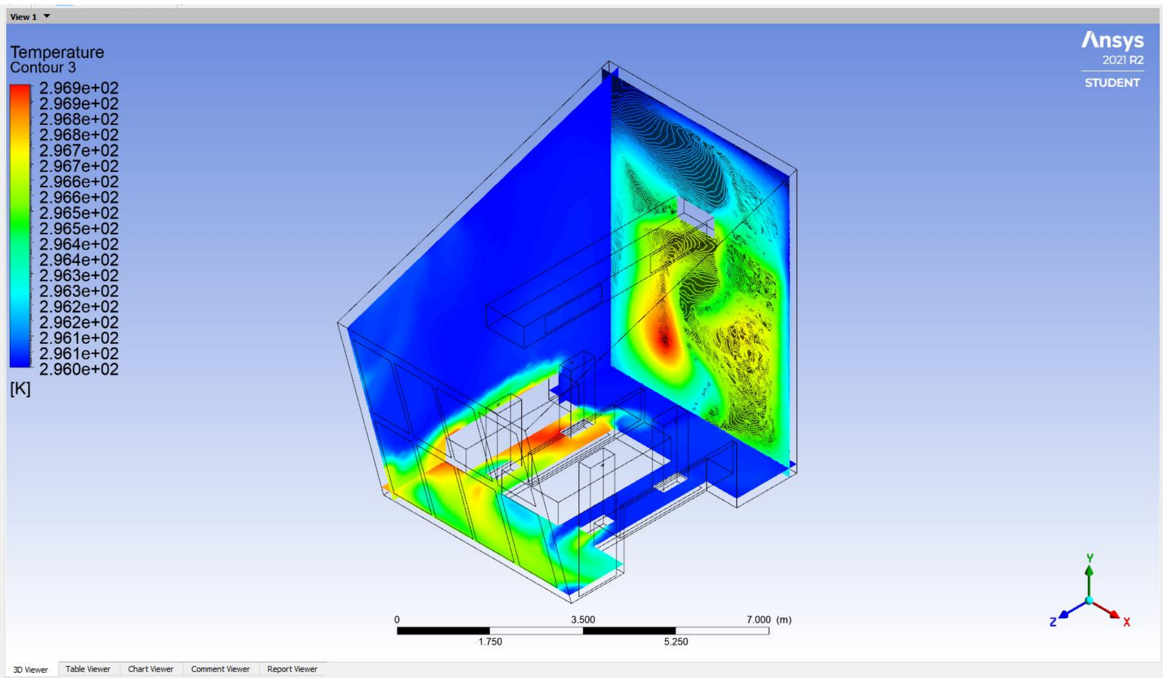


Figure 5-74 FFO 2-D surfaces illustrating the contour of ambient temperature_ Autumn/spring simulation

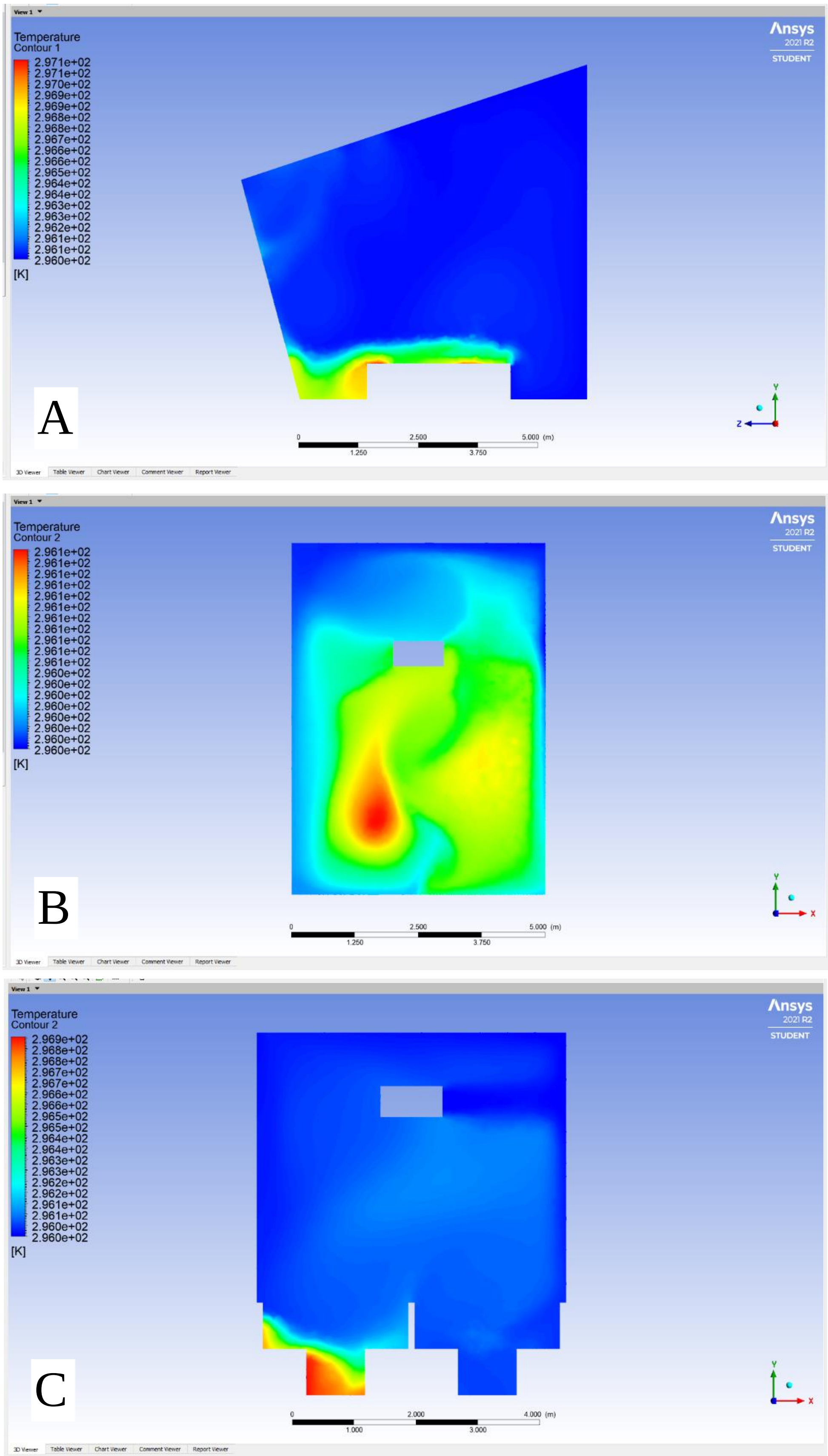


Figure 5-76 FFO_multiple 2-D surfaces illustrating the contour of ambient temperature_ Autumn/spring simulation

Table 5-24 FFO_ Autumn/spring simulation_ Ambient Temperature

Monitoring points	Ambient Temperature (HVAC inlet)	Ambient Temperature (Pressure outlet)	Ambient Temperature (monitoring-point-2)	Ambient Temperature (monitoring-point-3)	Ambient Temperature (monitoring-point-4)	Ambient Temperature (monitoring-point-1)
Average reading (Kelvin)	296	296.029	296.056	296.070	296.539	296.440

The thermal conditions inside the FFO are very much affected by the exterior ambient temperature and in these cases, the ambient temperature in both the winter and the summer is either too cold or too hot. The case is different in both autumn and spring. The ambient temperature outside the FFO is mild and does not follow extreme trends of excessive heat or excessive cold. This phenomenon is well translated into the result of the ambient temperature inside the FFO during the autumn and spring scenario. When examining the average reading from table (5-24) it shows that all the monitoring point are showing the same average temperature of 296 °K (22 °C). however, when looking at the chart from figure (5.74) it demonstrates that the ambient temperature around both monitoring 1 and 4 has a slightly high average temperature compared to the average readings from monitoring point 2 and 3. It is important to mention that the border window is contributing to the rise in the ambient surrounding monitoring point 1 and 4. The temperature of the border window is a little bit higher than the MVHR system, therefore the area close to the border window could be affected by the increase in high temperature attributed to the boarded windows.

5.8.3 FFO_Autumn/Spring simulation

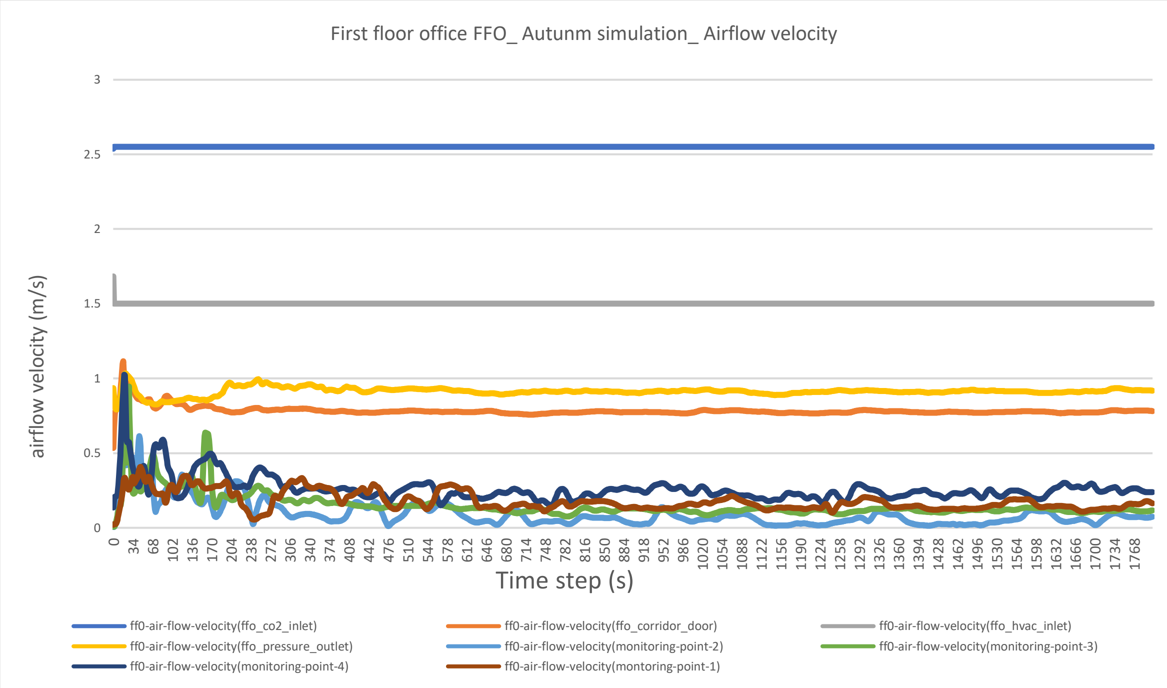


Figure 5-77 FFO_ Autumn simulation_ Airflow velocity

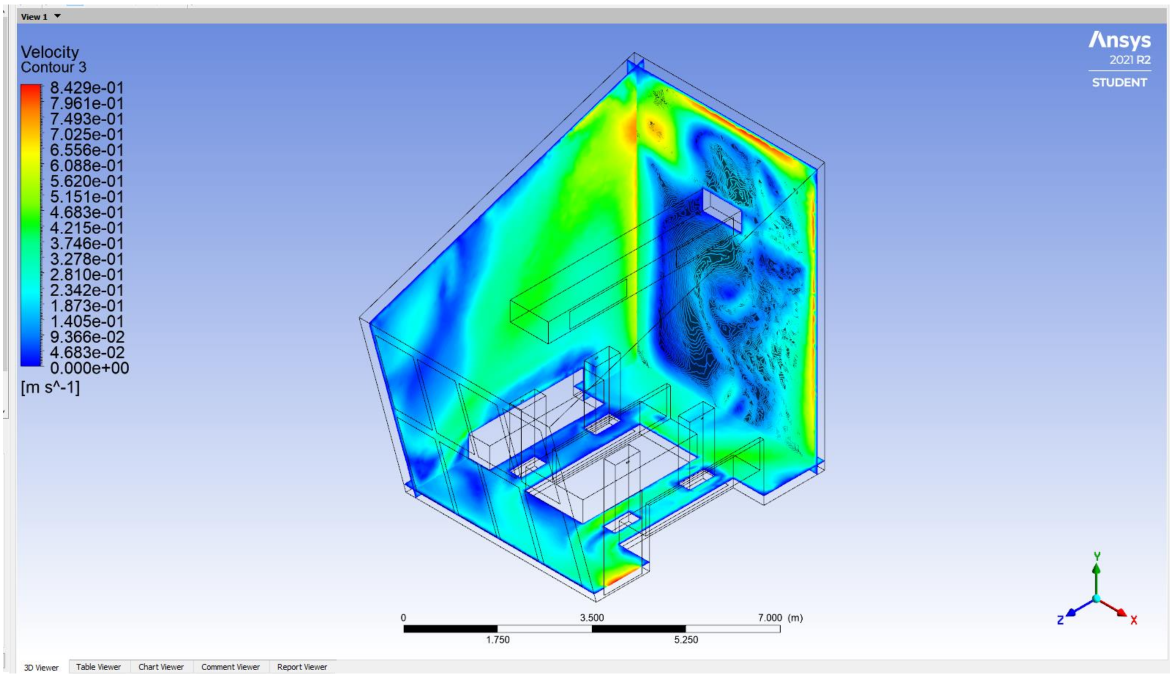


Figure 5-78 FFO_ Autumn simulation_ Airflow velocity

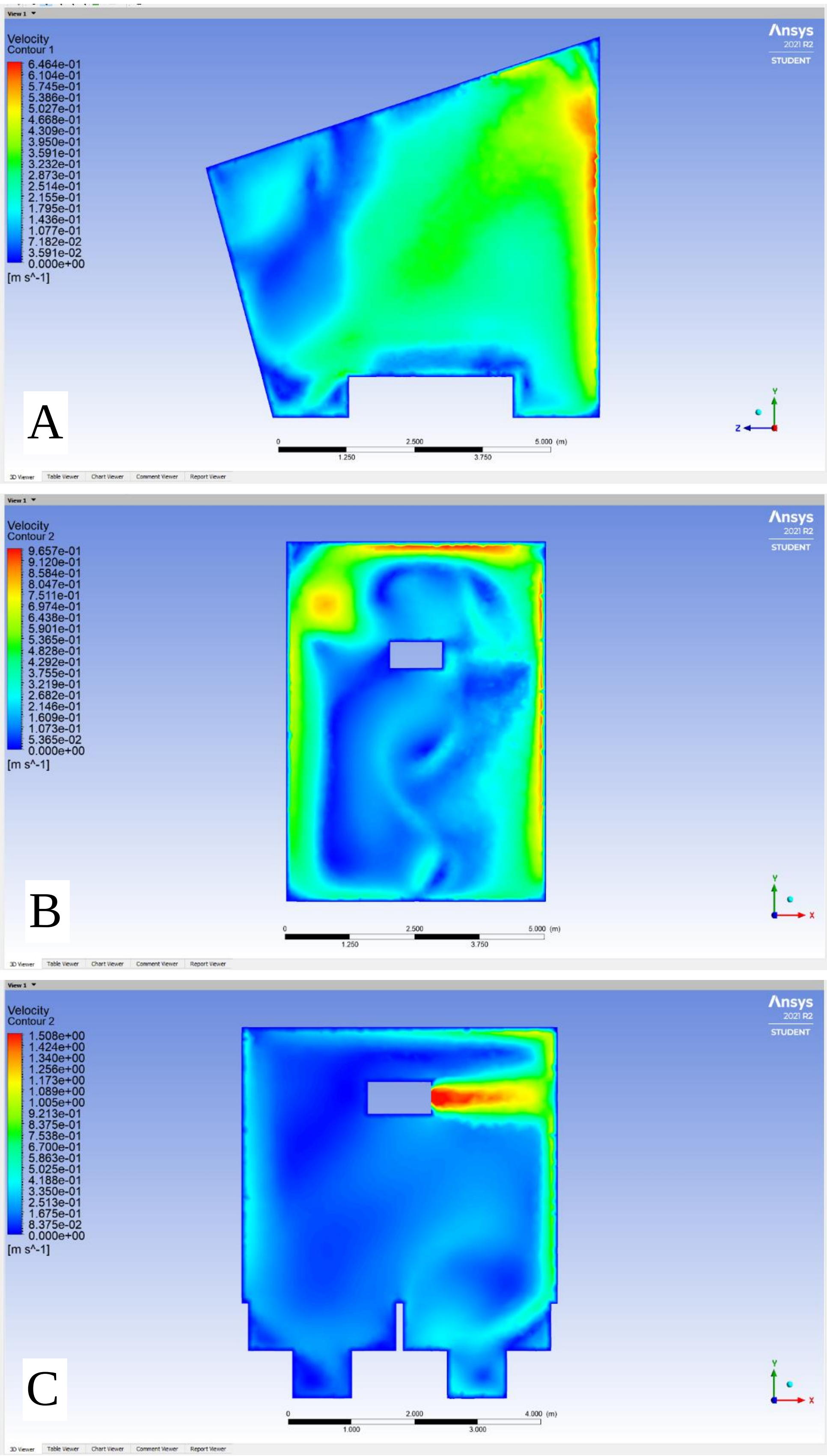


Figure 5-79 FFO_ Autunm simulation_ Airflow velocity

Table 5-25 FFO_ Autumn simulation_ Airflow velocity

Monitoring points	Air-flow-velocity (HVAC inlet)	Air-flow-velocity (Pressure outlet)	Air-flow-velocity (monitoring-point-2)	Air-flow-velocity (monitoring-point-3)	Air-flow-velocity (monitoring-point-4)	Air-flow-velocity (monitoring-point-1)
Average readings (m/s)	1.500	0.913	0.092	0.149	0.258	0.178

As stated before, the boundary condition in the autumn/spring simulation is different from the winter and summer simulation. One key difference is the inclusion of the exterior door that is located adjacent to the corridor. This door was set as a pressure outlet that would allow air to escape the room model. The average reading collected from the four monitoring point shows the following trend. The first is that the lowest airflow velocity was registered near monitoring point 1 (0.17 m/s). The second-lowest airflow velocity was recorded near monitoring point 2 (0.09 m/s). the other two monitoring point 3 and 4 have registered higher airflow velocity (0.14 and 0.25 m/s, respectively). The reason for the higher airflow velocity near monitoring point 3 and 4 is because the MVHR inlet is directly above these two monitoring points, therefore, the first region to be hit by the incoming air from the MVHR system in the region close to monitoring point 3 and 4.

5.8.4 FFO_Autumn/Spring simulation_CO_2 concentration

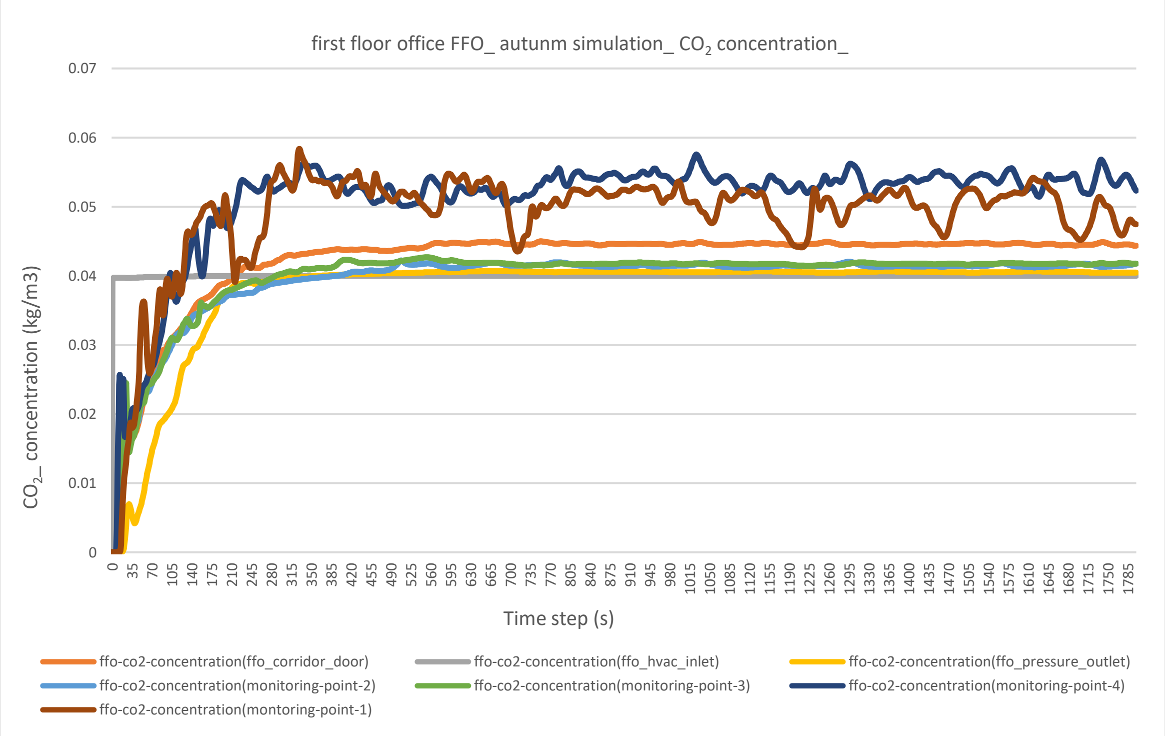


*Figure 5-81 FFO_ autumn/spring simulation_ CO2 concentration_*

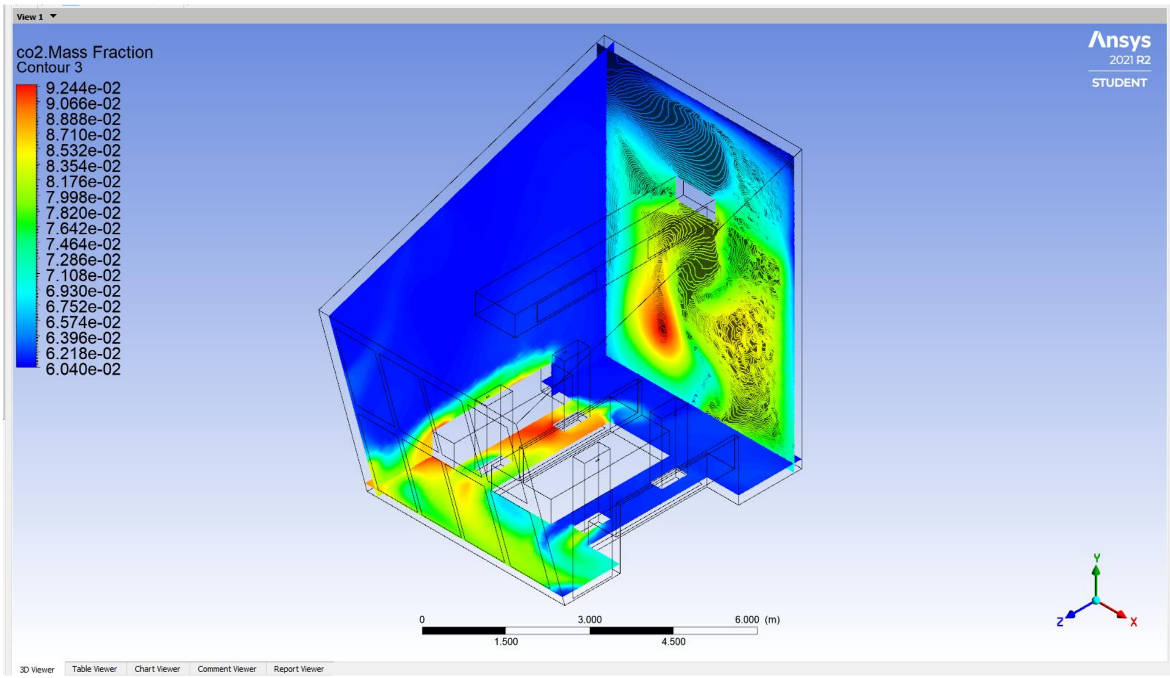


Figure 5-80 FFO 2-D surfaces illustrating the contour of ambient temperature_ Autumn/spring simulation

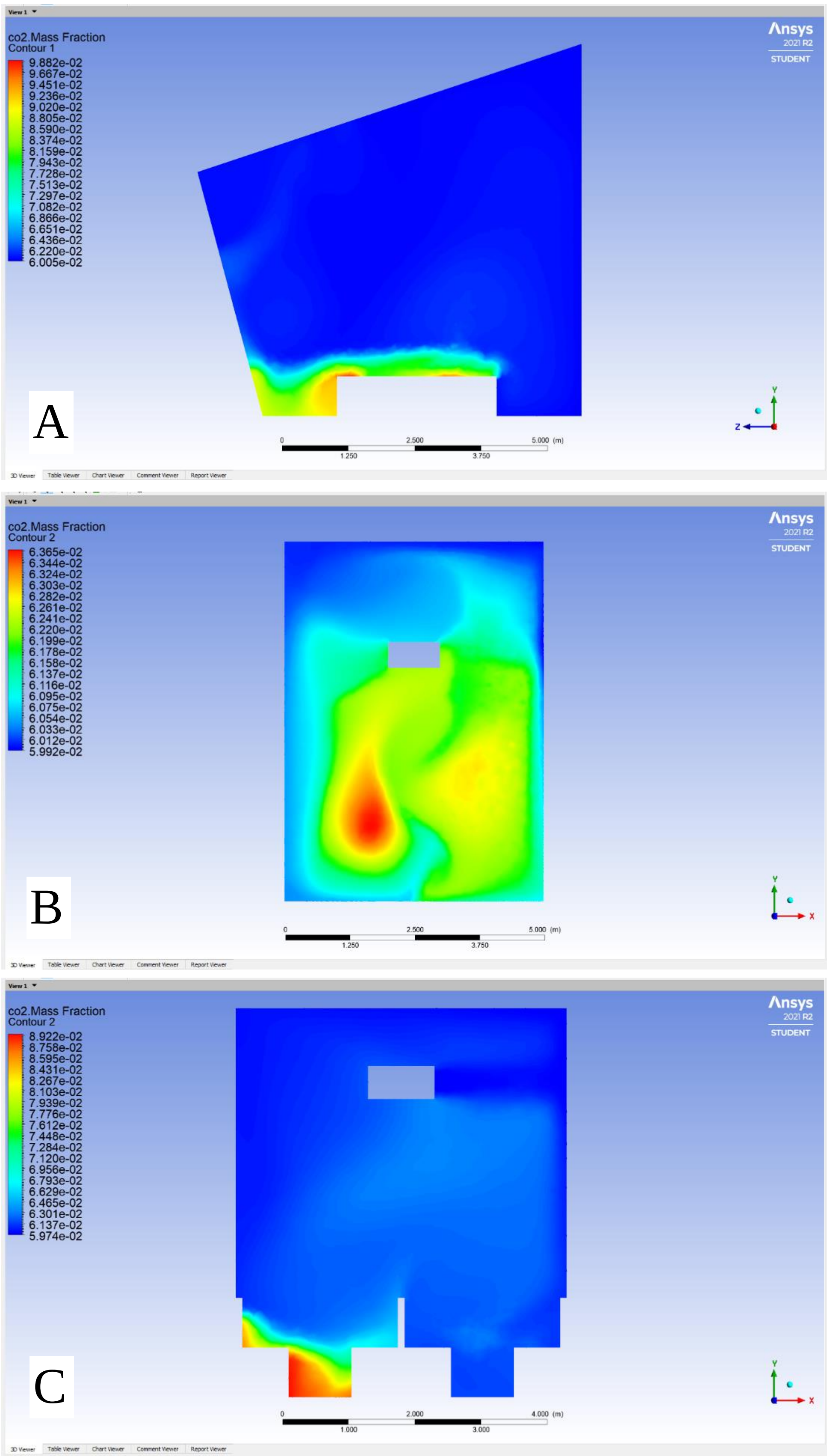


Figure 5-82 FFO_multiple 2-D surfaces illustrating the contour of ambient temperature_ Autumn/spring simulation

Table 5-26 FFO_ Autumn simulation_ CO_2 concentration

Monitoring points	CO2-concentration (CO2_inlet)	CO2-concentration (HVAC inlet)	CO2-concentration (pressure outlet)	CO2-concentration (monitoring-point-2)	CO2-concentration (monitoring-point-3)	CO2-concentration (monitoring-point-4)	CO2-concentration (montoring-point-1)
Average readings (ppm)	0.391	0.0399	0.0380	0.0394	0.0399	0.0510	0.0487

Interestingly, the concentration of CO_2 in the autumn/spring simulation has similar characteristics to the summer simulation. These two simulation results showed that the concentration of CO_2 is higher in the 1 and 4 monitoring point and lower in the 2 and 3 monitoring point. Another similar finding in both simulations shows that the area with the highest concentration of CO_2 was in the far right corner of the room. However, when analyzing all monitoring point individually they show that the concentration of CO_2 in the autumn/spring simulation in monitoring point 4 is slightly higher when compared with the same monitoring point from the summer simulation. One possible explanation is that the airflow could influence the concentration of CO_2 in a certain area of the room. For example, the concentration of CO_2 in monitoring point 4 in the autumn/spring simulation has an average CO_2 concentration of 510 ppm while in the summer simulation the same monitoring point has an average CO_2 concentration of 422 ppm. The difference in both situations is the characteristics of the airflow surrounding these areas. In the first condition (the autumn/spring simulation) a large sum of air is being extracted from the FFO crossing the area around monitoring point 4, therefore, carrying a large portion of CO_2 along the way. On the other hand, in the summer simulation, monitoring point 1 has a much larger concentration of CO_2 compared to the same monitoring point from the autumn/spring simulation. The same reasoning could be applied to this situation as well in which there is a large sum of air is entering the FFO from the exterior door. Also, there is the added effect of the MVHR air the also passes through monitoring point 1 that would lead both to an increase in the concentration of CO_2.

5.8 Eco-House (mark groups house)

The Eco-House is one of the energy efficient homes that were built on a hilltop in the University of Nottingham next to the architectural building called the Lenton Firs building. the building is a two-story building (ground floor, and first floor) in addition to a basement. The basement has an office space and an HVAC room. The ground floor has an open space office that encompasses six desks occupied by both students and researchers, a kitchen where the main measurement was taken.

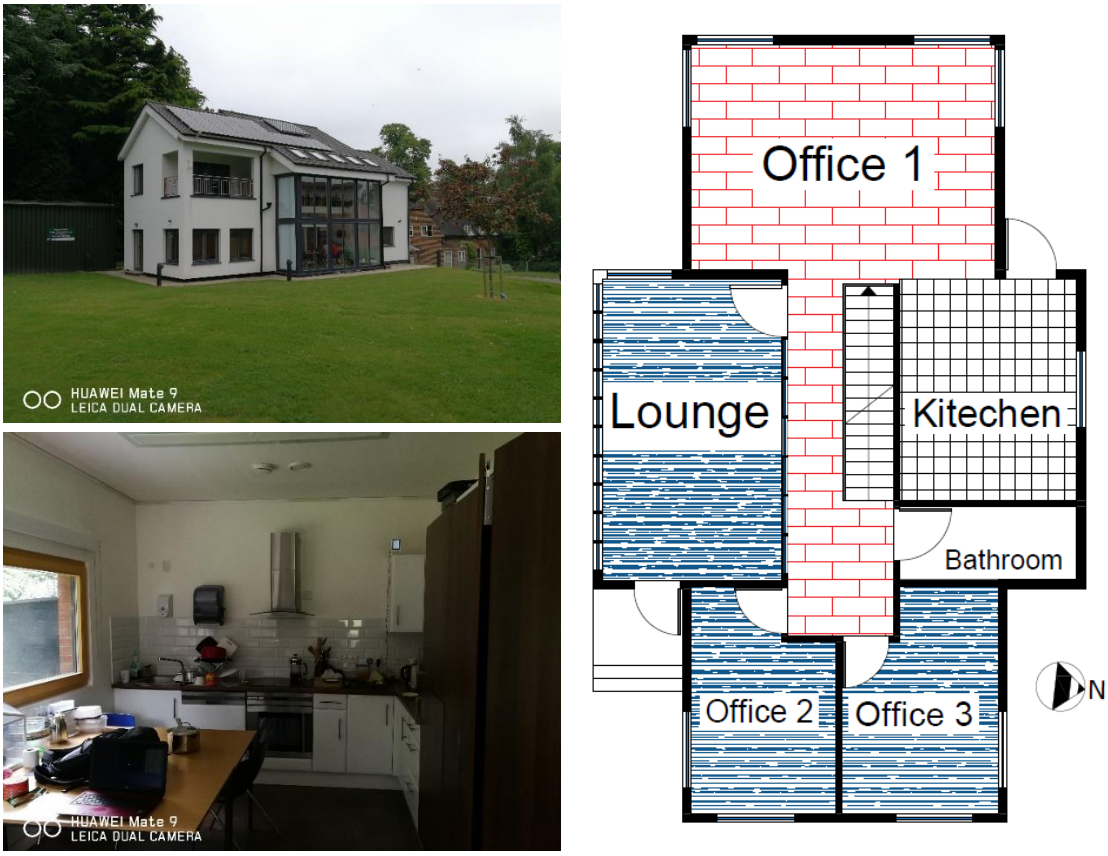


Figure 5-83 on the left hand side is the figure taken from the actual building, on the right hand side is the floor plan floor for the simulated

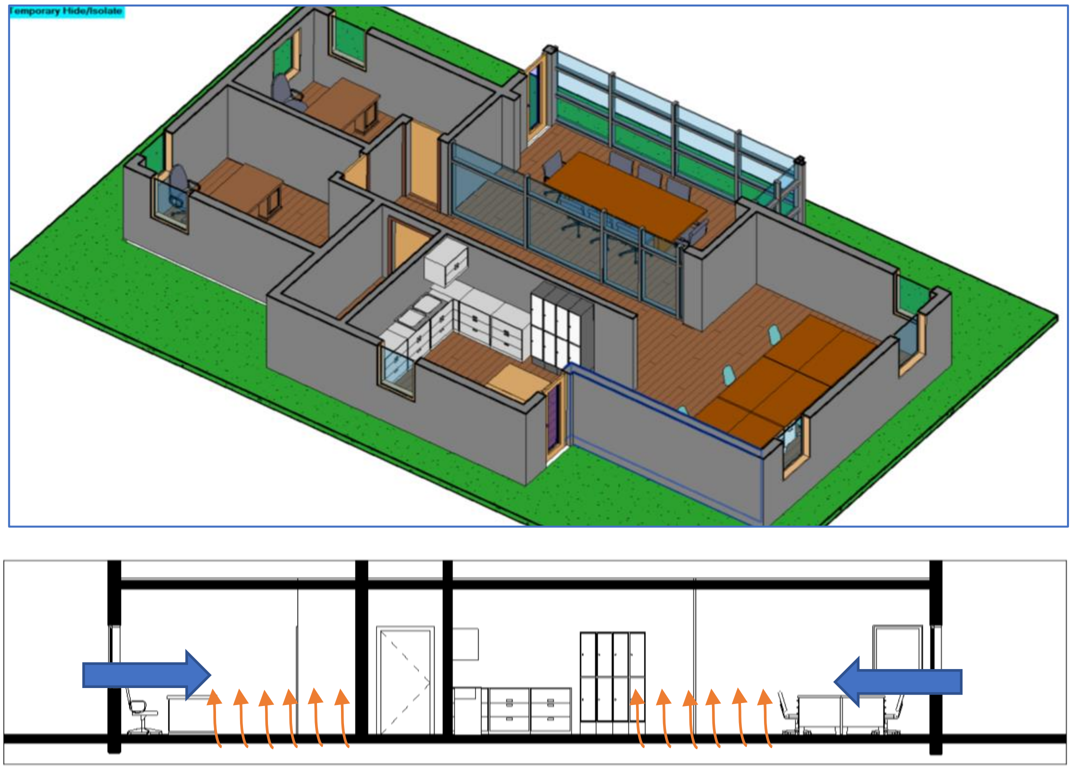


Figure 5-84 theupper picture shows a 3D-section of the floor plane, the lower picture shows the a 2D-section of the kitchen and the adjacent open office with digrams showing the airflow movement

The simulation model is comprised of several rooms that are connected together due to their shared influence on indoor air quality. The first room is the sunroom (or the lounge room) it is on the west side of the building and its houses a meeting table and is connected vertically to the upper hallway. The second room is the open space office (office1) (figure 5.85). This room contains six working station for student and researchers. The third space is the hallway that connects all the spaces together. The last room is the kitchen and it is where the monitoring devices were installed. The simulation model is comprised of 50592 with an average cell size of 12 centimetres tetrahedral cells with an aspect ratio of 1.163.

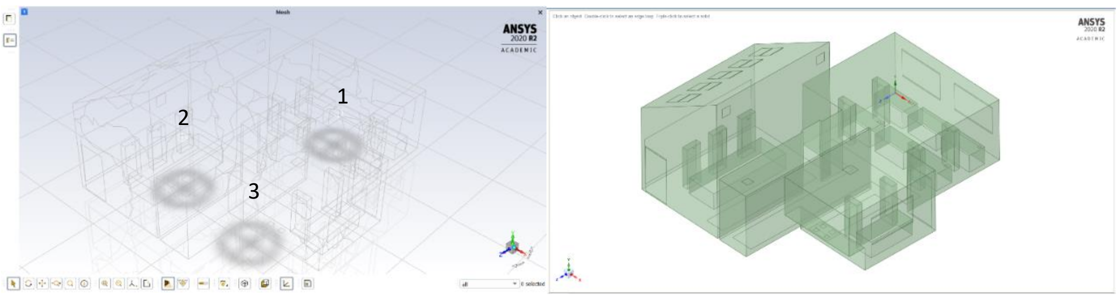
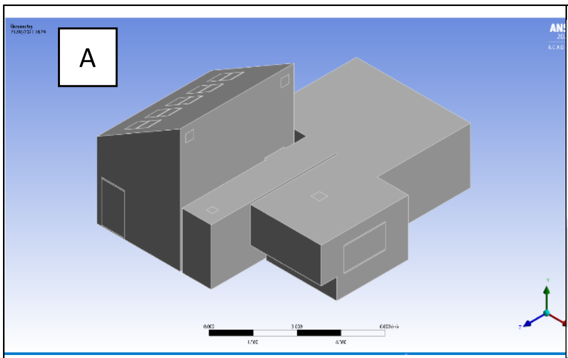
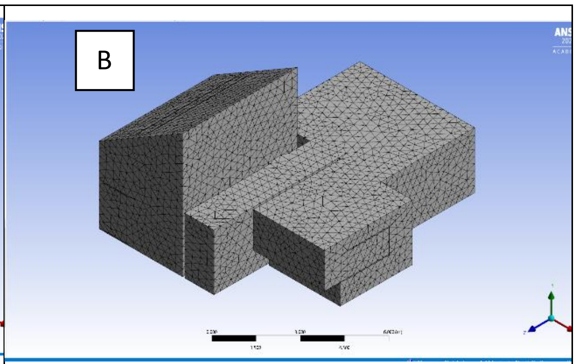
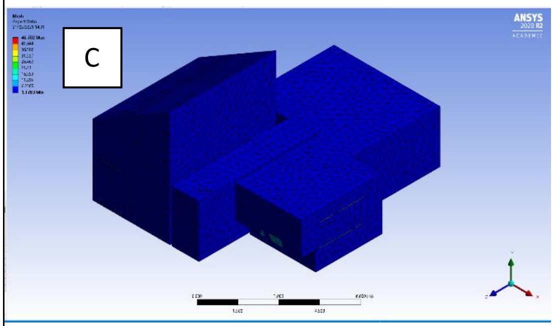
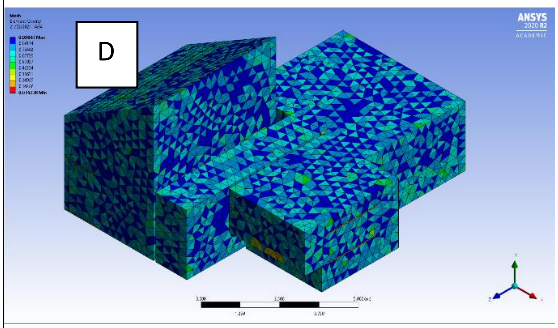
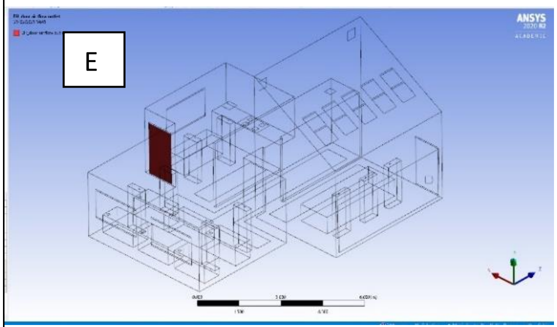
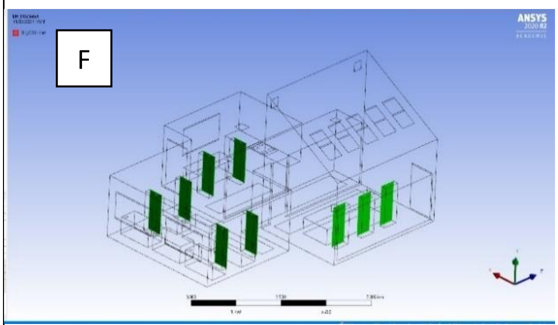
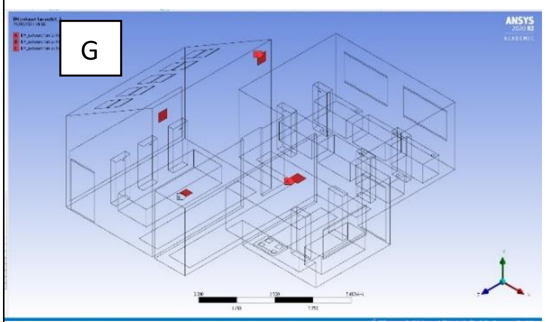
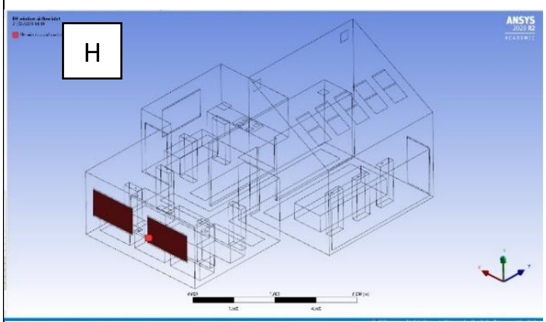


Figure 5-85 the right hand picture shows the location of the sensors, the left hand picture shows the 3-D model

Table 5-27 OSO simulation set up

	
	
	
	
These images represent the following: **A)** shows the 3-D geometry of the OSO, **B)** shows the mesh structure of the simulation model, **C)** shows the aspect ratio, **D** mesh quality, **E)** the exterior door, **F)** CO_2 inlet location, **G)** the extract fans **H)** border windows.	

5.9 EHS_Winter-simulation

5.9.1 EHS_winter simulation_PM concentration

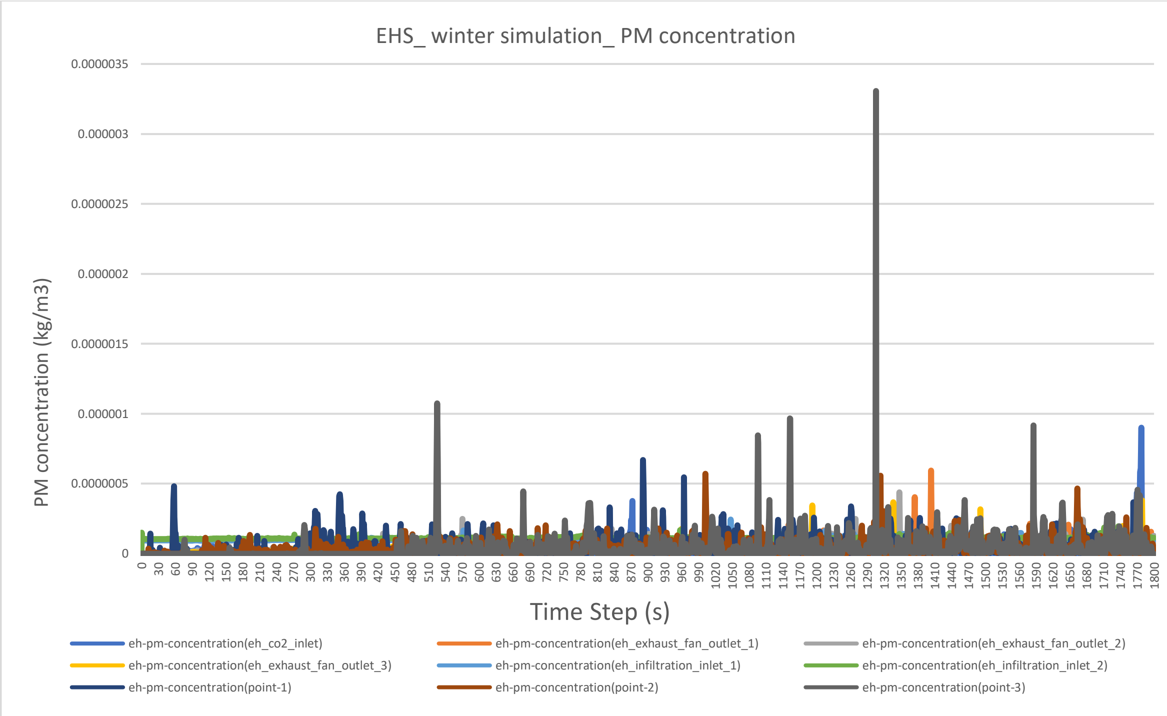


Figure 5-87 EHS_ winter simulation_ PM concentration

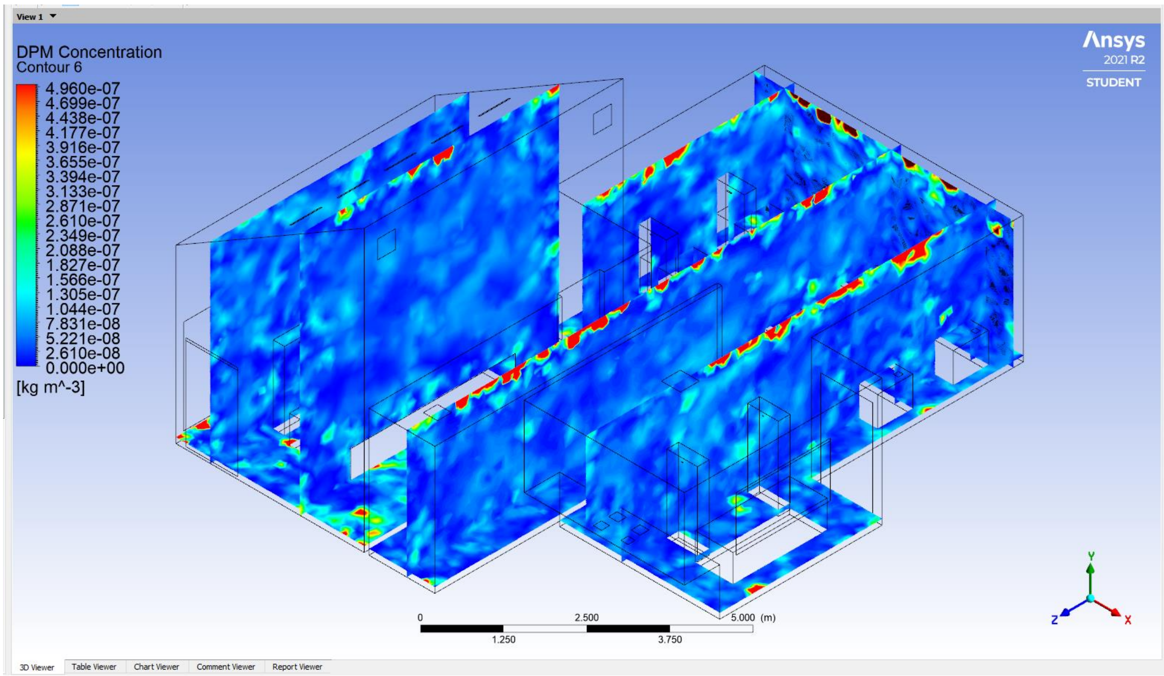


Figure 5-86 EHS_multiple 2-D surfaces illustrating the contour of (PM) concentration_ Winter simulation

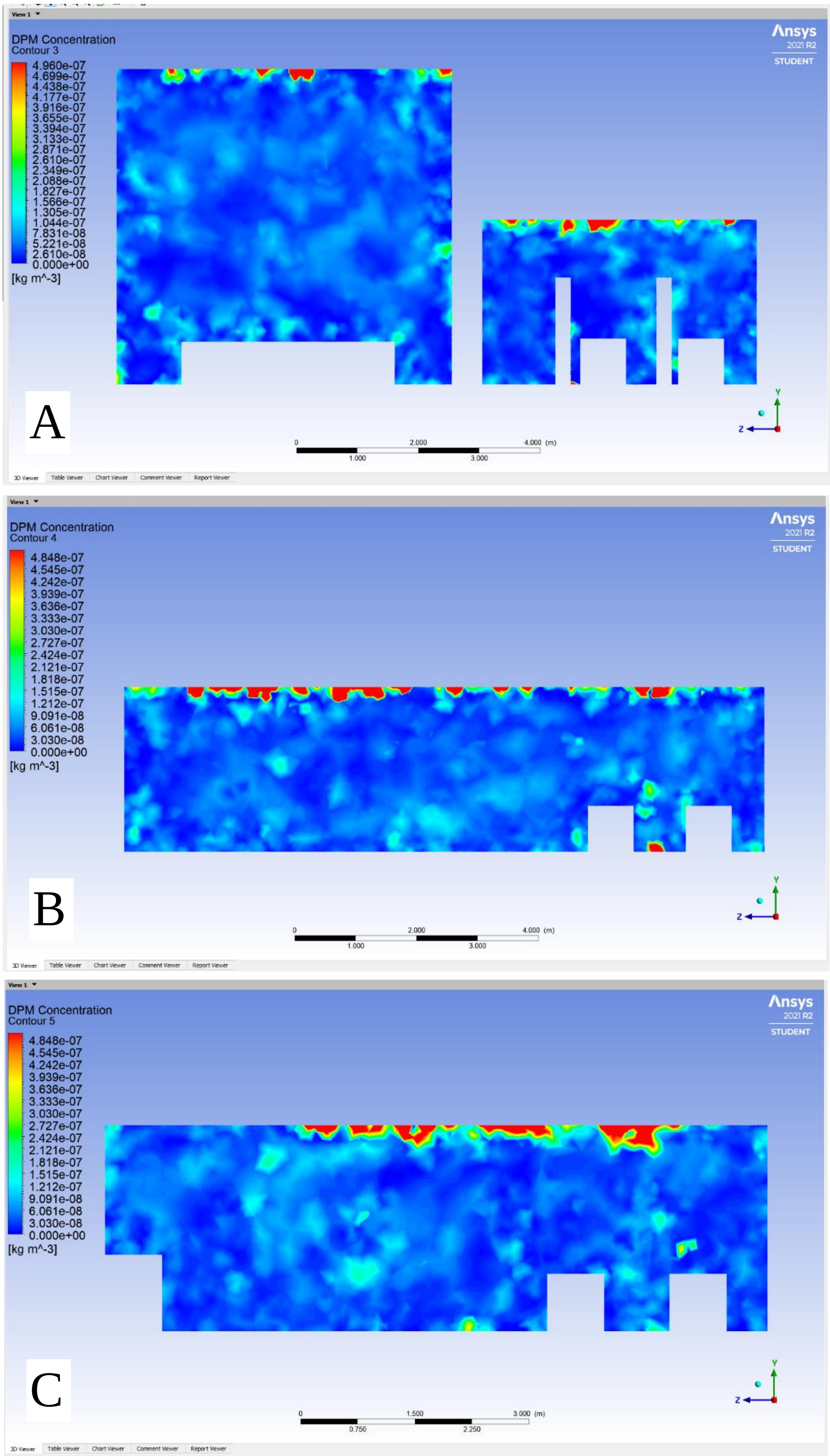


Figure 5-88 EHS_multiple 2-D surfaces illustrating the contour of (PM) concentration_ Winter simulation

Table 5-28 EHS_ winter simulation_ PM concentration

Monitoring points	PM concentration (exhaust fan outlet 1)	PM concentration (exhaust fan outlet 2)	PM concentration (exhaust fan outlet 3)	PM concentration (Infiltration inlet 1)	PM concentration (point-1)	PM concentration (point-2)	PM concentration (point-3)
Average readings (Kg/m^3)	3.278E-08	3.937E-08	4.069E-08	1.044E-07	4.215E-08	3.650E-08	3.939E-08

The Eco-House is a separate building from the chemistry building. The building relies mostly on natural ventilation. Therefore, the airflow inside the space is distinctly different from the chemistry building. the sources of PM inside the space were the infiltration from windows and doors and floor particle resuspension. The floors are covered in wood which does not allow the particles to adhere to them very often. From looking at the 2-D surface in figure (5.88) contour for the PM concentration it could be said that the particles are not spread evenly throughout the entire room. There are some areas of very high concentration and other areas where there is almost no presence of PM is detected. The difference between these areas is overt and it is uniquely different from the chemistry building. The reason for that could be the absence of the HVAC system. The HVAC system moves the particle constantly, thus allowing the air to carry more particles along the way. What could also be determined from looking at the result of the simulation from figure (5.87) is that these cluster of particles are mostly gathered at the upper part of the room. However, when looking at the average readings from all three monitoring points, they show that the concentration of PM in these three monitoring points are very similar. The highest average concentration of PM is near monitoring point 1 with an average concentration of 42 $\mu g/m^3$. When compared to the concentration of PM near monitoring point 2 (36 $\mu g/m^3$) it is clear that the former has a higher level of PM concentration because it is closer to a source of PM injection.

5.9.2 EHS_winter simulation_ Ambient temperature

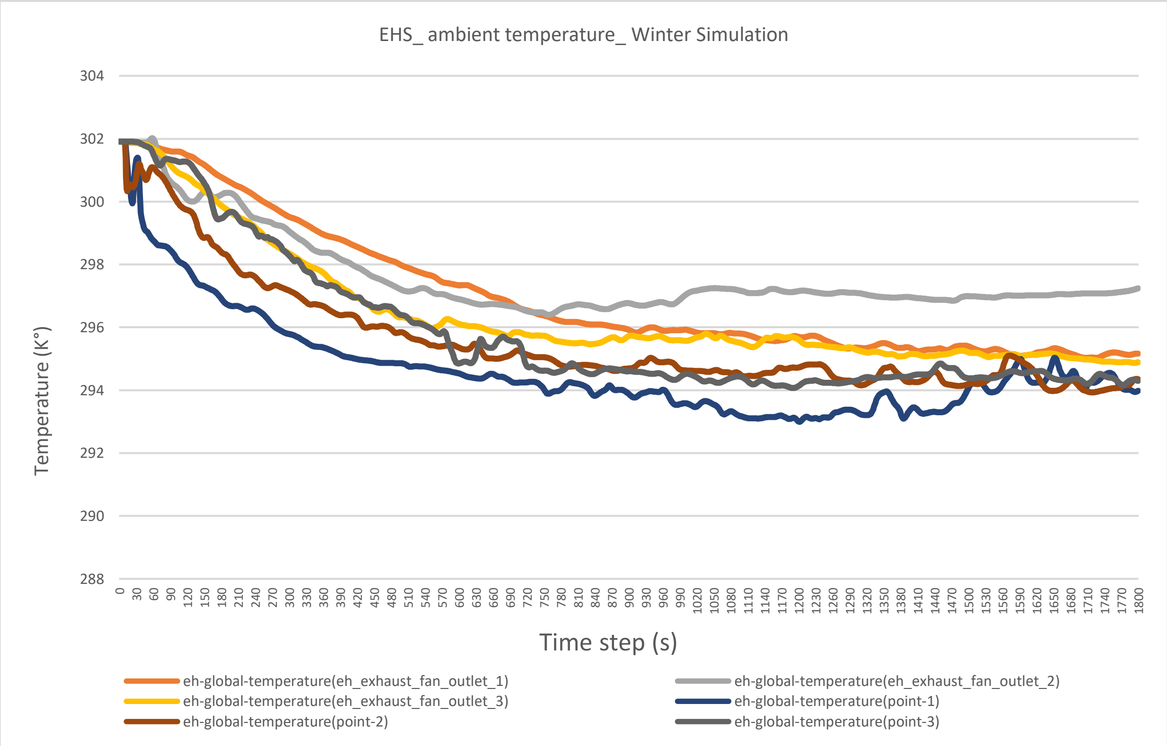


Figure 5-89 EHS_ ambient temperature_ Winter Simulation

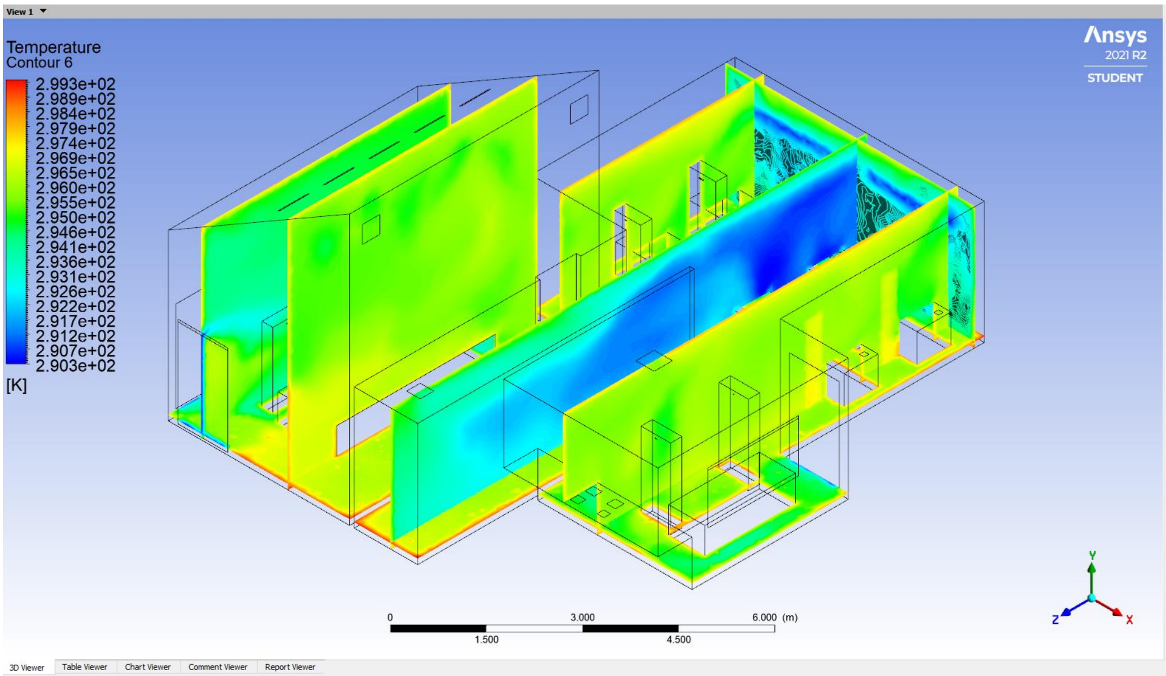


Figure 5-90 EHS _multiple 2-D surfaces illustrating the contour of ambient temperature_ Winter simulation

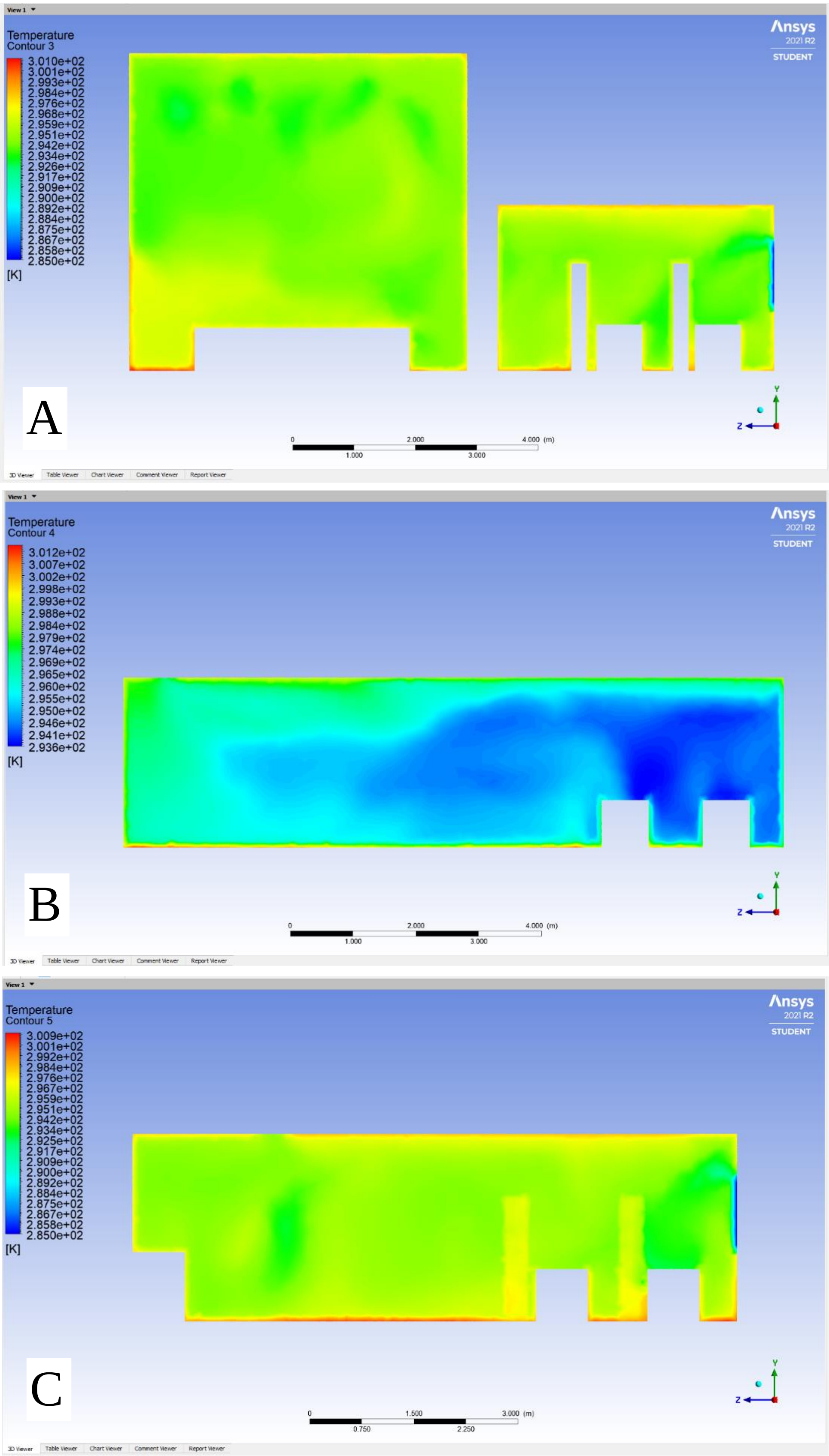


Figure 5-91 EHS _multiple 2-D surfaces illustrating the contour of ambient temperature_ Winter simulation

Table 5-29 EHS_ ambient temperature_ Winter Simulation

Monitoring points	Ambient Temperature (exhaust fan outlet 1)	Ambient Temperature (exhaust fan outlet 2)	Ambient Temperature (exhaust fan outlet 3)	Ambient Temperature (infiltration inlet 1)	Ambient Temperature (point-1)	Ambient Temperature (point-2)	Ambient Temperature (point-3)
Average readings (Kelvin)	297.042	297.653	296.476	290	294.693	295.601	295.863

The heating system in the Eco-House is different from the chemistry building in which the space is heated by radiant floor heating. The radiant floor heats up the space by the use of radiant tubes. These tubes are connected to a heating system that is located outside of the building. This heating system works mainly in the winter system. The average temperature taken from the three monitoring points shows that the average temperature in the EHS is around 294 CK (20 °C) table (5-29). That is also apparent from looking at the contour surfaces in figure (5.91) where it demonstrates that the heat is coming from the radiant floor and then it rises up until it reaches the ceiling.

5.9.3 EHS_winter simulation_ Airflow velocity

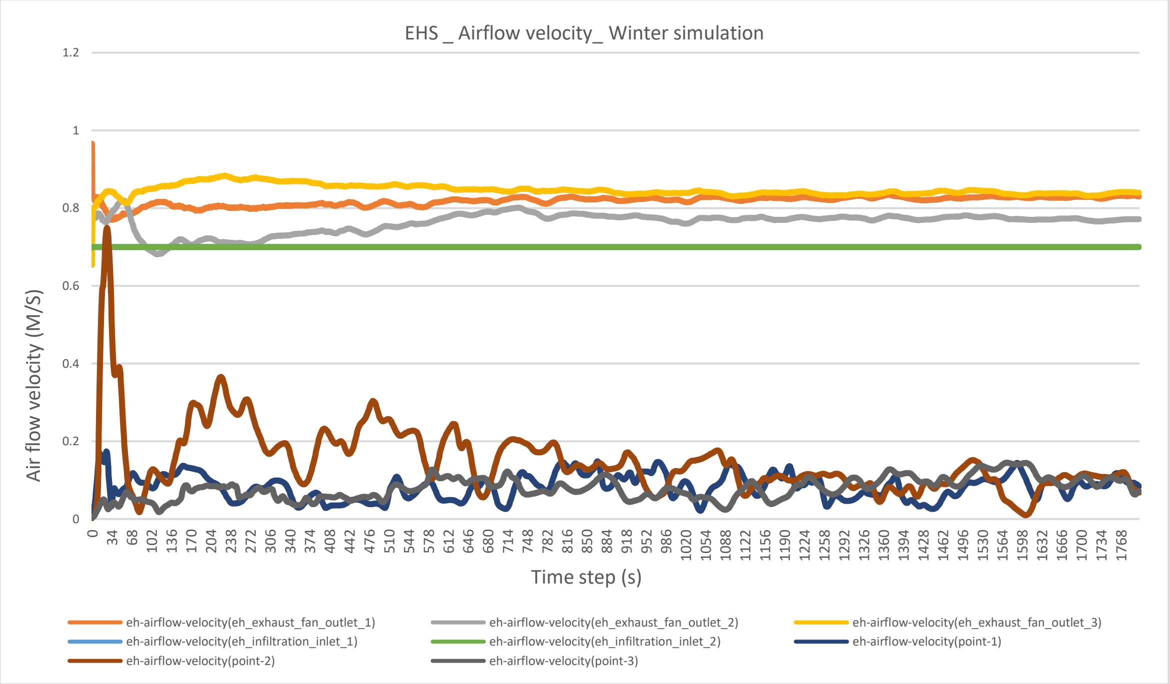


Figure 5-92 EHS _ Airflow velocity_ Winter simulation

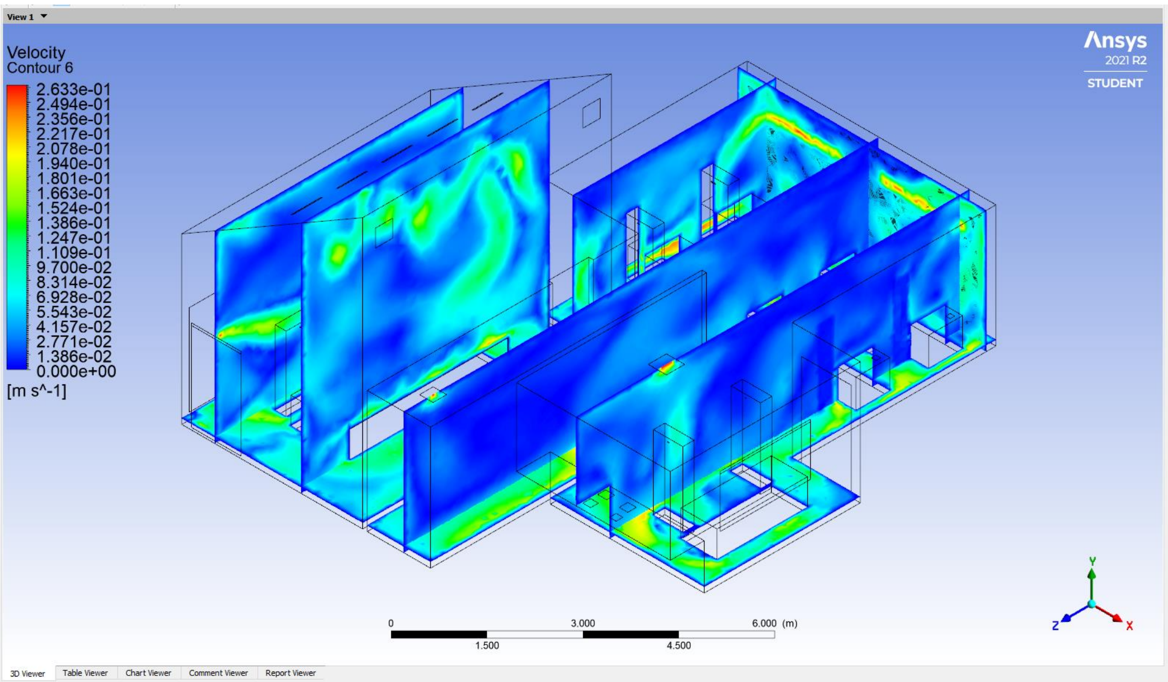


Figure 5-93 EHS_multiple 2-D surfaces illustrating the contour of airflow velocity_ Winter simulation

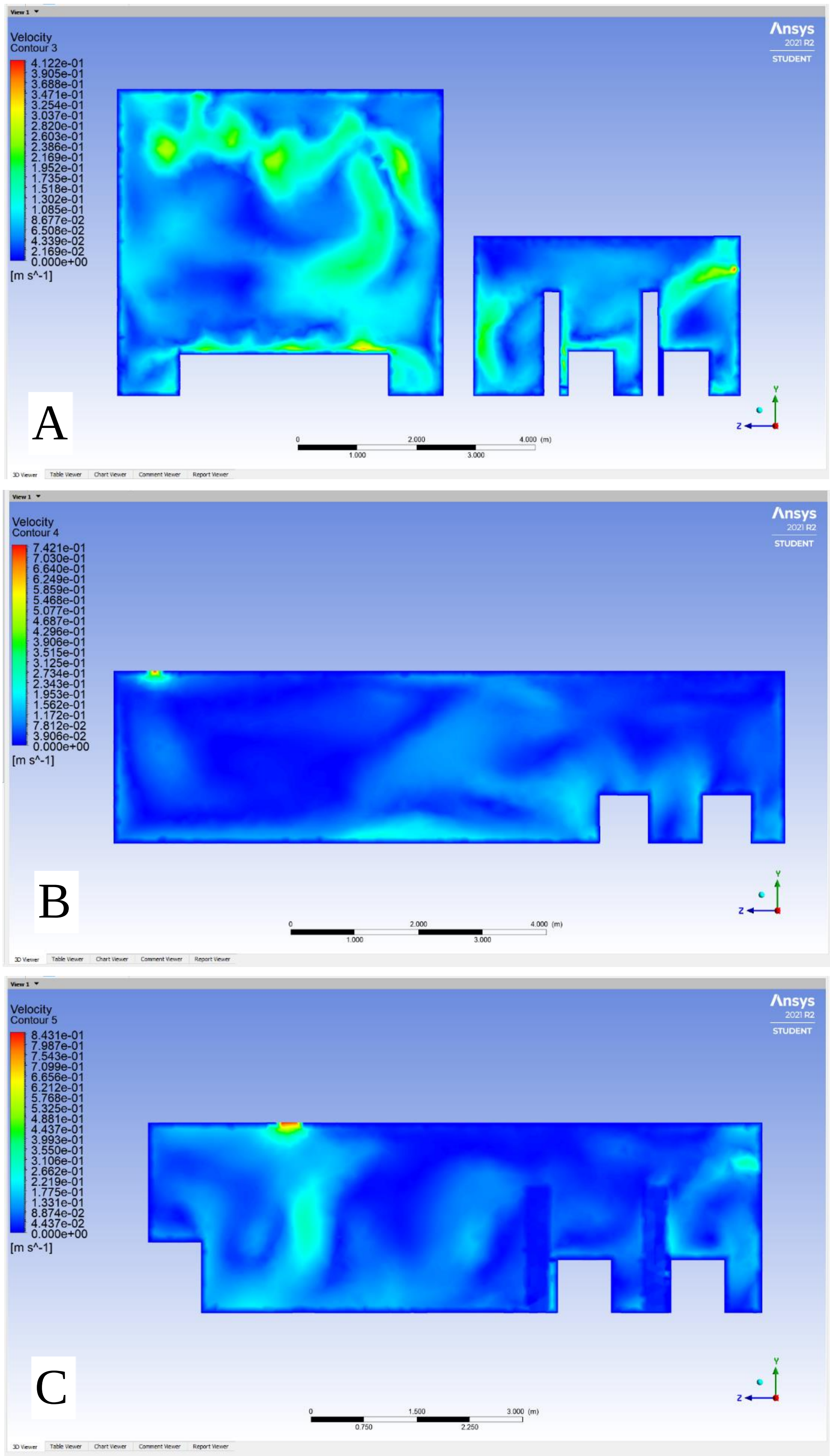


Figure 5-94 EHS_multiple 2-D surfaces illustrating the contour of airflow velocity_ Winter simulation

Table 5-30 EHS _ Airflow velocity_ Winter simulation

Monitoring points	Airflow-velocity (exhaust fan outlet 1)	Airflow-velocity (exhaust fan outlet 2)	Airflow-velocity (exhaust fan outlet 3)	Airflow-velocity (Infiltration inlet 1)	Airflow-velocity (point-1)	Airflow-velocity (point-2)	Airflow-velocity (point-3)
Average readings (m/s)	0.818	0.762	0.846	0.699	0.083	0.149	0.079

As stated before, the airflow in the Eco-House is very different from the airflow in the chemistry building. the Eco-House relies mostly on natural ventilation with extract fans located in the kitchen and other parts of the building. Therefore, airflow velocity is very low in comparison with the airflow in the chemistry building. another problem that might thwart the air movement inside the EHS is the fact that all doors and windows are closed all the time. There are, however, many incidences where people frequently open the door. As soon as the door is open a large flow of air enters the building that mixes with the existing air inside the space. The kitchen area in particular has the lowest airflow velocity around 0.07 m/s. this rate of airflow velocity is very low and it does not reach the optimum standard set by the CIBSE which is around 0.1 – 0.4 m/s. The highest airflow velocity was registered near monitoring point 2 around 0.14 m/s. This is because the sensor is located close to the windows with a small opening in which air is allowed to pass through. The small opening represents the effect of air infiltration.

5.9.4 EHS_winter simulation_CO_2 concentration

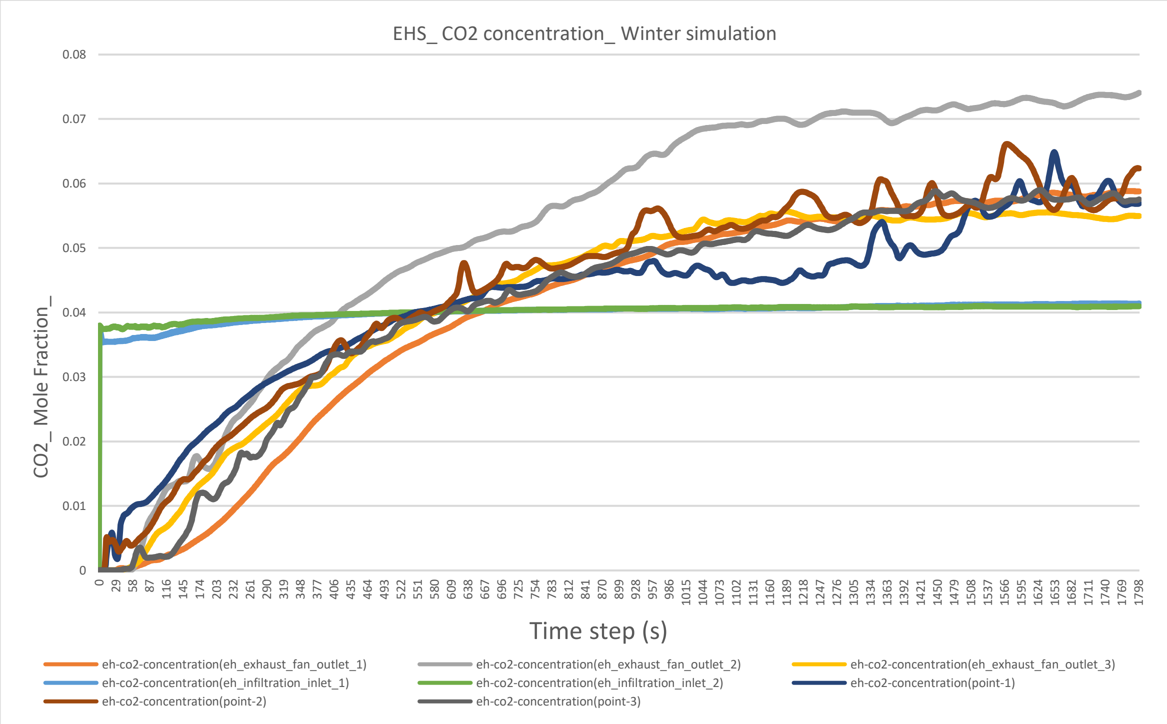


Figure 5-96 EHS_ CO2 concentration_ Winter simulation

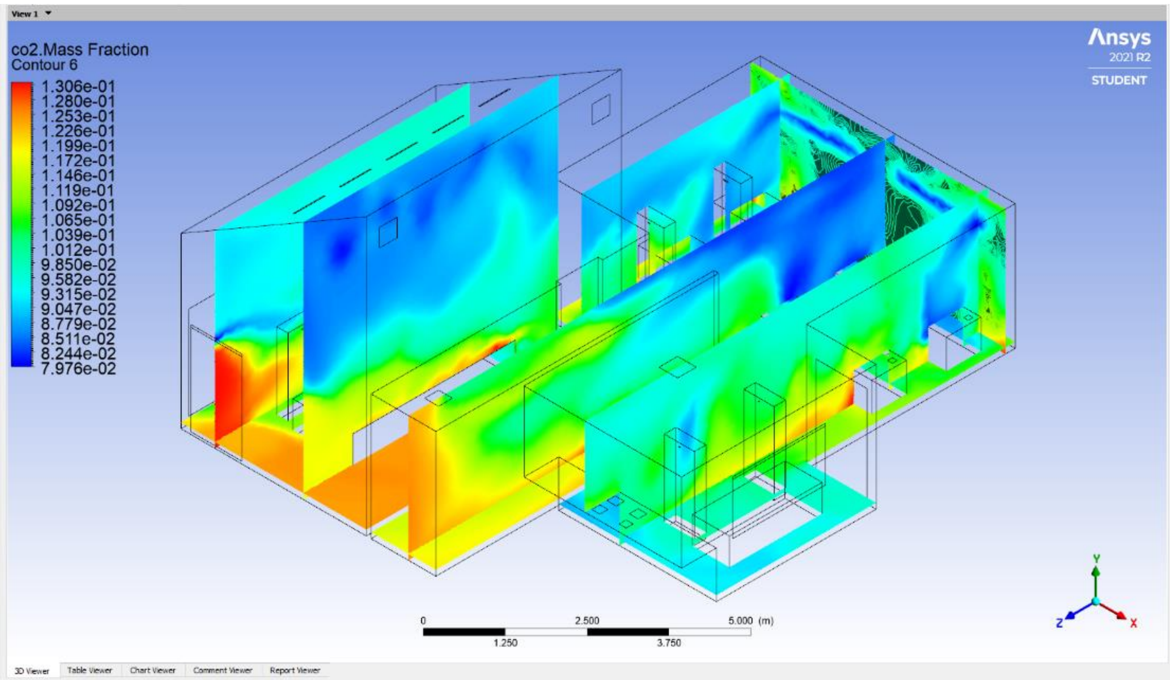


Figure 5-95 EHS_multiple 2-D surfaces illustrating the contour of ambient temperature_ Winter simulation

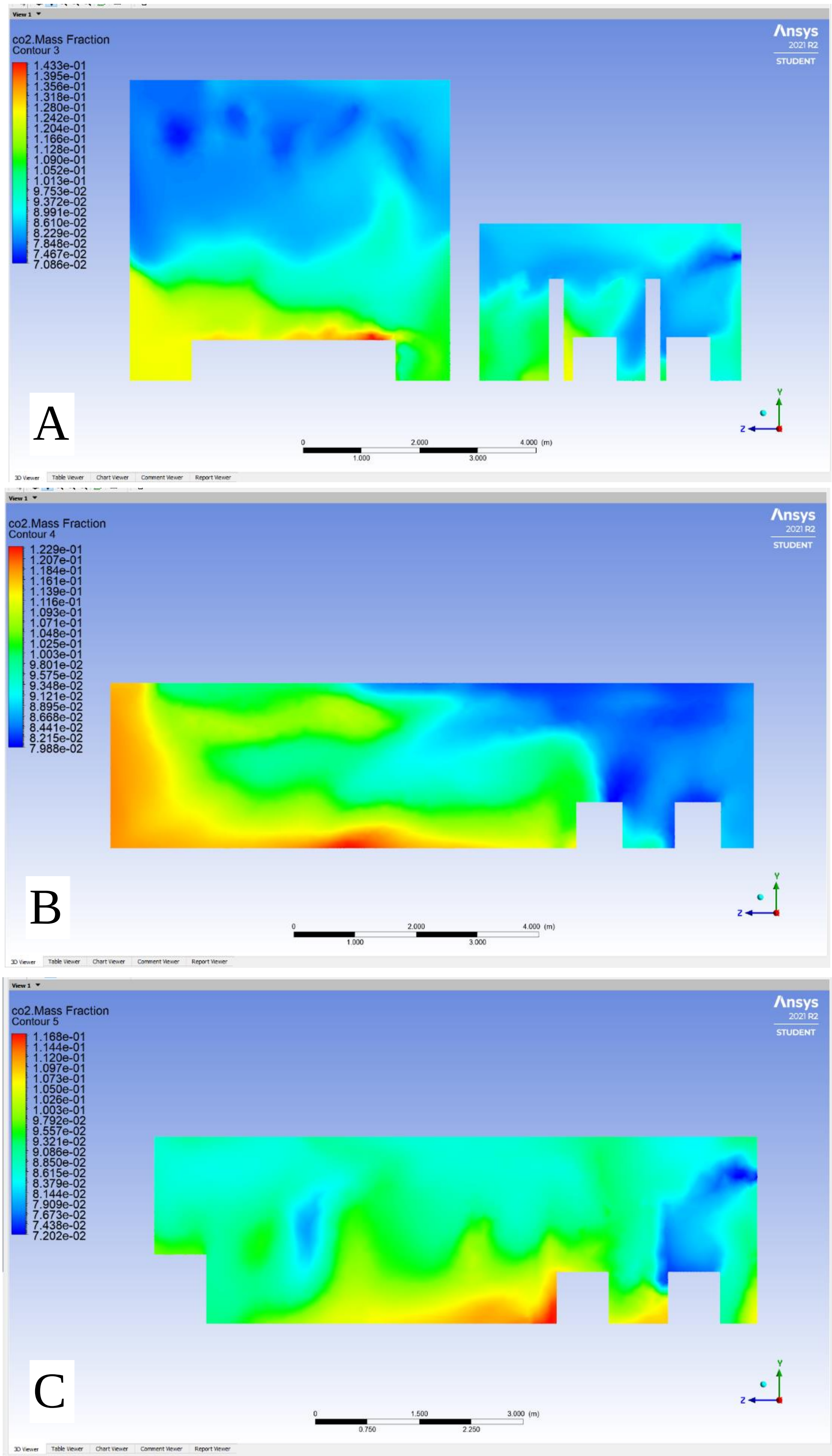


Figure 5-97 EHS_multiple 2-D surfaces illustrating the contour of ambient temperature_ Winter simulation

Table 5-31 EHS _ CO_2 concentration_ Winter simulation

Monitoring points	CO2 concentration (co2 inlet)	CO2 concentration (exhaust fan outlet 1)	CO2 concentration (infiltration inlet 1)	CO2 concentration (point-1)	CO2 concentration (point-2)	CO2 concentration (point-3)
Average readings (ppm)	0.359	0.0402	0.0399	0.0417	0.044	0.0414

Just like the previous models, the Eco-House has two main sources of CO_2. The first is the Human model and the second is the airflow coming from outside of the model. Since the airflow in the EHS is very much stale, the CO_2 concentration is almost the same in the entire model. The highest recorded area was near monitoring point 2 around 440 ppm. Because the air is not moving as much in comparison to other models, a large concentration of CO_2 is residing near the ground. This is evident in figure (5.97) where it shows that the concentration of CO_2 is higher near the floor areas than in other regions. One important thing to note is that the position of sensor 3 is higher than the other monitoring points at a height of 1.8 meters. That might explain why even though there is very little air moving inside the region, the CO_2 concentration is still not as high as was expected.

5.10 Summer simulation

5.10.1 EHS_Summer simulation_(PM) concentration

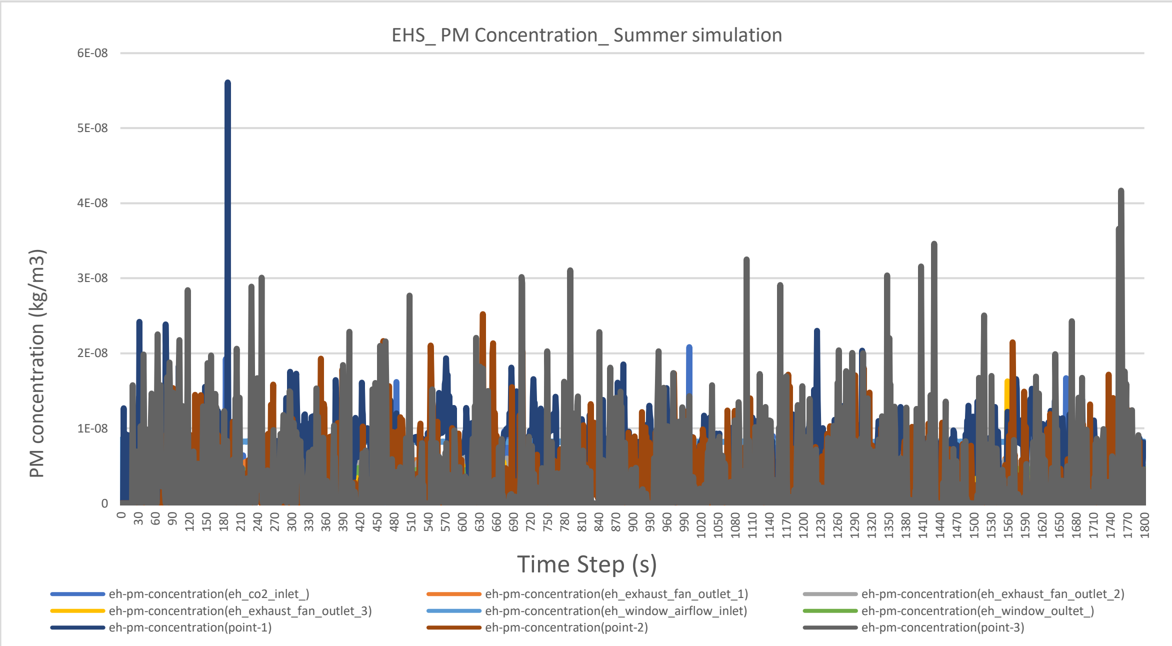


Figure 5-99 EHS_ PM Concentration_ Summer simulation

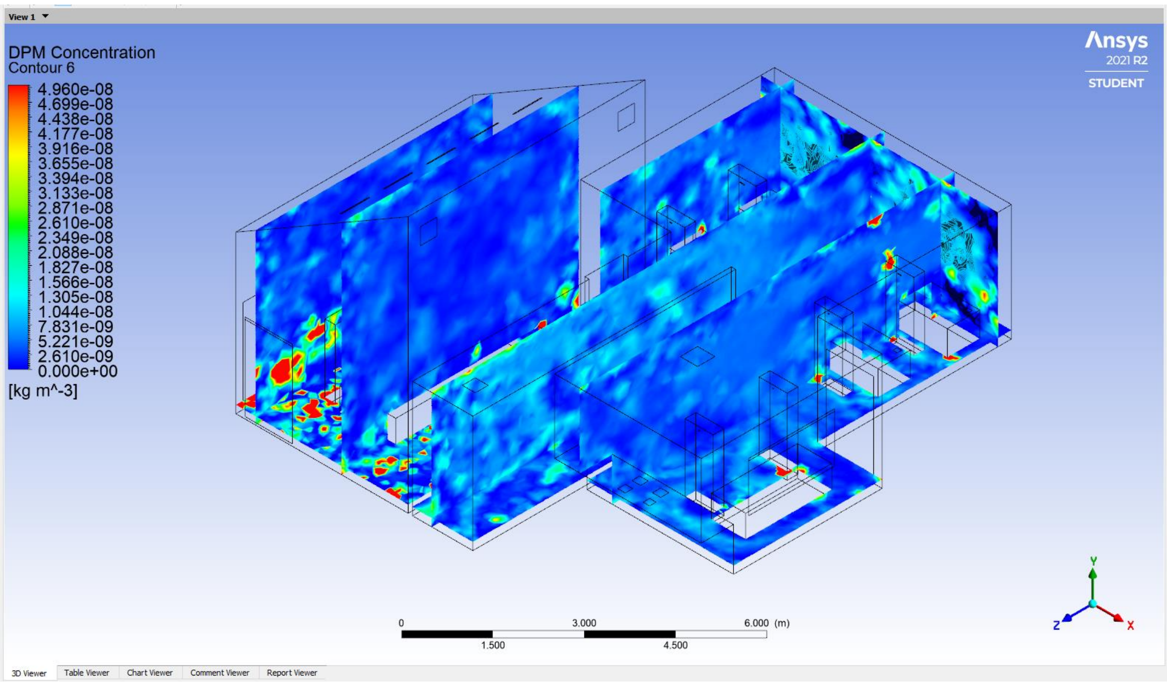


Figure 5-98 EHS 2-D surfaces illustrating the contour of (PM) concentration_ Winter simulation

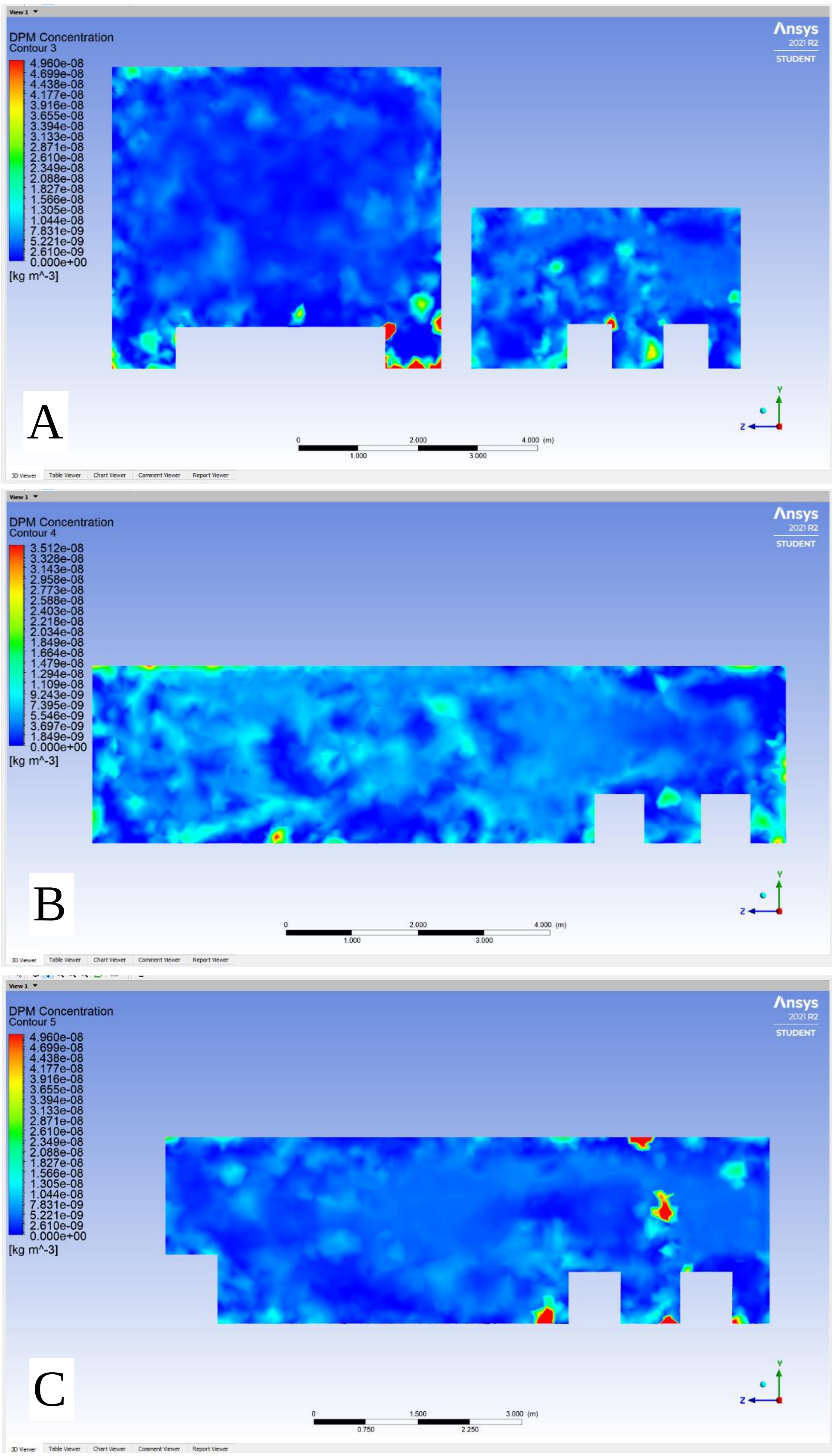


Figure 5-101 multiple EHS 2-D surfaces illustrating the contour of (PM) concentration_ Winter simulation

Table 5-32 EHS_ PM Concentration_ Summer simulation

Monitoring points	PM concentration (exhaust fan 1)	PM concentration (exhaust fan 2)	PM concentration (exhaust fan 3)	PM concentration (window airflow inlet)	PM concentration (point-1)	PM concentration (point-2)	PM concentration (point-3)
Average readings (Kg/m^3)	4.085E-09	4.342E-09	3.272E-09	8.203E-09	5.917E-09	2.298E-09	2.971E-09

The summer condition is vastly different from the winter condition. During the summer period, all the windows are kept open all the time. This had allowed a large quantity of air to enter the building and allowed for cross ventilation to take place inside the EHS. When comparing the concentration of PM from the winter simulation, the results show that the concentration of PM in the summer is significantly lower. Starting from monitoring point 1 which is located near the open space office. The concentration in the summer period in this region is 5.9 $\mu g/m^3$ compared to 42 $\mu g/m^3$ from the same monitoring point. The second monitoring point (2) is located near the lounge room area. The concentration in the summer simulation is around 2.2 $\mu g/m^3$ compared to 36 $\mu g/m^3$ in the winter simulation of the same monitoring point. The third monitoring point is located near the kitchen. The summer simulation showed that the concentration of PM was 2.9 $\mu g/m^3$ compared to 39 $\mu g/m^3$. The aforementioned readings show that the air movement in the summer period has affected the concentration of the PM drastically. Not only that but it also reveals in figure (5.101) that the concentration of PM is spread much more evenly throughout the EHS with fewer areas of high PM concentration and others with much lower concentration.

5.10.2 EHS_Summer simulation_ Ambient Temperature

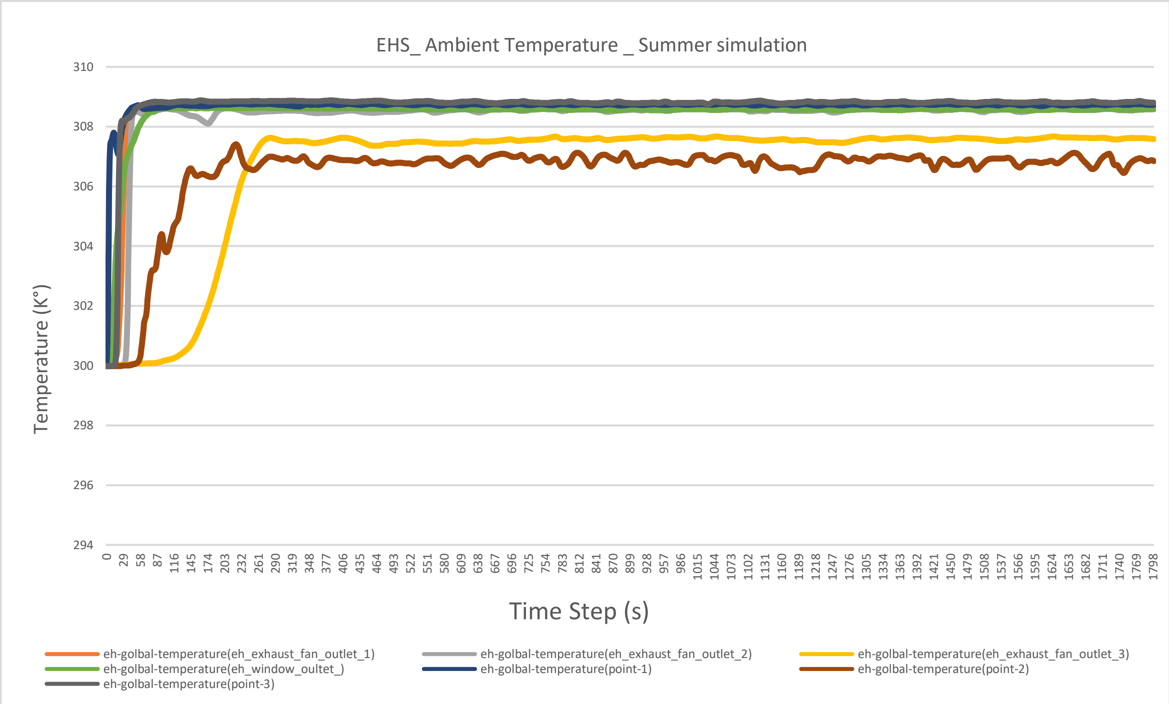


Figure 5-102 EHS_ Ambient Temperature _ Summer simulation

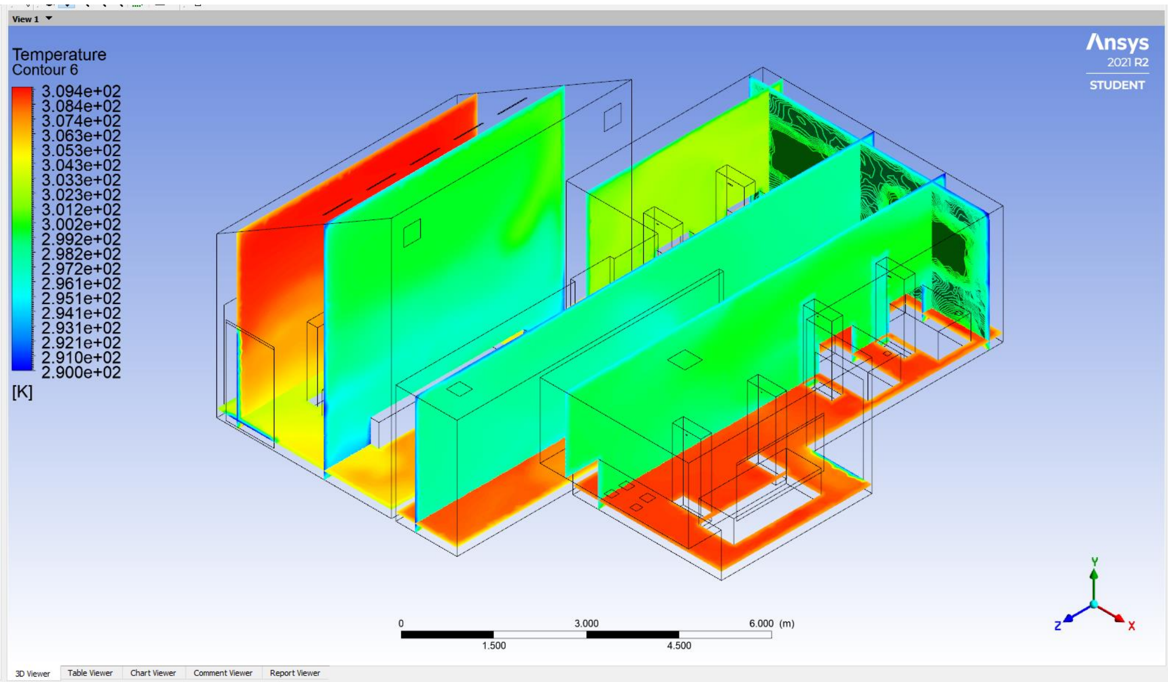


Figure 5-103 EHS_ Winter simulation_2-D surfaces illustrating the contour of ambient temperature

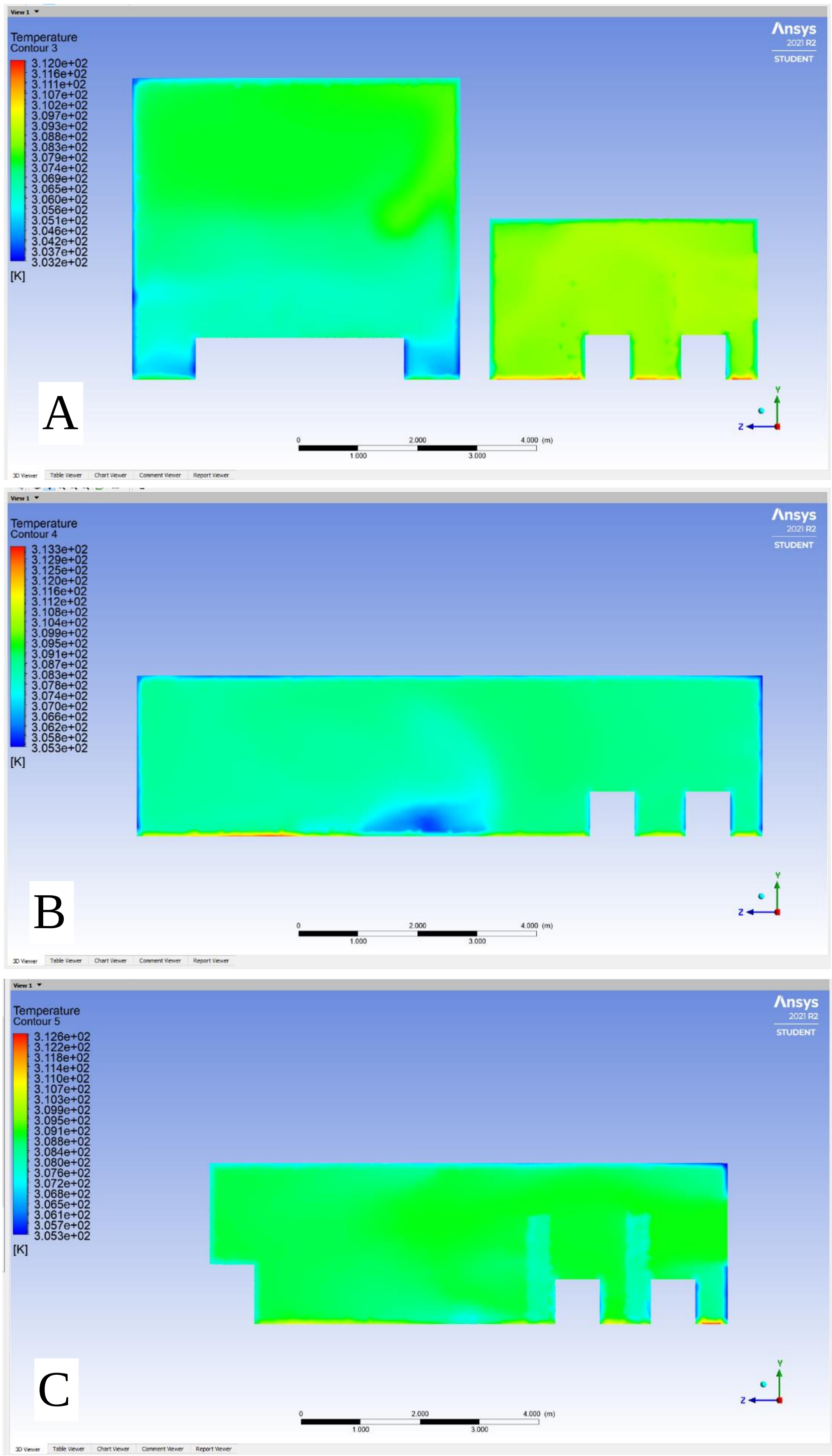


Figure 5-104 EHS_ Winter simulation_2-D surfaces illustrating the contour of ambient temperature

Table 5-33 EHS_ Ambient Temperature _ Summer simulation

Monitoring points	Ambient Temperature (exhaust fan 1)	Ambient Temperature (exhaust fan 2)	Ambient Temperature (exhaust fan 3)	Ambient Temperature (point-1)	Ambient Temperature (point-2)	Ambient Temperature (point-3)
Average readings (Kelvin)	308.545	308.363	306.733	308.690	306.485	308.709

The ambient temperature in the summer period is much higher than in the winter period. Since EHS relies on natural ventilation, the ambient temperature inside the EHS is very similar to the outside ambient temperature. The average recorded ambient temperature inside the EHS is around 308 °K (34 °C) which is very close to the highest temperature in the summer period. The lowest recorded temperature is near monitoring point 2 in the lounge room. The reason being is that the is a source of air coming from the outside of the building.

5.10.3 EHS_Summer simulation_ Airflow velocity

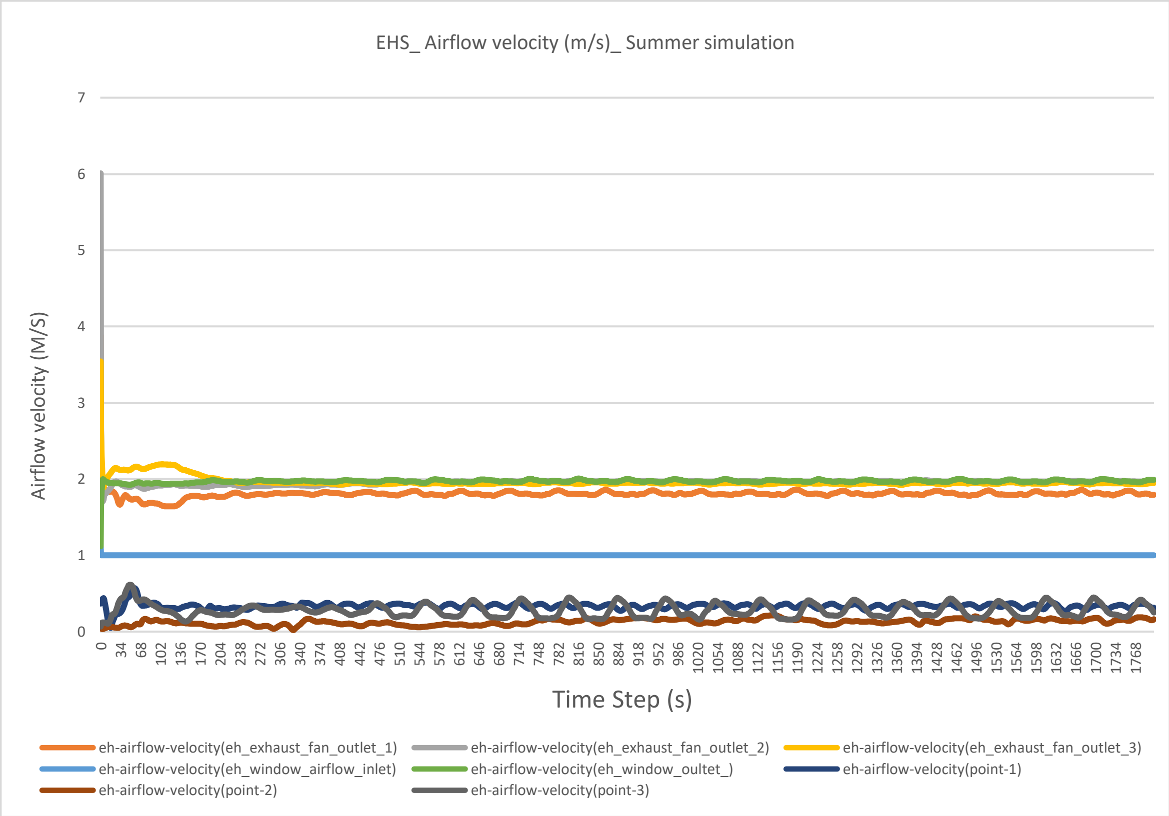


Figure 5-105 EHS_ Airflow velocity (m/s) _ Summer simulation

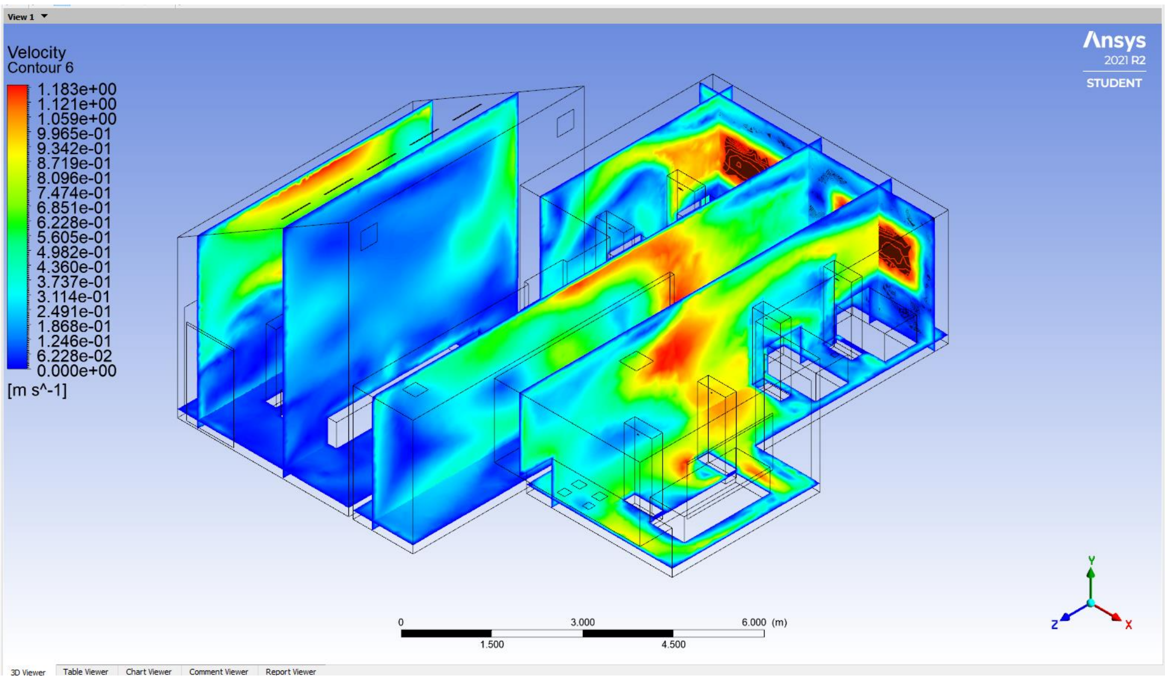


Figure 5-106 EHS_multiple 2-D surfaces illustrating the contour of airflow velocity_ Summer simulation

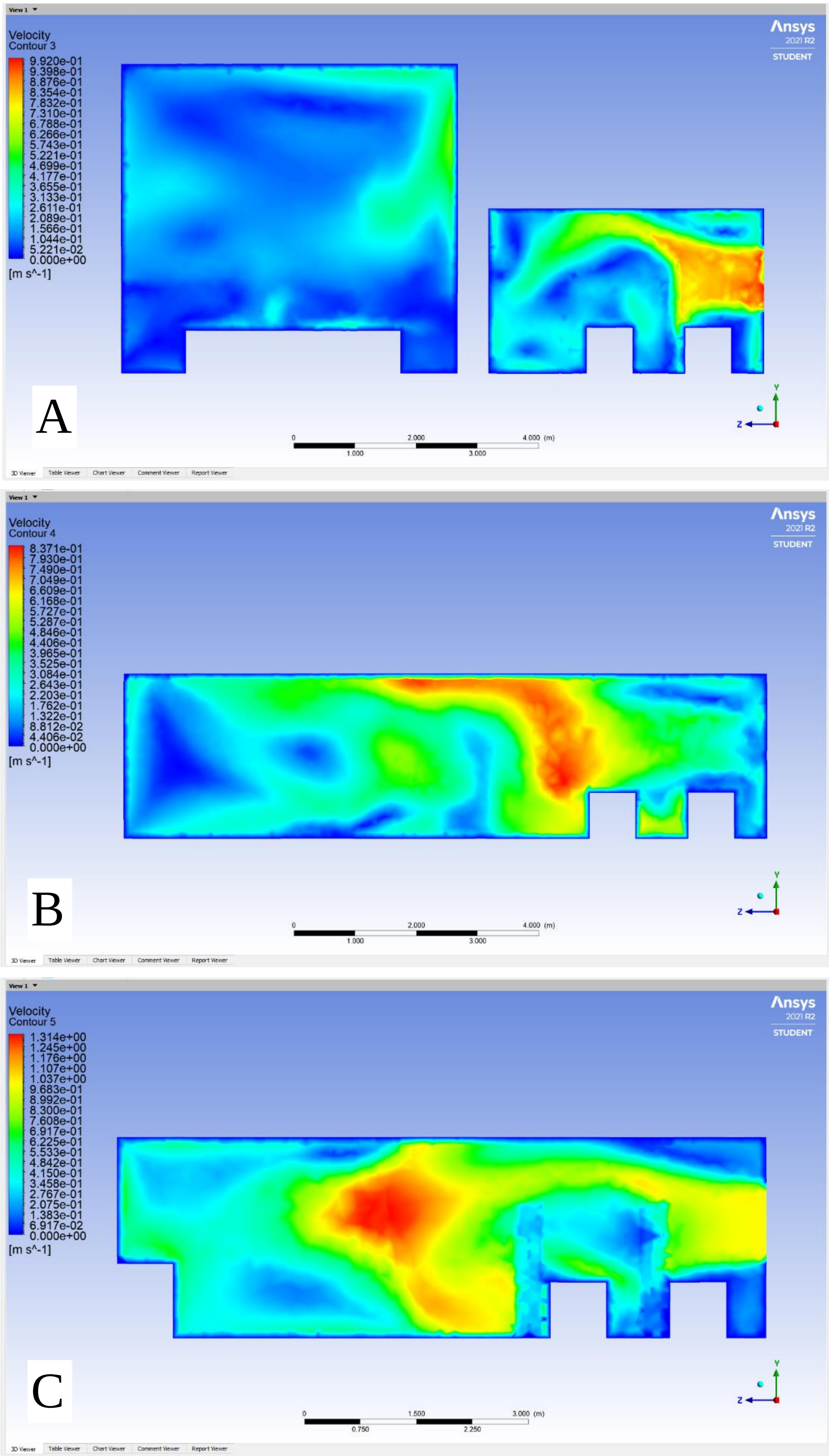


Figure 5-107 EHS_multiple 2-D surfaces illustrating the contour of airflow velocity_ Summer simulation

Table 5-34 EHS_ Airflow velocity (m/s) _ Summer simulation

Monitoring points	Airflow-velocity (exhaust fan 1)	Airflow-velocity (exhaust fan 2)	Airflow-velocity (eh exhaust fan3)	Airflow-velocity (window airflow inlet)	Airflow-velocity (point-1)	Airflow-velocity (point-2)	Airflow-velocity (point-3)
Average readings (m/s)	1.803	1.955	1.964	1.000	0.335	0.125	0.278

The opening of the windows in the summer period has allowed for air to enter the building. this phenomenon has increased the airflow velocity in all regions of the EHS. Starting from monitoring 1 the average airflow velocity in that region is around 0.33 m/s compared to 0.08 in the winter period from the same monitoring point. The second monitoring point has recorded an airflow velocity of 0.12 m/s which is interestingly lower than the winter period which is 0.14 m/s. The third monitoring point has recorded an airflow velocity of 0.27 m/s compared to 0.07 m/s in the winter period.

5.10.4 EHS_Summer simulation_CO_2 concentration

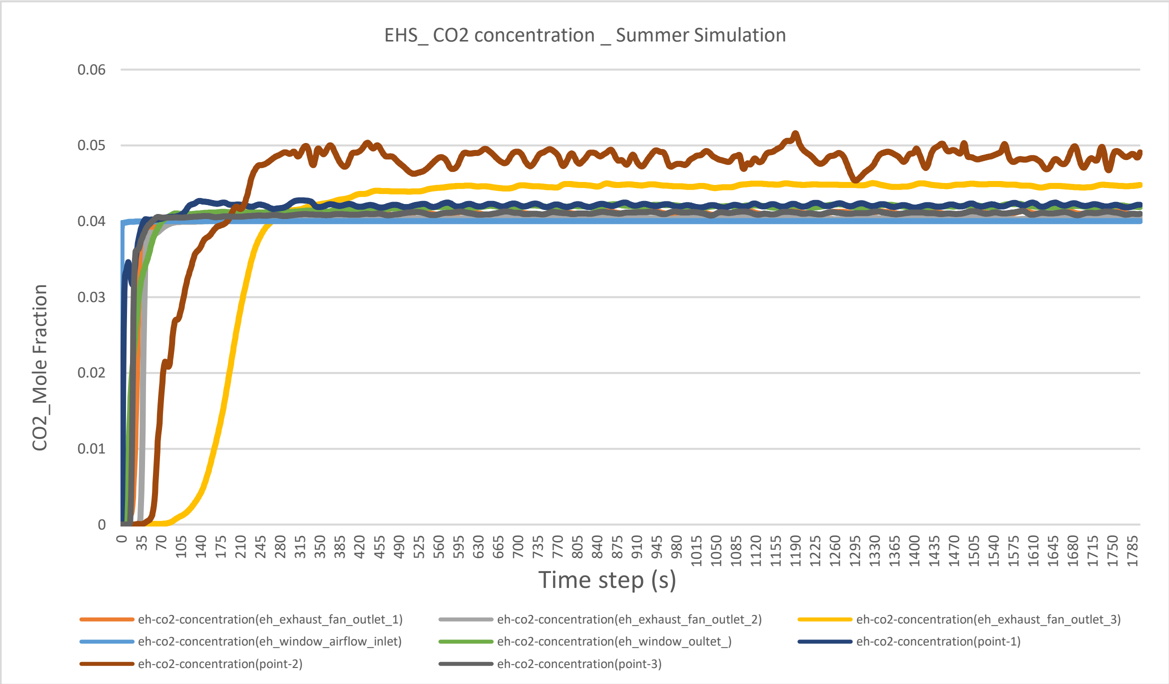


Figure 5-109 EHS_ CO2 concentration _ Summer Simulation

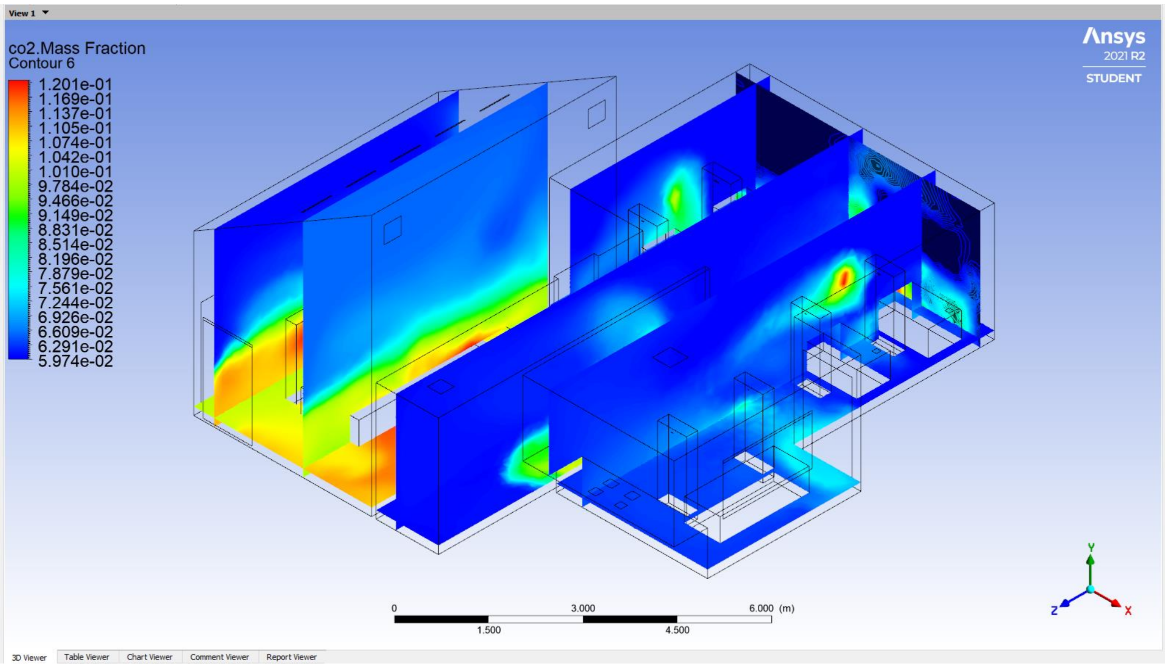


Figure 5-108 EHS _multiple 2-D surfaces illustrating the contour of ambient temperature_ Summer simulation

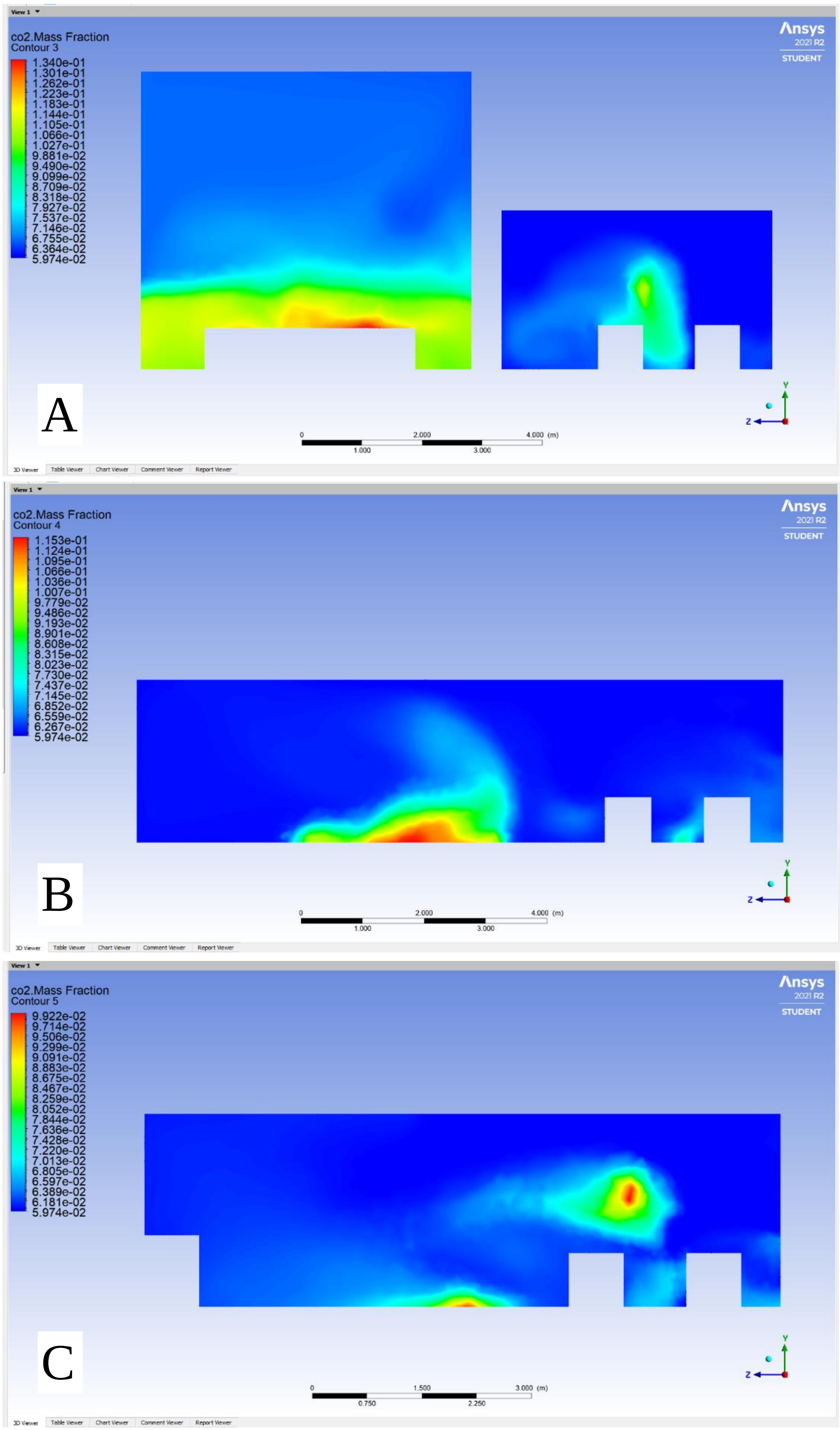


Figure 5-111 EHS _multiple 2-D surfaces illustrating the contour of ambient temperature_ Summer simulation

Table 5-35 EHS_ CO2 concentration _ Summer Simulation

Monitoring points	CO_2 concentration (co2 inlet)	CO_2 concentration (exhaust fan 1)	CO_2 concentration (exhaust fan 2)	CO_2 concentration (exhaust fan 3)	CO_2 concentration (point-1)	CO_2 concentration (point-2)	CO_2 concentration (point-3)
Average readings (ppm)	0.3201	0.0402	0.0394	0.0395	0.0418	0.0453	0.0404

In both the winter and summer, the concentration of CO_2 is very similar. Especially in the lounge room where the lower part of the room near the ground has the highest concentration of CO_2 compared to other parts of the EHS. One explanation of this phenomenon is the lack of airflow in that region which allows the exhaled CO_2 from the human models in the lounge region to remain in the same vicinity. But that is not the case in the other monitoring point (1, and 3). In these regions, the CO_2 concentration is lower in the summer period than in the winter. In the winter the CO_2 concentration near monitoring point 1 was 418 ppm while in the summer it was around 418 ppm. In monitoring point 3 the average CO_2 concentration was around 414 ppm while in the summer period it was around 404 ppm. In both cases, the introduction of extra airflow from the outside have diluted the existing CO_2.

5.11 Autumn/Spring simulation

5.11.1 EHS_Autumn/Spring simulation_(PM) concentration

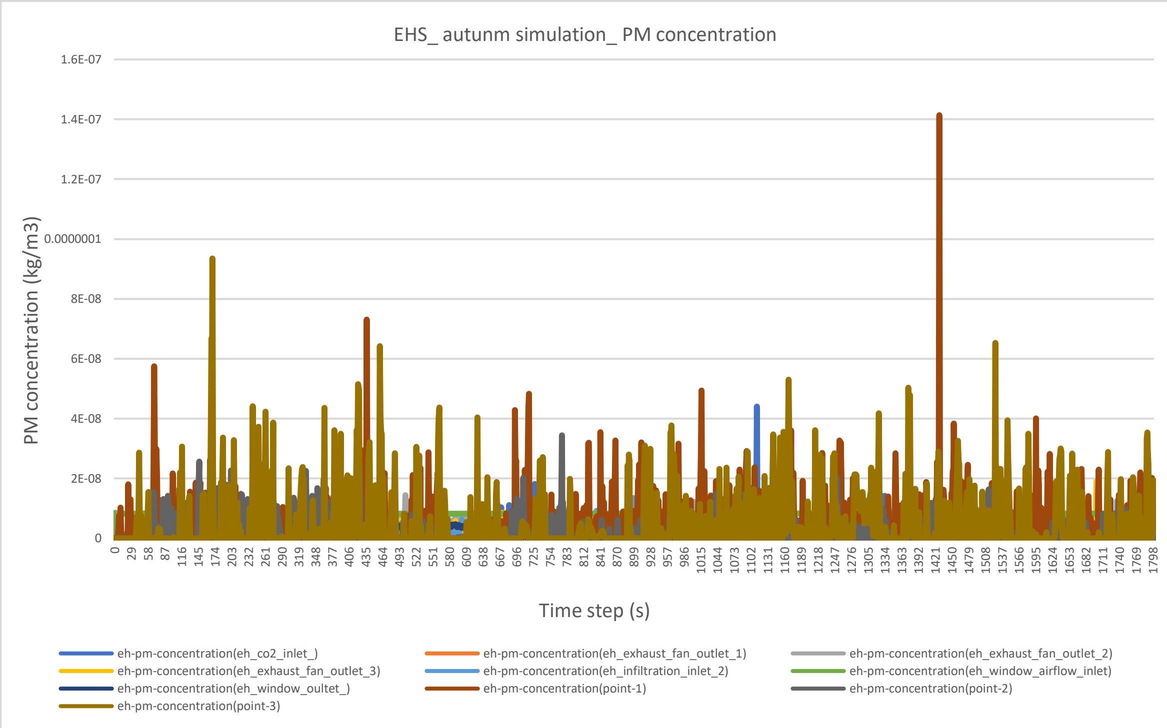


Figure 5-113 EHS_ autumn simulation_ PM concentration

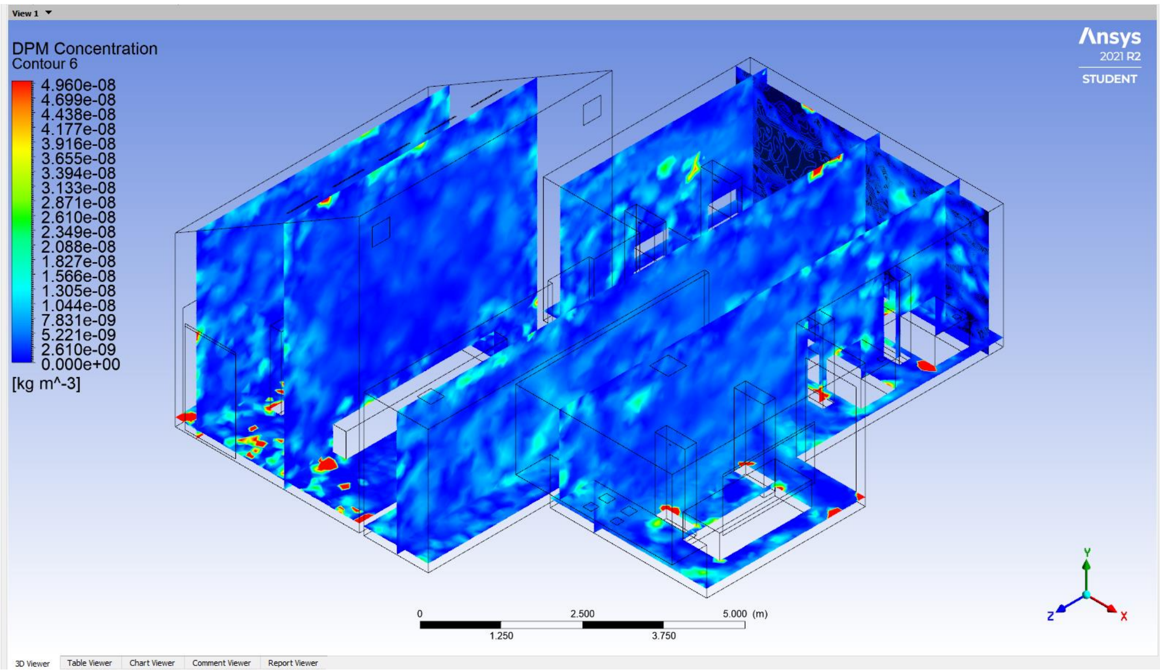


Figure 5-112 EHS 2-D surfaces illustrating the contour of ambient temperature_ Autumn/Spring simulation

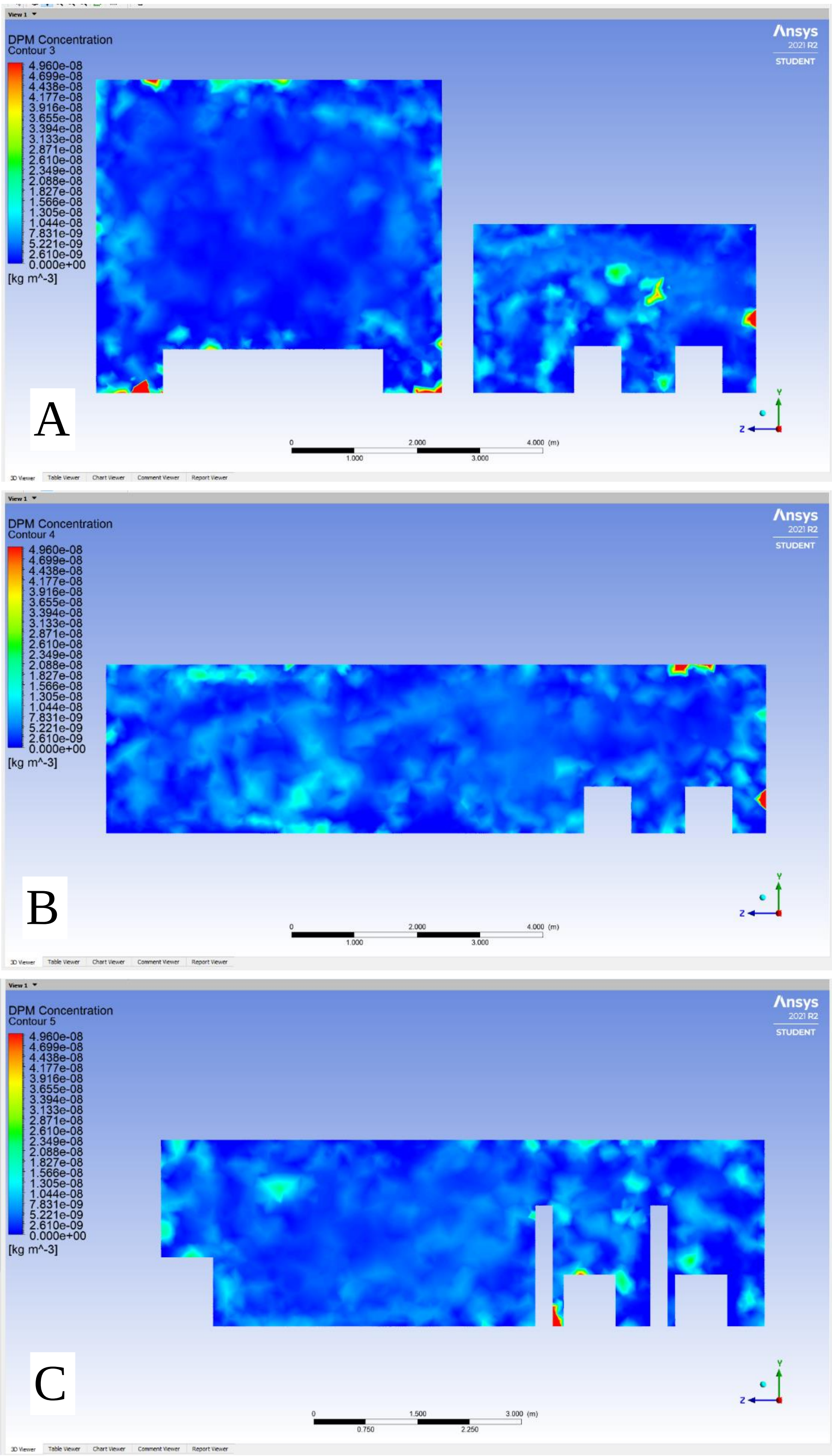


Figure 5-114 EHS_multiple 2-D surfaces illustrating the contour of ambient temperature_ Autumn/Spring simulation

Table 5-36 EHS_ Autumn/spring simulation_ PM concentration

Monitoring points	PM concentration (exhaust fan 1)	PM concentration (exhaust fan 2)	PM concentration (exhaust fan 3)	PM concentration (infiltration inlet 2)	PM concentration (point-1)	PM concentration (point-2)	PM concentration (point-3)
Average readings (Kg/m^3)	3.328E-09	4.216E-09	3.425E-09	3.589E-09	4.622E-09	1.669E-09	4.476E-09

The nature of airflow inside the EHS during both the autumn and the spring season is somewhat in the middle between the summer and the winter season. When analysing the difference in PM concentration between the autumn/spring and compare that to the other previous cases it is clear that in general, the concentration of PM in the autumn/spring simulation is somewhat lower than the winter simulation but higher than the summer simulation in some regions inside the EHS. The first example is in monitoring point 1. In the winter season, the concentration of PM was the highest concentration around 42 $\mu g/m^3$ and in the summer the concentration was reduced enormously to 5.9 $\mu g/m^3$ in the autumn/spring simulation the same monitoring point shows that the concentration of PM was around 4.6 $\mu g/m^{3.}$ This figure is in the middle between the winter and the summer simulation figure (5.114). The same thing with monitoring point 2 where the concentration in the winter period is around 36 $\mu g/m^3$ and in the summer period the concentration is around 2.2 $\mu g/m^3$ while in the autumn/spring period the concentration is around 1.6 $\mu g/m^3$. Monitoring point 3 recorded a level of concentration that is around 4.4 $\mu g/m^3$. This reading is higher than the summer reading and it is closer to the winter reading of 2.9 $\mu g/m^3$. This could be explained by the fact during the winter period, a very small sum of continuous air is flowing to the kitchen area, where the monitoring point is located, but all this air is residing in this region and not being extracted by the extract fan. In the summer period, there are large sums of air that bring even more pollutant to the kitchen, however, this air has many ways to leave the kitchen either by the windows or by the extract fan. In the autumn/spring period, there are large sums of air coming to the kitchen, but it could only leave the kitchen through the extract fan.

5.11.2 EHS_Autumn/Spring simulation Airflow velocity

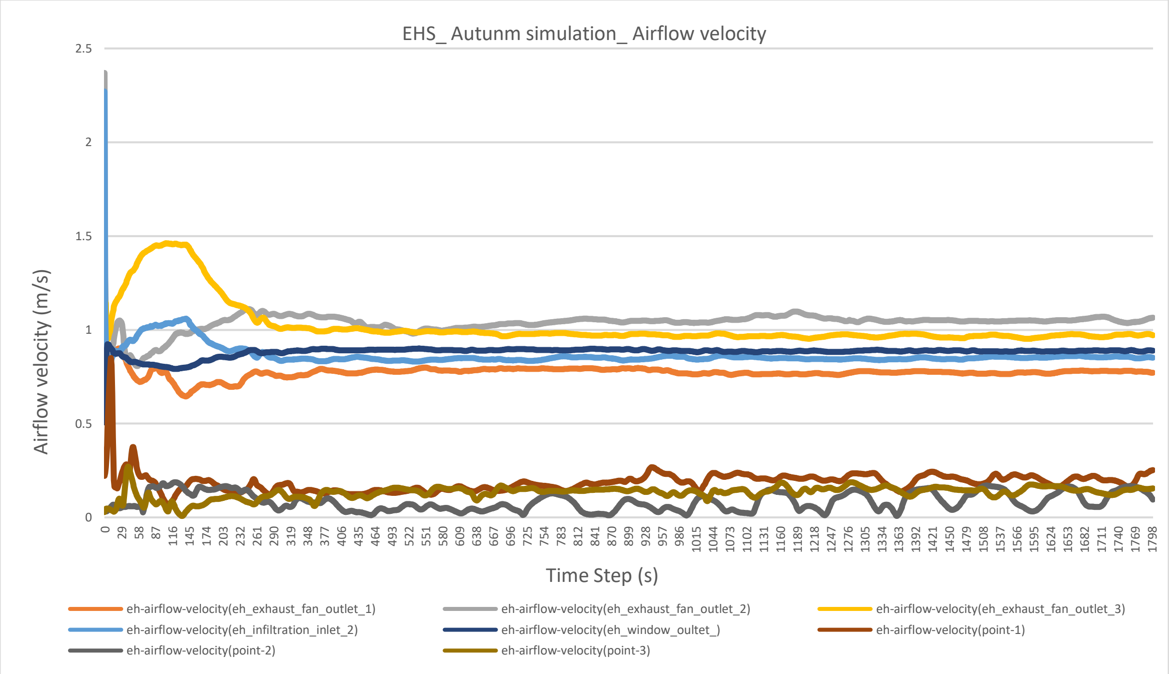


Figure 5-115 EHS_ Autumn/spring simulation_ Airflow velocity

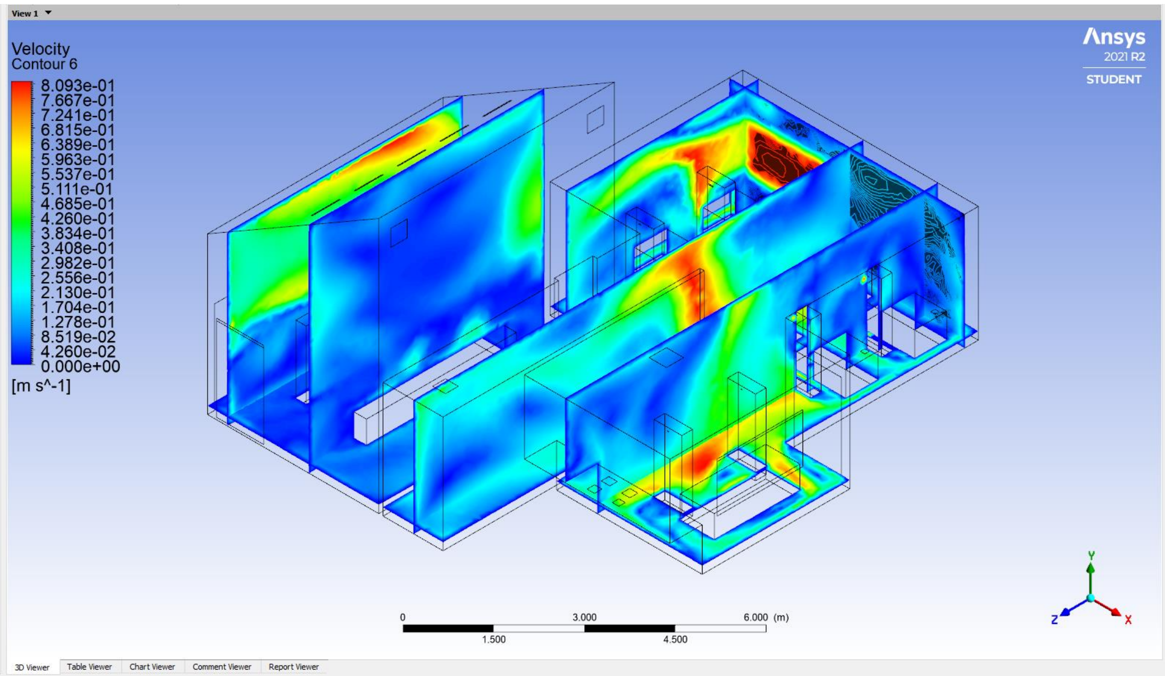


Figure 5-116 EHS_multiple 2-D surfaces illustrating the contour of Airflow velocity_ Autumn/spring simulation

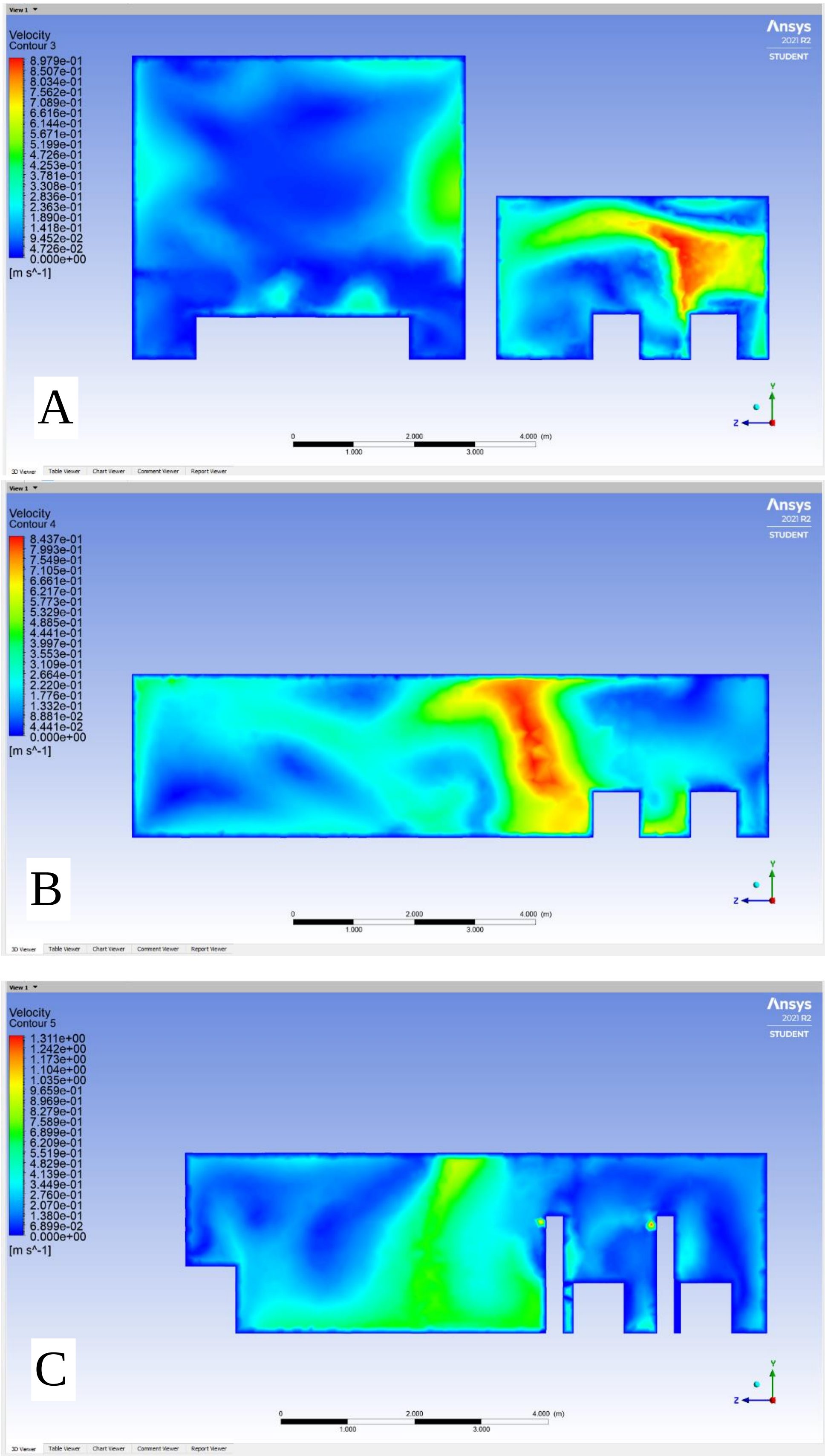


Figure 5-117 EHS_multiple 2-D surfaces illustrating the contour of Airflow velocity_ Autumn/spring simulation

Table 5-37 EHS_ Autumn simulation_ Airflow velocity

Monitoring points	Airflow-velocity (exhaust fan 1)	Airflow-velocity (exhaust fan 2)	Airflow-velocity (exhaust fan 3)	Airflow-velocity (window airflow inlet)	Airflow-velocity (point-1)	Airflow-velocity (point-2)	Airflow-velocity (point-3)
Average readings (m/s)	0.773	1.037	1.021	1.000	0.186	0.085	0.132

The windows and door are not open all the time just like in the summer period, instead only some windows are kept open while others remain closed. The velocity of air inside the space is less than adequate. For the airflow velocity in monitoring point 1 and 2, the average airflow velocity is around 0.085 m/s which is unnoticeable by the occupants and it is less than the recommended airflow rate by the CIBSE. The airflow velocity near monitoring point 3 is 0.1 m/s, however, this reading is the highest among the three monitoring points. That is because the amount of air coming to the kitchen is greater than in the winter period and yet there are no windows open in the kitchen, during the autumn period, to extract that air out to create cross ventilation between the open space area and the kitchen.

5.11.2 EHS_Autumn/Spring simulation_ Ambient temperature

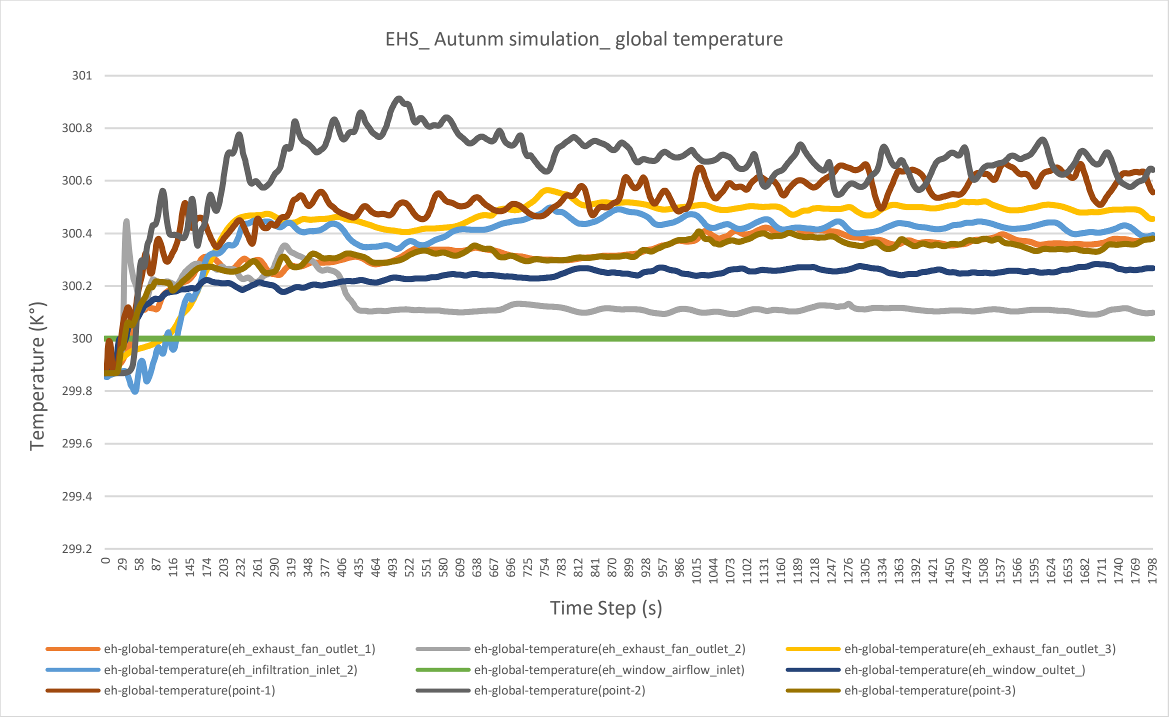


Figure 5-119 EHS_ Autumn simulation_ global temperature

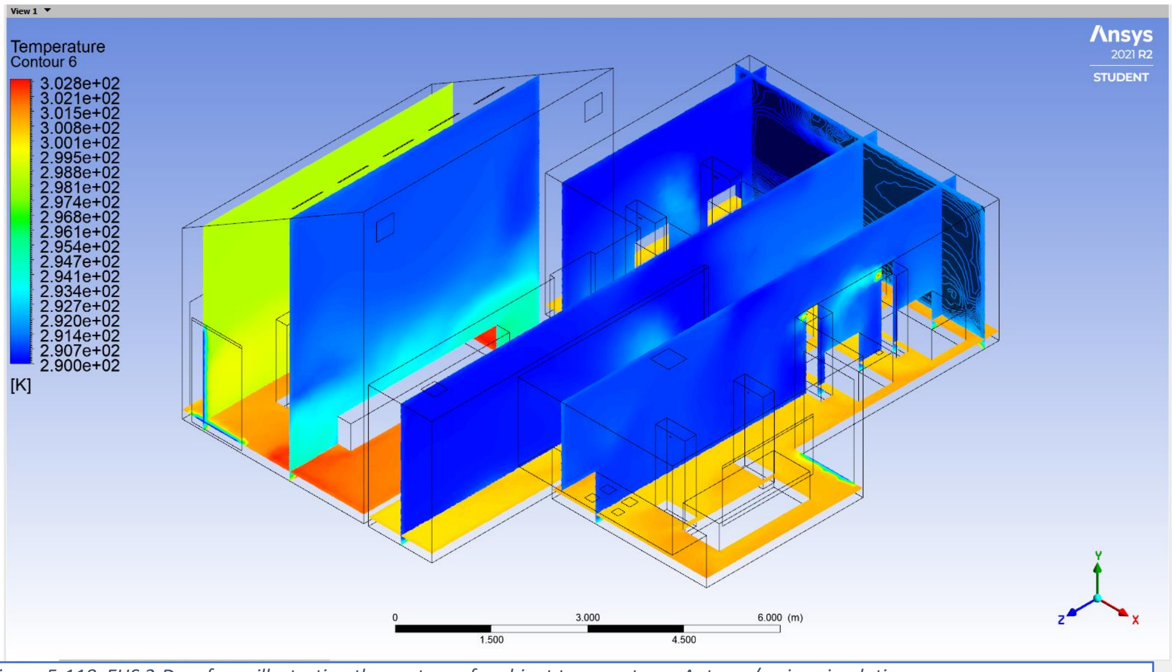


Figure 5-118 EHS 2-D surfaces illustrating the contour of ambient temperature_ Autumn/spring simulation

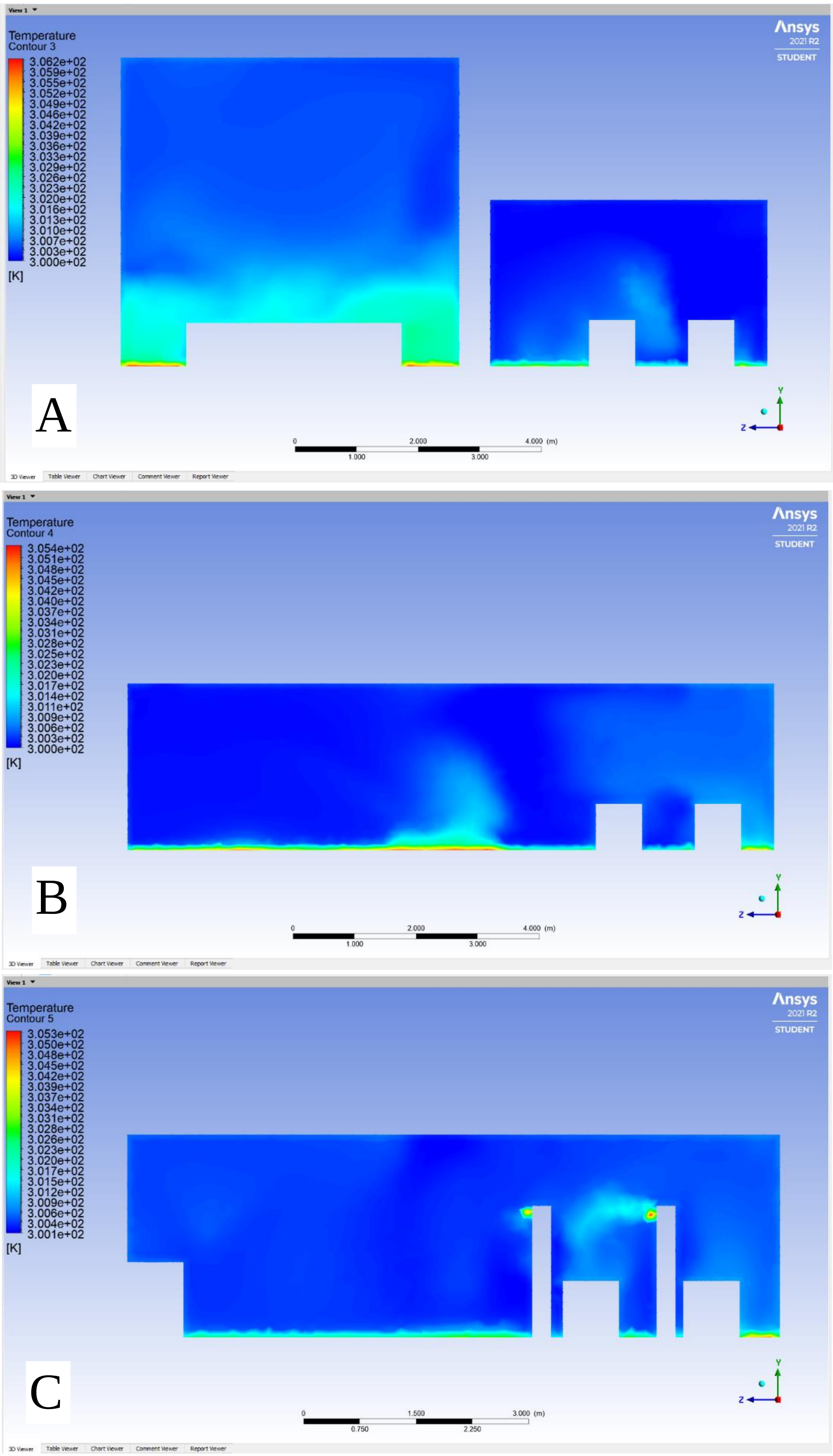


Figure 5-120 EHS 2-D surfaces illustrating the contour of ambient temperature_ Autumn/spring simulation

Table 5-38 EHS_ Autumn/spring simulation_ Ambient temperature

Monitoring points	Ambient Temperature (exhaust fan 1)	Ambient Temperature (exhaust fan 2)	Ambient Temperature (exhaust fan 3)	Ambient Temperature (window airflow inlet)	Ambient Temperature (point-1)	Ambient Temperature (point-2)	Ambient Temperature (point-3)
Average readings (Kelvin)	300.321	300.136	300.435	300	300.517	300.651	300.315

The outside temperature in the autumn/spring season is not consistent. Therefore, the heating system in those periods is in operation most of the time. That is why the temperatures in this period are somewhat higher than expected. However, these readings from table (5-38) are not always the case. These results represent a typical day in the spring season when the outside temperature is around 300 °K (26 °C). nevertheless, if the temperature outside is lower than that, then the temperature inside the space will be affected base on the fact that the building is relying on natural ventilation in most situations.

5.11.4 EHS_Autumn/Spring simulation_CO_2 concentration

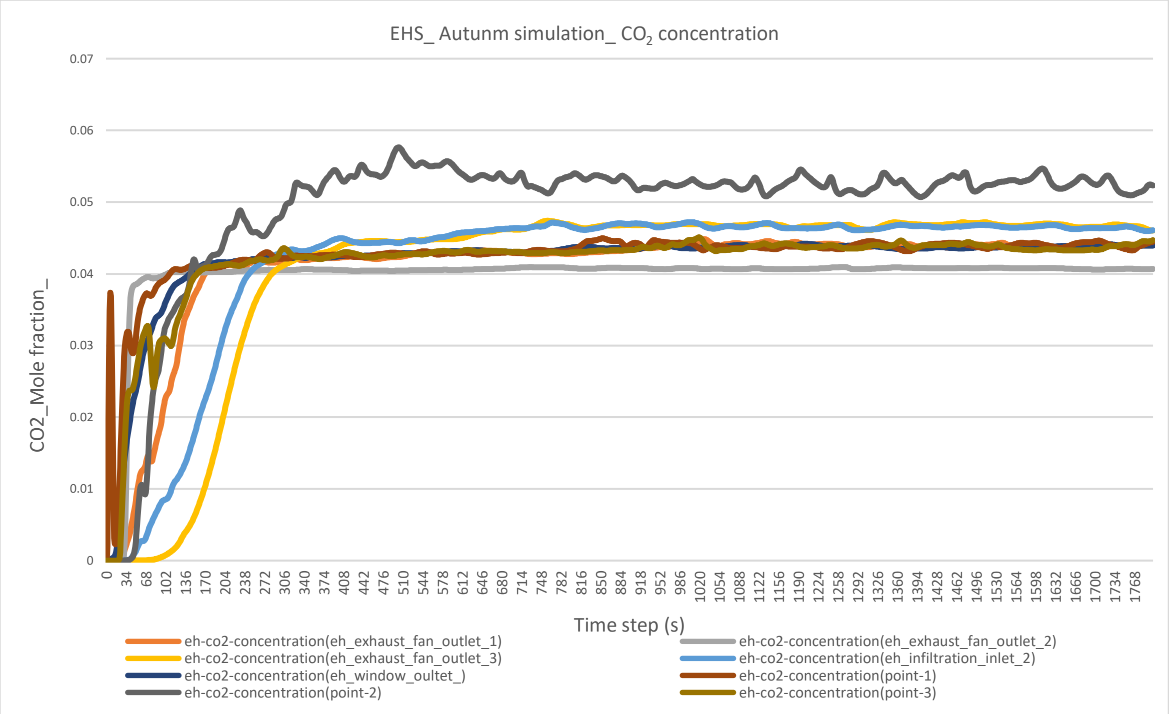


Figure 5-122 EHS_ Autumn/spring simulation_ CO_2 concentration

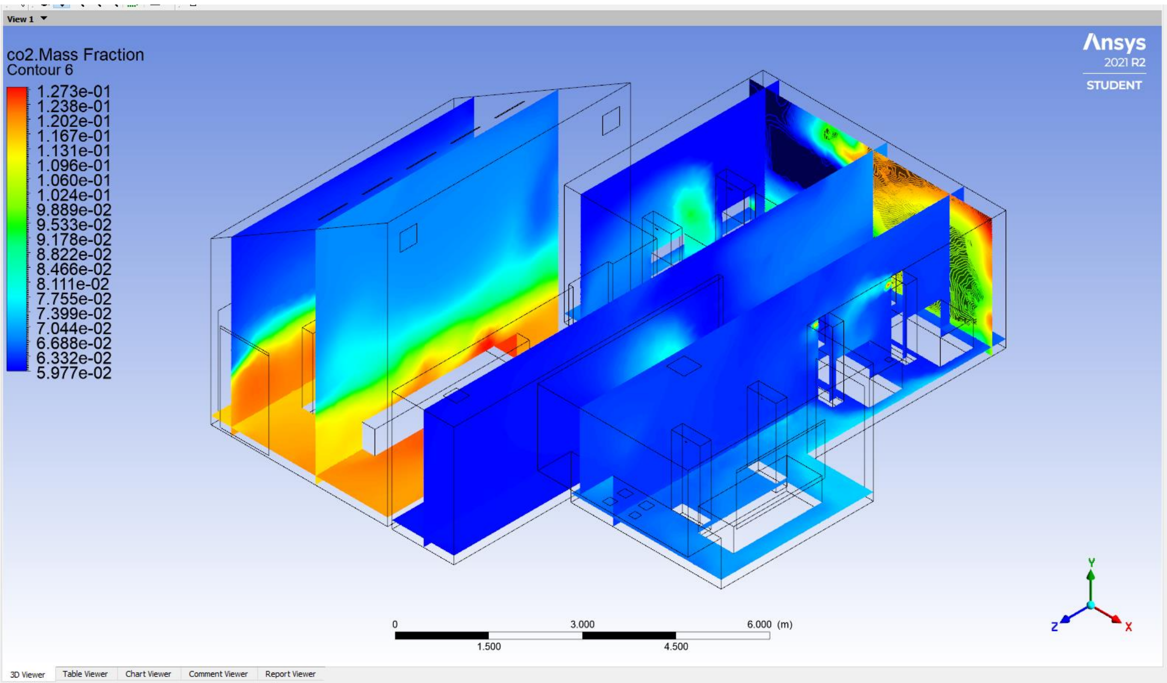


Figure 5-121 EHS 2-D surfaces illustrating the contour of CO_2 concentration_ Autumn/spring simulation

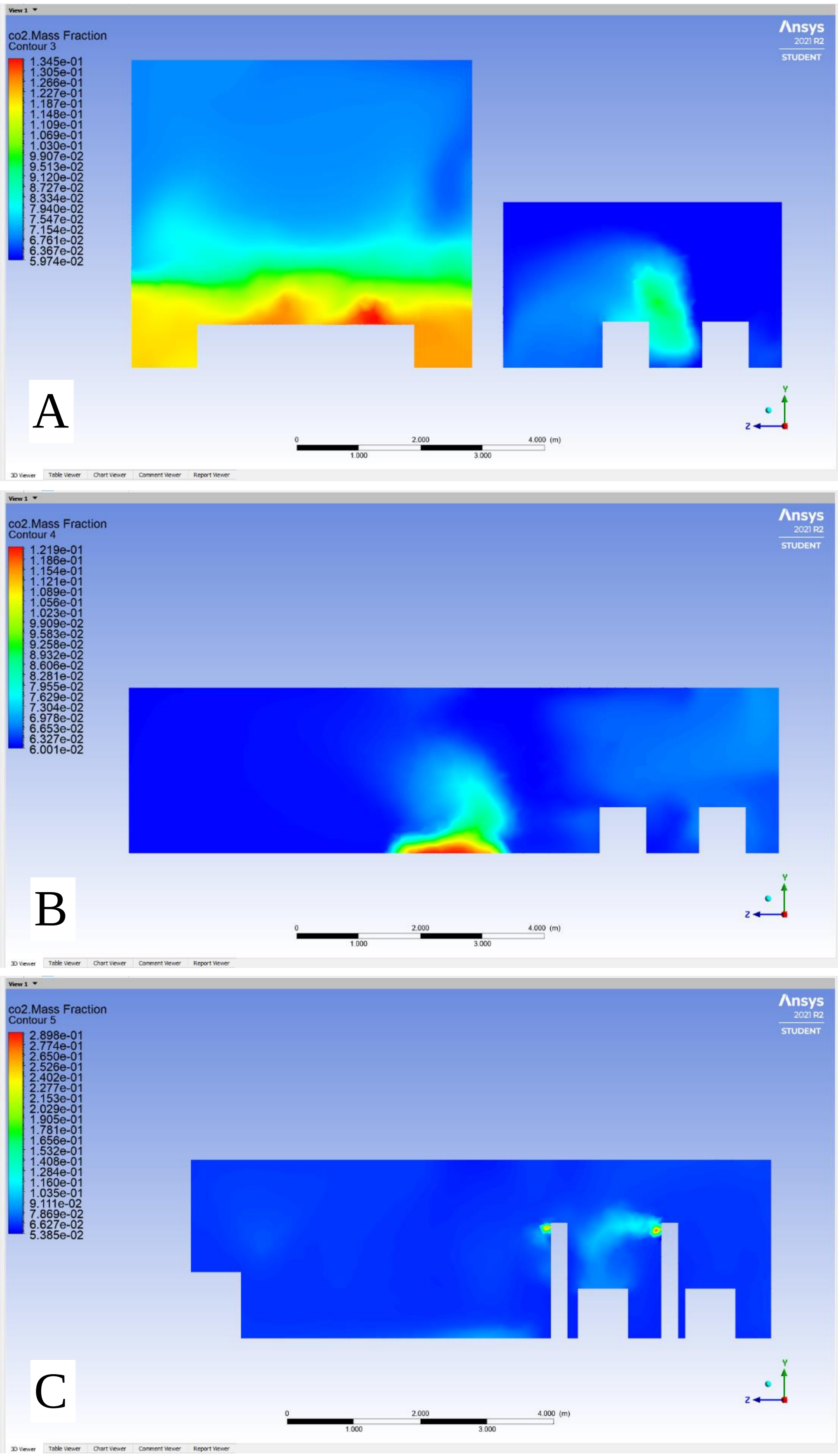


Figure 5-123 EHS 2-D surfaces illustrating the contour of CO_2 concentration_ Autumn/spring simulation

Table 5-39 EHS_ Autumn simulation_ CO2 concentration

Monitoring points	CO_2 concentration (exhaust fan 1)	CO_2 concentration (exhaust fan2)	CO_2 concentration (exhaust fan 3)	CO_2 concentration (window airflow inlet)	CO_2 concentration (point-1)	CO_2 concentration (point-2)	CO_2 concentration (point-3)
Average readings (ppm)	0.0408	0.0397	0.0406	0.0399	0.0425	0.0493	0.0416

The concentration of CO_2 in the autumn/spring period is very similar to the other periods. With the exception of monitoring point 2 having a higher CO_2 concentration of 504 ppm compared to even the winter season recorded from the same monitoring point.

5.12 discussing the findings from the CFD simulation

In this chapter three indoor spaces were simulated using the commercial software ANSYS FLUENT R20. The main purpose of simulating the airflow in these three indoor spaces is to analyze the indoor air quality condition in terms of PM concentration, CO_2 concentration, ambient temperature, and airflow velocity. These parameters will give a good overall indication of the indoor air quality inside the space. In addition, because of the overt differences between many season periods, the three indoor spaces were simulated in three different scenarios (winter, summer, and autumn/spring scenario). Each of these scenarios represents a certain time period when the airflow inside the space is very distinct from the rest of the year. The winter period was simulated because the airflow inside the space is very restricted, and therefore, provide an opportunity for many pollutants to accumulate inside the space if the airflow inside the space is not adequate enough to remove these pollutants. The summer scenario was simulated because the airflow inside the space during the summer period is almost the complete opposite of the winter season, and allow for many sources of airflow to pass through the indoor space enabling pollutant to be removed from the space. And finally, the autumn/spring represents an intermediary scenario between the winter and summer scenarios. These three scenarios will give a good representation of the condition of the indoor air quality inside the three indoor space throughout the year.

The first building houses two of the three indoor spaces simulated in this thesis. The first is the OSO and the second is the FFO. Both of these indoor spaces are equipped with the MVHR system that provides the main source of airflow inside the space. However, the two of them differ in many aspects like the architectural layout of the room, the volume size of the two spaces, the location of the inlet and outlet of the MVHR, and the number of people occupying the space. The first indoor spaces OSO has multiple inlet diffusers that are spread very well over the whole area of the space and provided adequate airflow inside the space. The (PM) concentration inside the space is very low even in the winter scenario which shows that a well-designed airflow system will keep the space clean even at low airflow velocity. It is, however important to note that the OSO has more than enough extract fans to remove all sorts of pollutant inside the space regardless of season condition. The CO_2 concentration is also very low and very suitable for occupants inside the space. The same thing could be said about the airflow velocity inside the space, which showed from the previously mentioned result, that the airflow design of the space has provided an adequate air quality condition inside the space. The temperature on the other hand did have the same positive result. This is apparent in the summer period where a large sum of hot summer air is been allowed to reach into the OSO and mix with the existing MVHR air. The space inside the space does overheat during the summer period and that will be discussed in the following chapter.

The second indoor space FFO shows very similar trends as the OSO. The airflow inside the space is mainly controlled by the MVHR system. However, the corridor door is left for a significantly long period of time which allow the airflow condition inside the space to be in some situation semi-naturally ventilated. This outside airflow is affecting the condition inside the space. Like for instance, in some areas inside the FFO, the concentration of PM in some areas inside the space is much higher compared to the average PM concentration in the OSO. Another example is the concentration of CO_2 during the summer period where a large flux of air is introduced into the space which carries copious amount of CO_2 inside the space.

The last indoor space was the EHS. This indoor space is located in another building that has a very different indoor air quality condition from the previous two indoor spaces. The indoor space relies on both radiant heat floor and natural ventilation for providing the airflow necessary. The airflow condition inside the EHS is not as good as the OSO and the FFO. The low velocity of the airflow coming from the outside is allowing the pollutant inside the space to reside longer and have very little chance of being transported outside the space. Thus, the indoor air quality condition inside the space was less than adequate at some times during the three scenarios simulated. This could be seen from the concentration of PM inside the space which was much than the concentration recorded in both the OSO and the FFO. The ambient temperature inside the space during the summer scenario is less than acceptable in which the ambient temperature has reached almost 34 °C.

5.13 Conclusion

When looking at the three simulated rooms with all three scenarios in each simulation, the trend shows that mechanical ventilation has played an important role in the indoor condition of the space. This effect is coupled with the fact the airflow pattern plays a vital role in determining the air quality condition inside the space. For example, in the OSO there are 10 air inlet registers installed in the drop ceiling. These air registers are very well designed and are spread evenly throughout the space allowing air to flow continuously through the space and it also allows the air to carry all the pollutant along the way toward the extract fan. However, the situation in the FFO is different from the OSO even though the space is equipped with MVHR for ventilation. The air movement inside the space is very different in which the air movement inside the FFO has a circular motion. This type of movement is great for some areas inside the space to have great air quality but other areas might not have the same condition because the air does not pass through them very often. The other example is the EHS, the air movement inside the space is mostly stale especially in the winter season. This creates a great disparity between certain areas inside the space in which some areas would have very high concentrations of pollutant like PM and CO_2 and other regions where there is no pollutant present at all. Several other factors might be responsible for the indoor air quality condition inside the three indoor spaces. the first is the architectural layout of the space. In the OSO the size volume and the layout of the room have allowed the pollutant inside the space to be spread in an area larger than the other spaces. Also, the design of the inlet and outlet of the MVHR system has a strong impact on the airflow inside the space and pollutant concentration. Another issue that emerged from the simulation is the problem of overheating during the summer period. This problem seems to be prevalent in all three spaces which show that even though these space are design according to the highest building code standard, they still have some drawbacks that could affect negatively on the occupants of the building.

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6. Chapter six:

6.0 Data collection and analysis:

6.1 Chemistry OSO PM $_{2.5}$ and VOCs readings

The data collected in the OSO had commenced on the 23 of January of the year 2018. As mentioned before several devices were implemented to collect important data about the indoor air pollutants existing in that space for this study. The temperature and relative and the PM along with the volatile organic compound were all measured using (TES 5322 PM2.5 Air Quality Monitor). The device was placed on a table with a height of 75 cm and connected to a power source so that the data is taken continuously. The same thing goes to the other device that had been used to collect the Carbon Dioxide concentration (Perfect-Prime CO2000 Carbon Dioxide (CO2) Air Temperature & Humidity Data Logger Meter). The time interval was set to be 30 minutes because of the lengthy time these devices are going to take data. It is worth noting that the OSO has 10 MVHR inlets that discharge clean at a speed of 1.5 m/s and two exhaust outlet that extract all the air from the OSO with an airspeed of 2.1 m/s.

6.1.1 January – February (2018):

Figure (6.1) shows very stable levels of $PM_{2.5}$ throughout this period in which the $PM_{2.5}$ levels have never changed from 10 µg/m^3. Furthermore, because the interior space is supplied with an MVHR system, the temperature is kept at 24-25 °C. However, the humidity does fluctuate ranging from 45 (%) to 27 (%). The relative humidity tends to increase during the weekends when the MVHR operation is kept at a minimum. It was revealed that the humidity levels in the month of February have gotten as low as 23 (%).

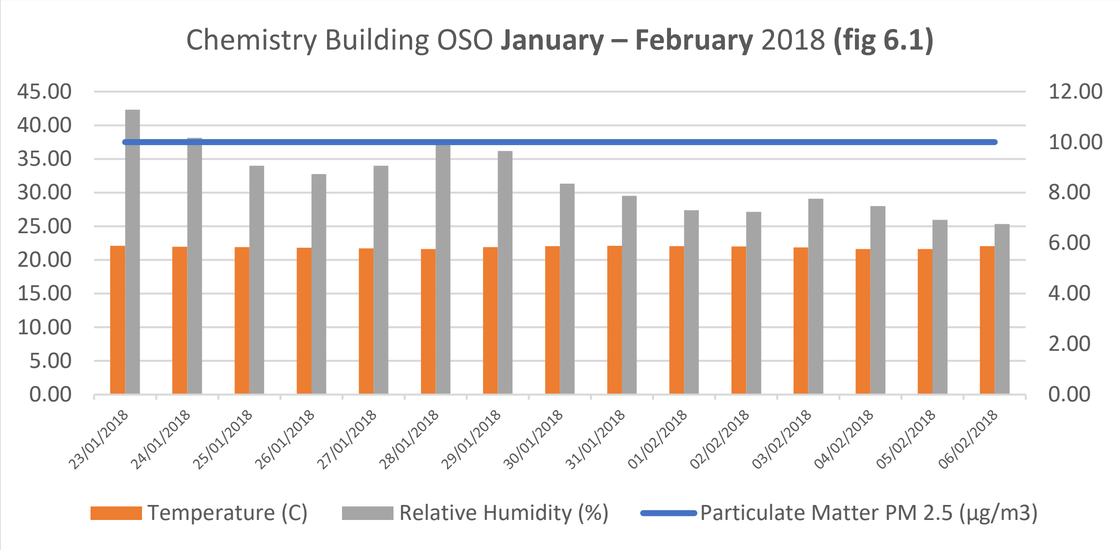

Figure 6-1 Chemistry Building OSO January – February 2018

6.1.2 April- May (2018)

One theme that is consistent in the month of April is that there is a constant reading of $PM_{2.5}$ during the weekend like for example on the 13th of April and the 14th of April when the $PM_{2.5}$ is averaging around 10 µg/m3. Also, the temperature is constant at 22.5 °C. when the workers and students come back from the weekend, a fluctuation in the $PM_{2.5}$ levels occur. This is probably due to the opening of the door and windows although not permanently. The levels of $PM_{2.5}$ fluctuate between 5-10 µg/m^3. During this time also, The temperature increases from 22.5 – 23.7 °C. The levels of $PM_{2.5}$ starts to decrease gradually. This decrease in $PM_{2.5}$ levels starts at the beginning of May. In this period the windows and doors are permanently opened and the air coming from the HVAC is mixed with the air coming from the Winter Garden adjacent to the OSO space. Not only that but also the humidity levels rise up as the air mixing the process between the OSO room and the Winter Garden. The temperature also rises as the air mixing occurs. The average humidity level on the weekdays is between 30.07 % on the 14th of May and rises up during the weekdays until it reaches 33.1 % on the 19th of May. Also, the temperature in the 14th averages around 23.8 °C to 24.0 °C on the 18th of May (figure 6.2).

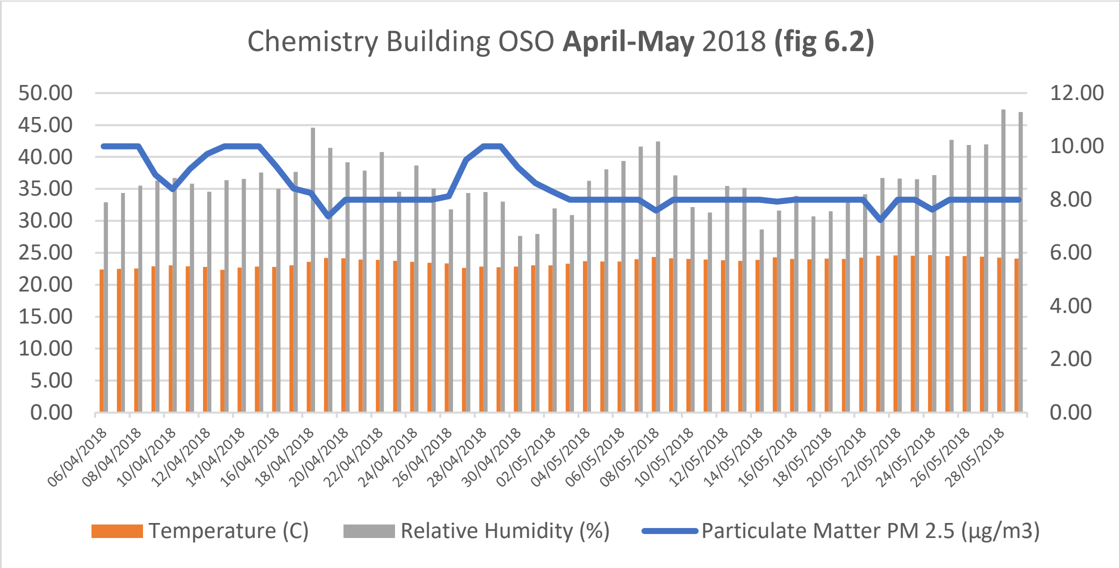

Figure 6-2 Chemistry Building OSO April-May 2018

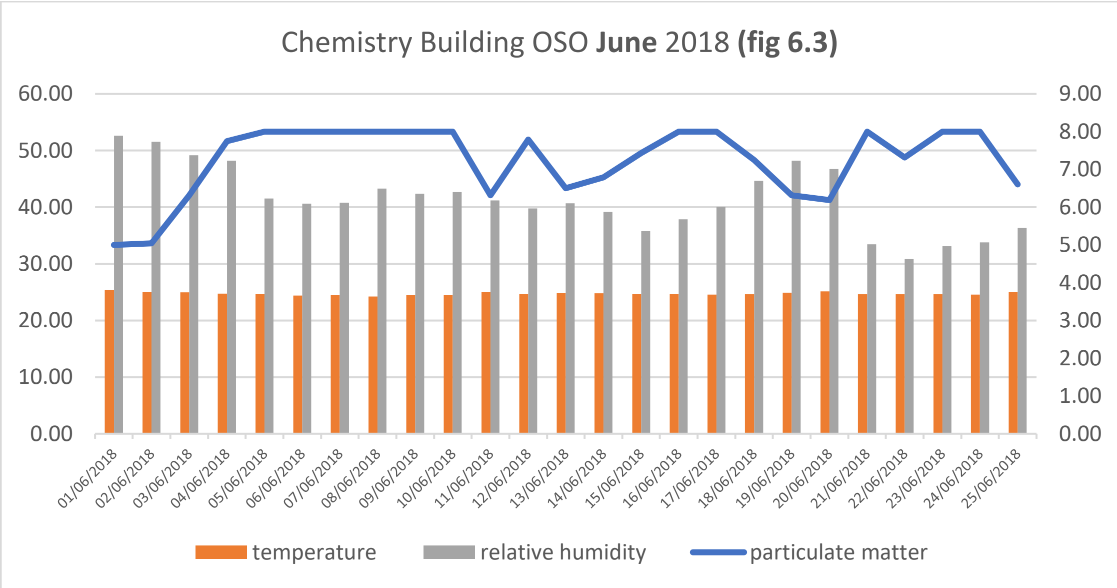

Figure 6-3 Chemistry Building OSO June 2018

6.1.3 June (2018)

At the beginning of the month of June data follow the previous trend of the month of May. However, on the 4th of May, the concentration of $PM_{2.5}$ starts to change where it starts to rise again from the average rate of 5 µg/m^3 to 8 µg/m^3. It was observed that from the 4th of June until the 11th of June the concentration of $PM_{2.5}$ was 8 µg/m^3 persistently. On the 11th of June, the concentration starts to change and mostly around 12:00 PM onward. The concentration decreases from 8 µg/m^3 to 5 µg/m^3. Even though June is not considered one of the cold months, still it is believed that overheating might play a role in this situation. This could be inferred from the temperature readings and when comparing the average temperature taken from the months of February to the month of March. In the month of February, the average temperature was around 21 – 22 °C and on one occasion it reached 20 °C. the relative humidity is also low at that time ranging from 25 – 30 % RH. On the contrary, in the cooling months of June, the temperature readings are very different. The average temperature is 25 °C. in fact in one time the highest recorded temperature was on the 25th of June was 26.9 °C. the relative humidity was also high in the month of June. The average RH was around 50 %.

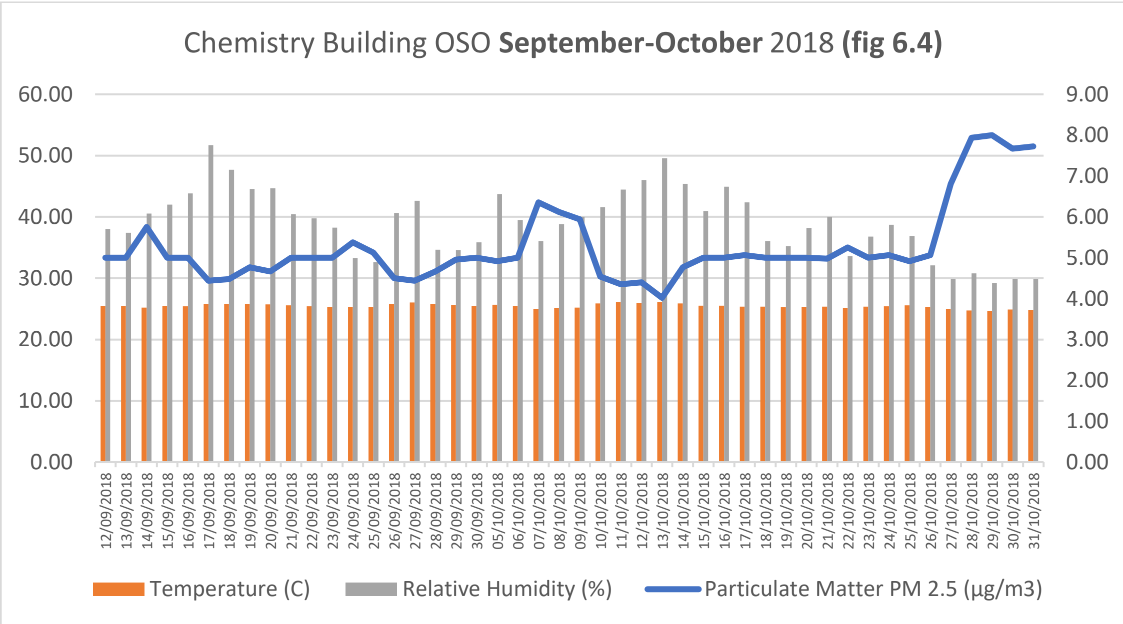

Figure 6-4 Chemistry Building OSO September-October 2018

6.1.4 September-October (2018)

In the middle of September, the average concentration of $PM_{2.5}$ was around 5 µg/m^3. On the 17th of September, the concentration of PM2.5 has further decreased to 4 µg/m3. Interestingly, the temperature and relative humidity also changed. The temperature was as high as 26.5 °C and the relative humidity was also high reaching as high as 56.1 %. It is worth noting that this phenomenon starts around 10:00 AM and it remains throughout the day even at night. On the weekends there is no fluctuation in the PM, temperature, or RH readings. In the month of October, the first few days have seen similar readings recorded in the month of September. Nevertheless, whenever there is an increase in the temperature and humidity, a decrease in the levels of $PM_{2.5}$ this is especially true during the 11th until the 13th of October when the $PM_{2.5}$ was 4 μg/m^3 the temperature was around 26 °C and the relative humidity was around 48 – 50 %. The days after that have seen a decrease in temperature and relative humidity which correlated with a slight increase in $PM_{2.5}$. on the 28th of October a dramatic increase in $PM_{2.5}$ from 5 μg/m^3 to 8 μg/m^3 that was coincidently correlated with a decrease in temperature from 25 °C to 24 °C and a significant reduction in RH from 45 % on average from the previous days to 30 %.

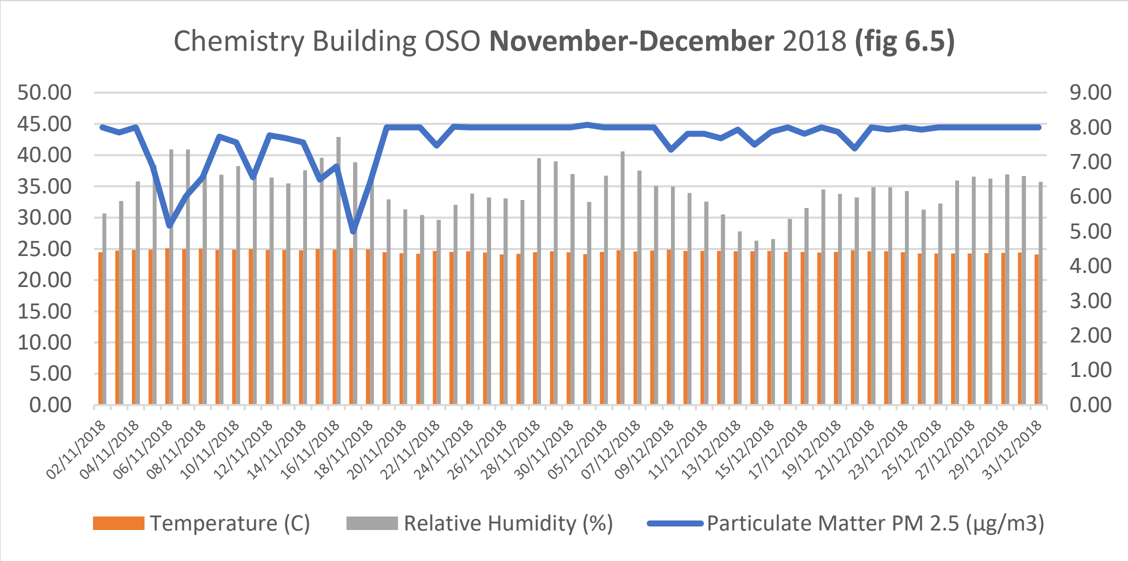

Figure 6-5 Chemistry Building OSO November-December 2018

6.1.5 November-December (2018)

The readings during the two months of November and December are very similar to each other. The average $PM_{2.5}$ is 8 μg/m^3. The concentration does decrease to 5 μg/m^3. Comparing the month of November and December readings to the beginning of the year readings from 2018 it could be seen that the temperature is higher in the months of November and December 2018 (24 °C) compared to January and February 2018 (21-22 °C).

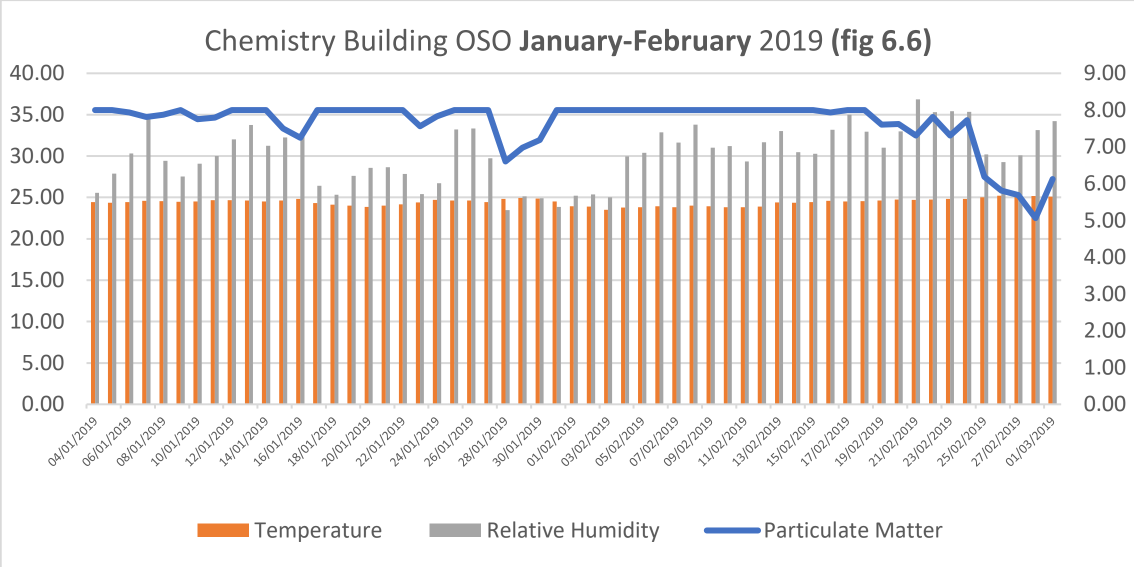

Figure 6-6 Chemistry Building OSO January-February 2019

6.1.6 January-February (2019)

The readings in the second year of 2019 are very similar to those reading from the previous year, although with a few exceptions. The $PM_{2.5}$ readings in the month of January were very similar to those readings from the previous year. The average $PM_{2.5}$ was consistent at 8 µg/m^3 with few exceptions. The average $PM_{2.5}$ does go down to 5 µg/m^3, but the pattern is inconsistent. In regards to the ambient temperature, the average temperature is slightly higher than that of last year when the average temperature was averaging around 22.5 °C whereas in January 2019 the average temperature is closer to 24 °C. On the other hand, the relative humidity is still low at 25 – 35 (%), however, there was a rare incident on the 28th of January when the $PM_{2.5}$ was 5 µg/m^3, the temperature was 25 °C and the relative humidity was 20 (%). As it is apparent from figure (6.6) that the concentration of $PM_{2.5}$ starts to gradually decrease to 5 µg/m^3. This could be due to the fact that the winter garden is much colder than the rest of the building since the atmosphere inside the winter garden is very similar to the outdoor climate conditions. Therefore, the windows and door that are adjacent to the winter garden are kept closed.

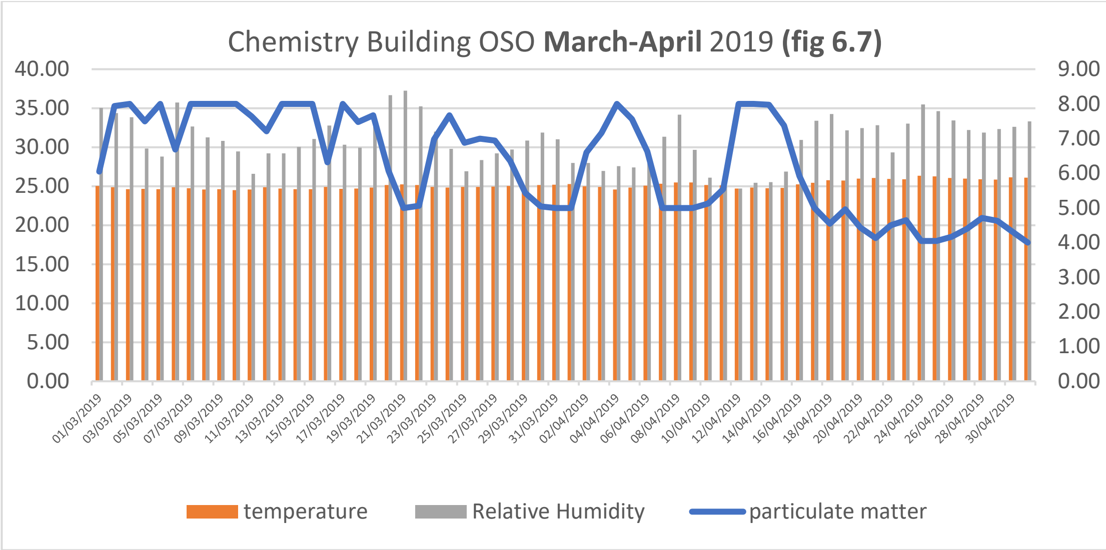

Figure 6-7 Chemistry Building OSO March-April 2019

6.1.7 March-April

The trend continues from the month of February toward the month of March where the concentration in $PM_{2.5}$ is averaging around 8 µg/m^3. Figure (6.7) shows a correlation between $PM_{2.5}$ and relative humidity. On the 6th of March when $PM_{2.5}$ decreases to 7 µg/m^3, the relative humidity increases from 28 (%) to 35 (%). The same thing happens on the 16th of March and on the 20, 21 and 22nd of March. During these dates, the pattern is the same in which the concentration of $PM_{2.5}$ decreases and the relative humidity increases. This could be happening because of the adjacent winter garden. The relative humidity is higher in the winter garden than in the OSO and therefore the difference in relative humidity is transferred from the winter garden to the OSO space whenever the windows are open. The same pattern occurs in April from the 7th of April 2019 up until the 10th of April 2019. The opposite happens on the 11th of April where the $PM_{2.5}$ increases (from 5-8 µg/m^3) and the relative humidity decreases from 35% to 25%. What could be inferred from this phenomenon is that on the 7th of April these readings coincide with a typical working day which means that students and employees might allow the air from the winter garden to enter the OSO and mix up with air from the OSO. On the other hand, on the 11th of April, during the weekends, the windows are closed and so the $PM_{2.5}$ starts to increase and the relative humidity begins to decrease.

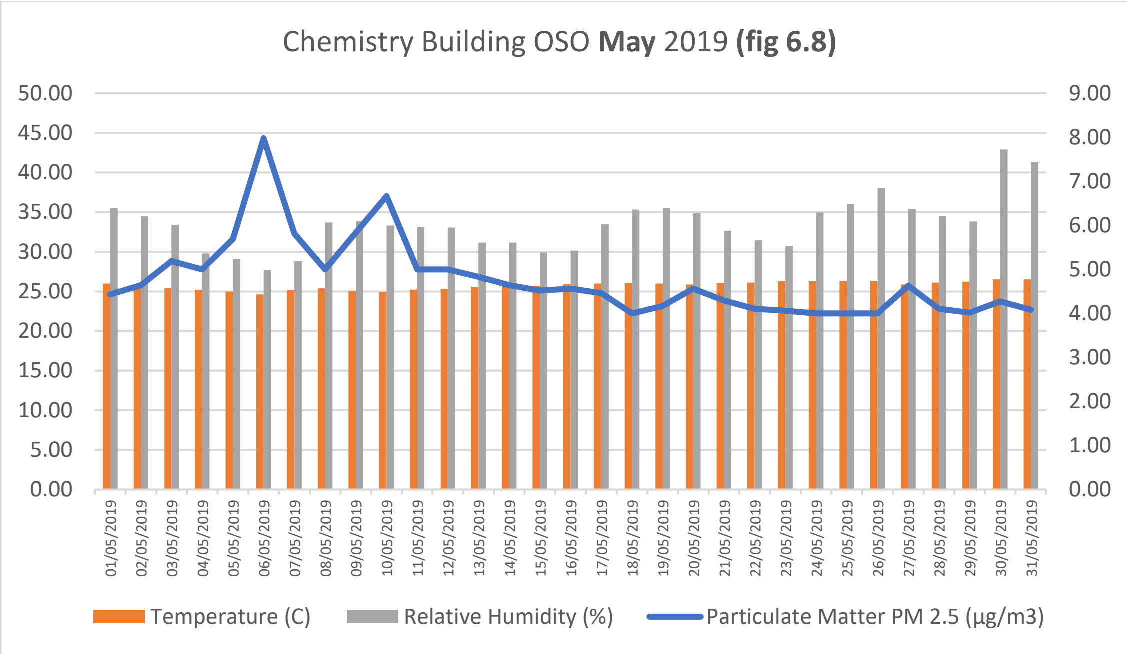

Figure 6-8 Chemistry Building OSO May 2019

6.1.8 May 2019

May is one of the hotter months of the year and that is reflected in the temperature readings. The average temperature during the month of May is 26 °C. Fig (6.8) shows a gradual increase of relative humidity throughout the month with the exception of the 7th of May which corresponds to a working day. The average $PM_{2.5}$ is averaging around 4 µg/m^3 during the whole month with few exceptions like for example on the 7th of May and 11th of May.

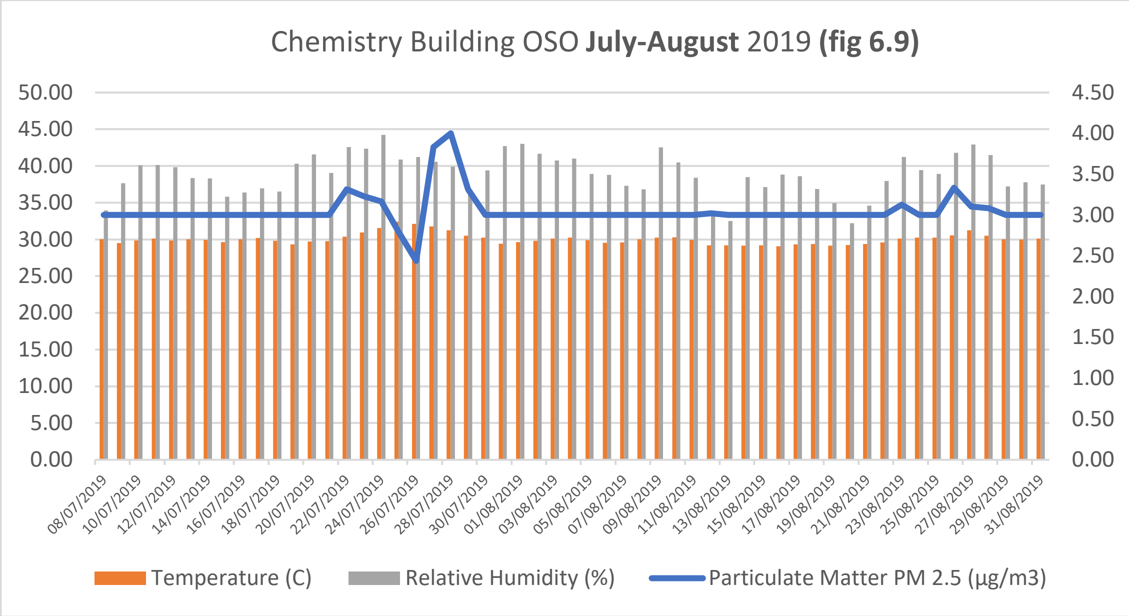

Figure 6-9 Chemistry Building OSO July-August 2019

6.1.9 July-August 2019

The month of July is by far the hottest month recorded during the whole research period from January 2018 all the way to January 2020. Figure (6.9) reveal that the average temperature is around 28- 30 °C during the whole month. In fact, the highest recorded temperature was on the 25th of July when it reached 34.3 °C. The relative humidity remains around 40 – 45 (%). Even though the temperature was very high, the $PM_{2.5}$ on the 25th of July was 2 μg/m^3 which was the lowest recorded concentration of $PM_{2.5}$.

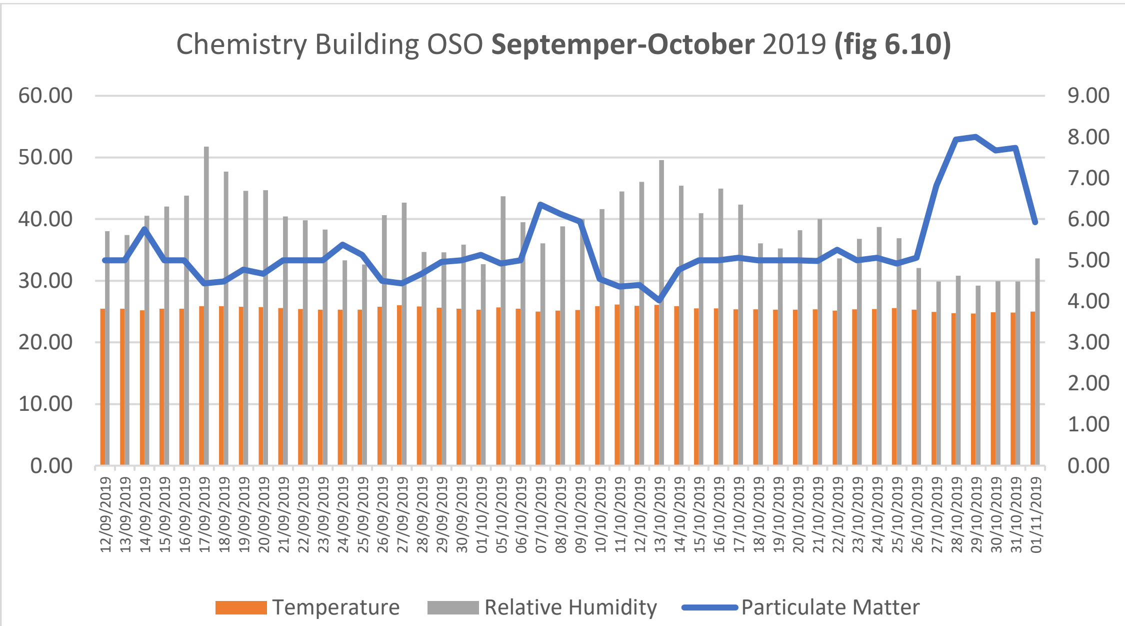

Figure 6-10 Chemistry Building OSO September-October 2019

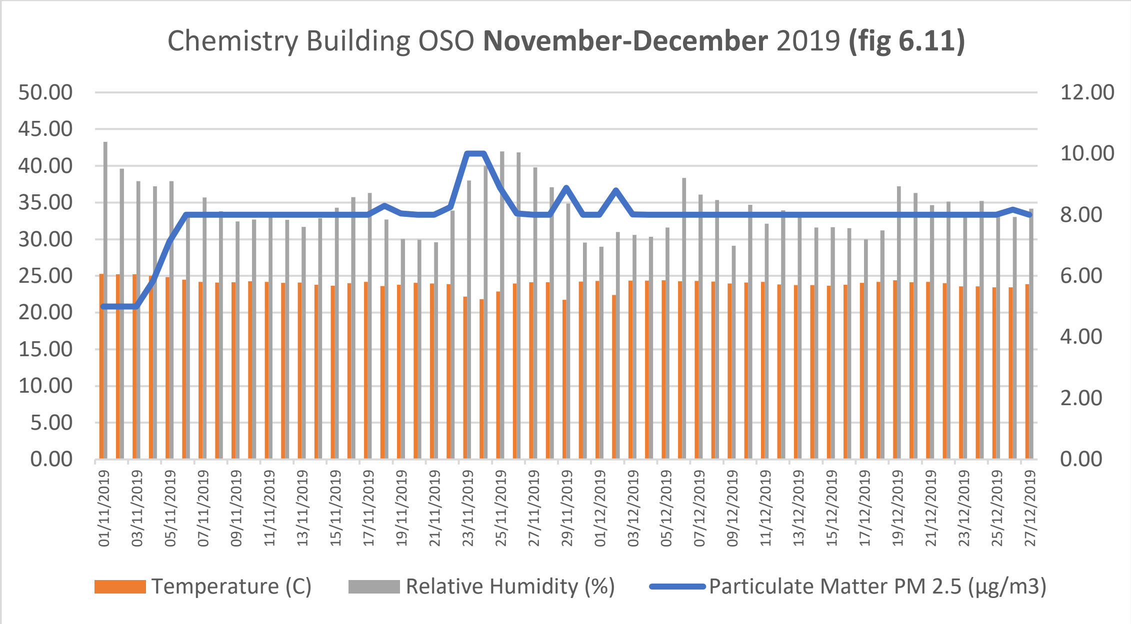

Figure 6-11 Chemistry Building OSO November-December 2019

6.1.10 November- December 2019

In the month of November, the concentration of $PM_{2.5}$ was 5 μg/m^3 at the beginning of the month and it started to gradually increase to 8 μg/m^3. One trend that is different from other months of the year is that there is an increase of $PM_{2.5}$ on a specific day like for example the 23rd and the 24th of November. This level of concentration is slightly higher than the readings that occurred in November 2018. On the 29th of November, the $PM_{2.5}$ concentration has increased on the same day around which could be attributed to the resuspension of particles dust although this observation is not persistent on other days. The temperature during the month of November is mostly around 23 – 24 °C and relative humidity around 28- 35 (%). On two separate occasions, the temperature has dropped down significantly from 24 to 16 °C on the 29th of November and on the 2nd of December where it dropped to 17.8 °C. The reason is unknown but it could be because the window office had opened to the winter garden temporarily which allowed the air from the winter garden to enter the OSO space. This could be also confirmed by the increase in relative humidity to 40 (%) instead of the usual 25-28 (%).

6.2 CO_2 readings chemistry building OSO

6.2.1 January -February 2018

Carbon dioxides concentrations seem to be different from particulate matter. One reason is that they are more susceptible to human presences inside the room and other sources, while $PM_{2.5}$ relies more on a particular source like printers, uncleaned dust filters, or combustion process and in many occasions' resuspension of particles by human movement. CO_2 concentration, on the other hand, is very sensitive to human presence inside the space. This could be shown from the readings that were taken during the month of January and February. On the 25th of January, it shows a typical weekday where the concentration of CO_2 starts low around 420 ppm and starts to rise up to 500 ppm around 1:30 PM. After that, a reduction in the concentration of CO_2 concentration carries on to the rest of the day especially at 7:30 PM when most of the workers have left the building (fig 6.11) and (fig 6.12). On the weekends the opposite happens (fig 6.13) and (fig 6.14) where it illustrates that on Saturday 27th of January the concentration of CO_2 starts high at 500 ppm and goes all the way down to 400 ppm and it carries on throughout the day and the next day on Sunday the 28th of January.

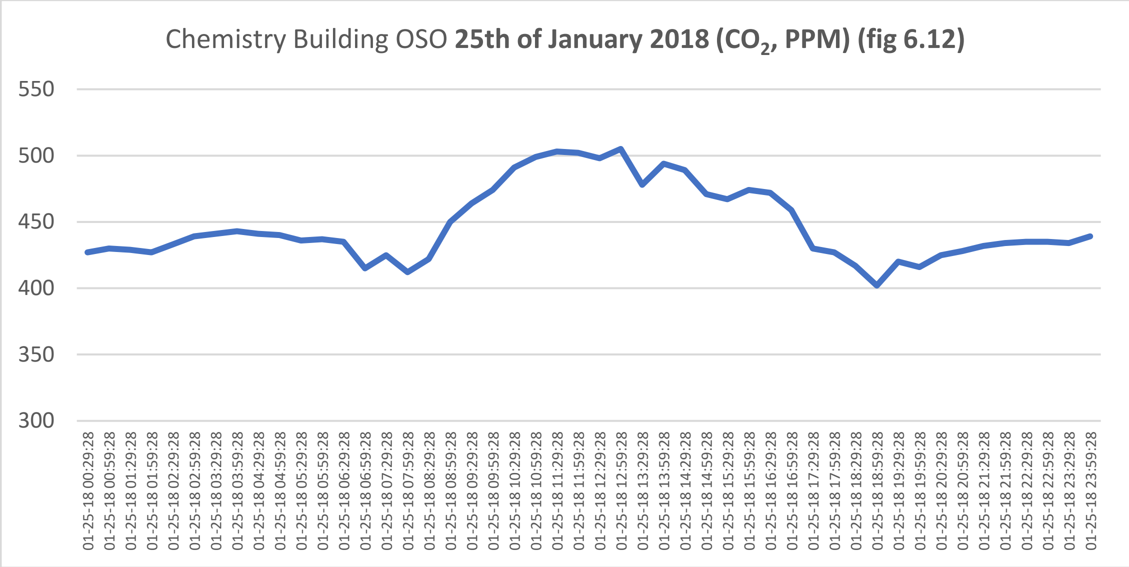

Figure 6-12 Chemistry Building OSO 25th of January 2018 (CO2, PPM)

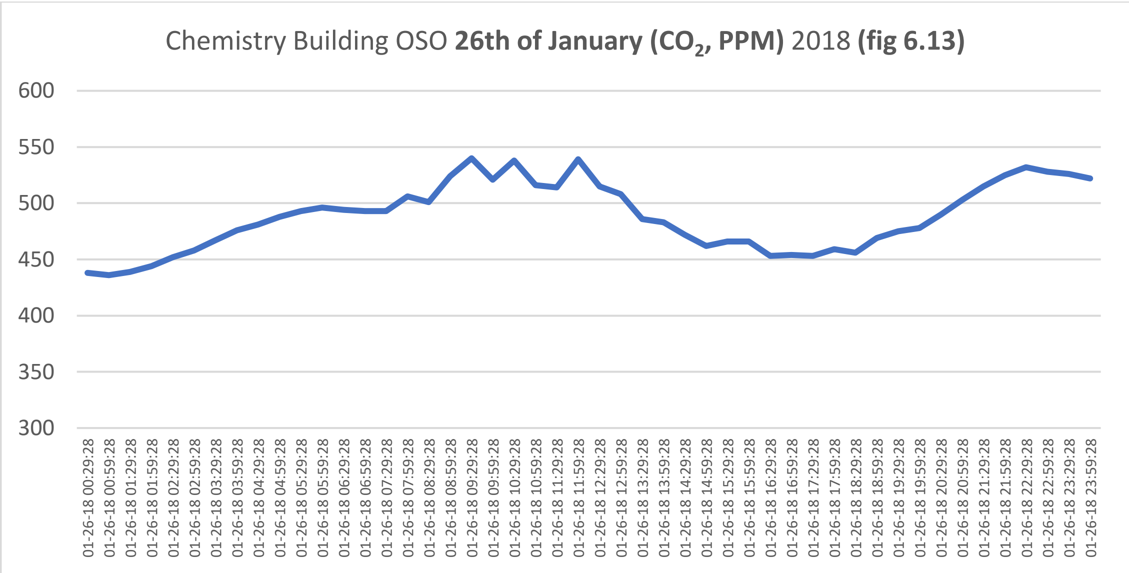

Figure 6-13 Chemistry Building OSO 26th of January (CO2, PPM) 2018

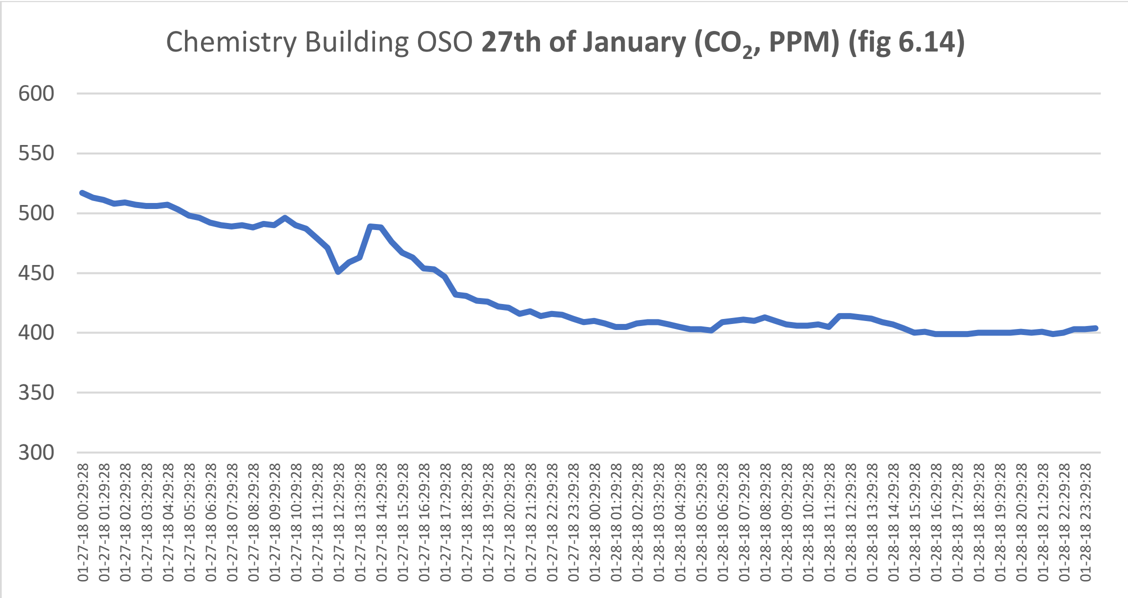

Figure 6-14 Chemistry Building OSO 27th of January (CO2, PPM)

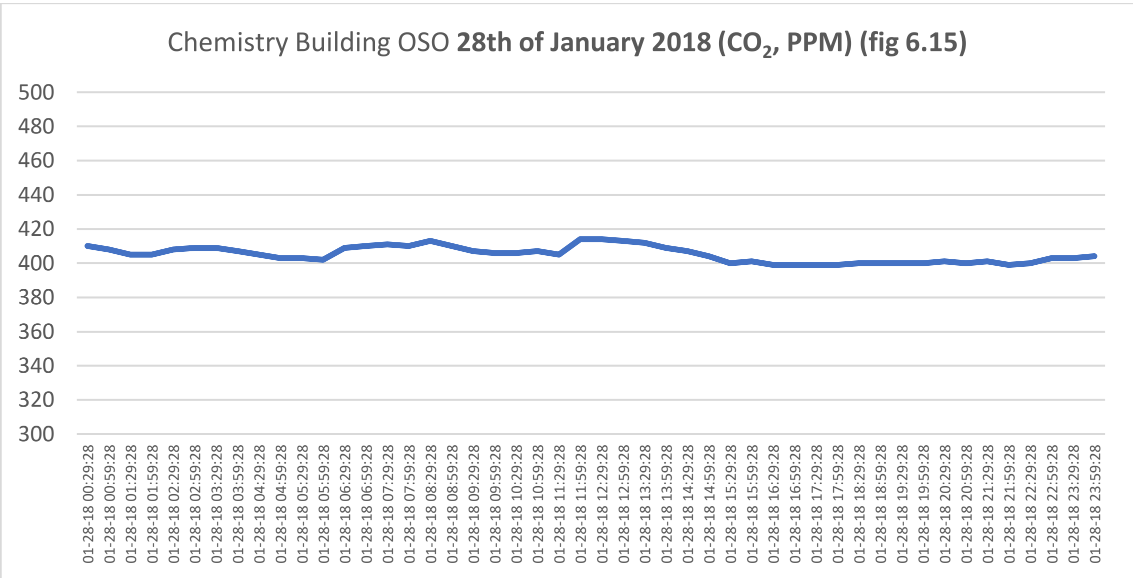

Figure 6-15 Chemistry Building OSO 28th of January 2018 (CO2, PPM)

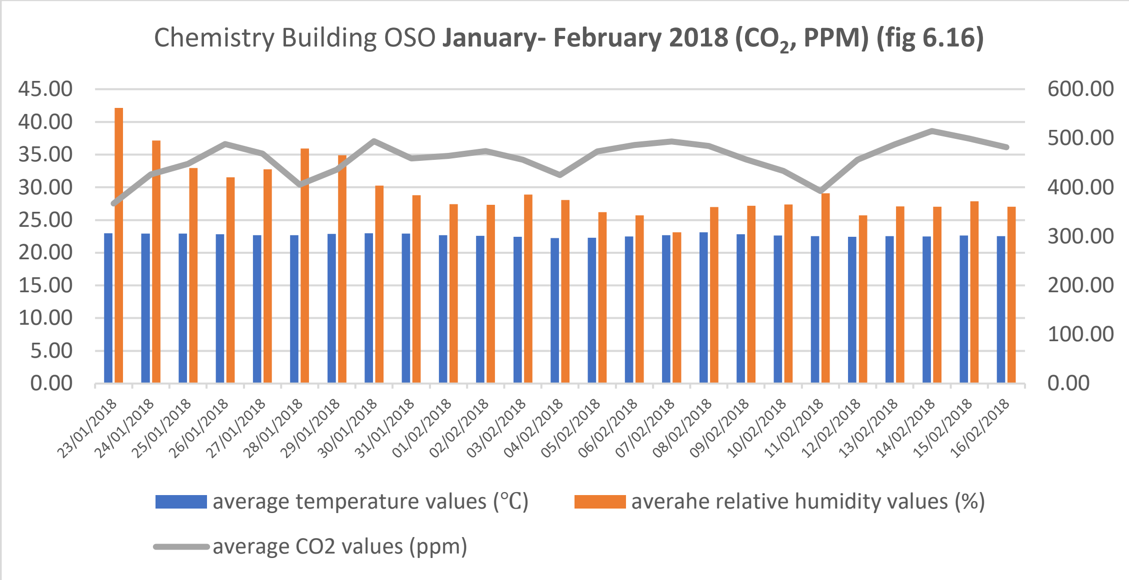

Figure 6-16 Chemistry Building OSO January- February 2018 (CO2, PPM)

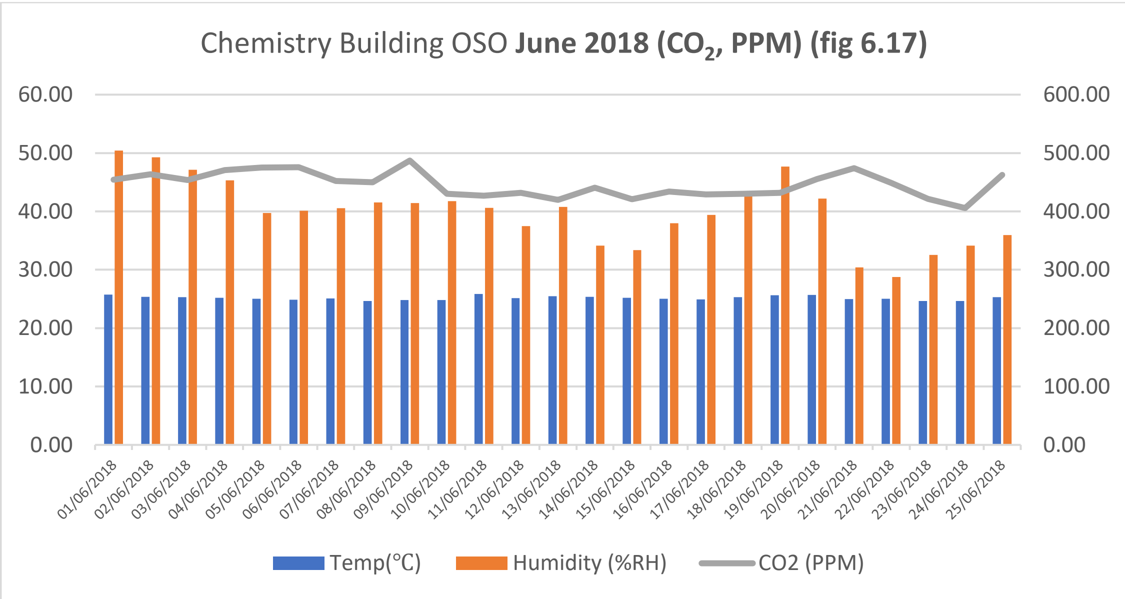

Figure 6-17 Chemistry Building OSO June 2018 (CO2, PPM)

6.2.2 June 2018

During the month of June, there is no significant increase in the concentration of CO_2 during the whole month. The average CO_2 concentration is around 450 ppm. The relative humidity does increase compared to the rest of the months from 35 (%) to 50 (%) with the exception of the 21st and the 22nd of June where a reduction in relative humidity occurs from 50 (%) to 29 (%).

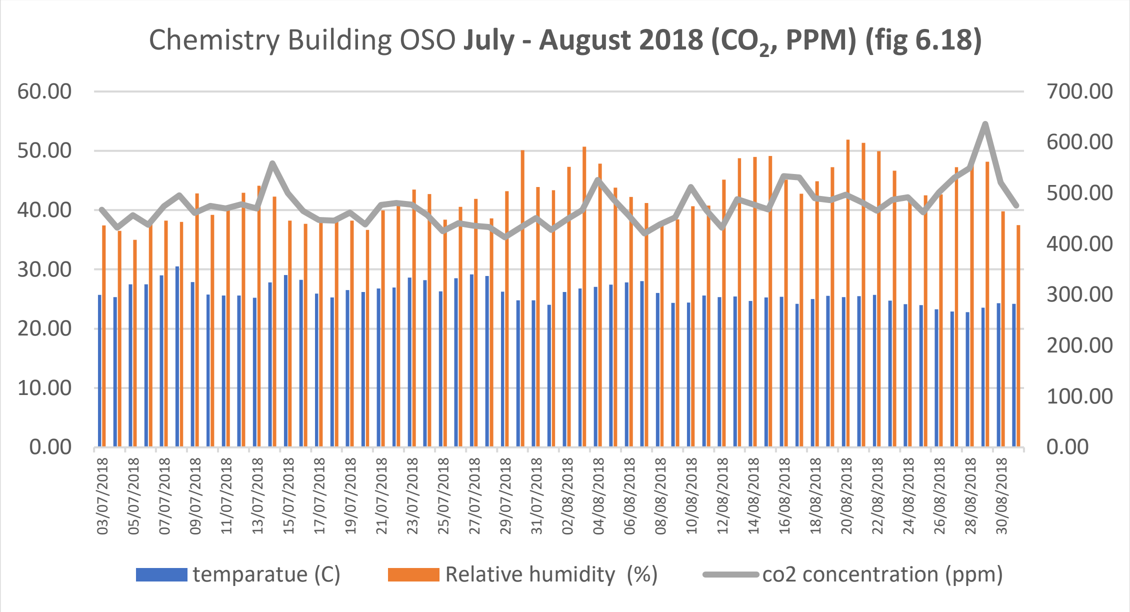

Figure 6-18 Chemistry Building OSO July - August 2018 (CO2, PPM)

6.2.3 July – August 2018

In the month of July, the average concentration of CO_2 is still similar to the previous month of June with an average concentration of 460 – 470 ppm. However, on the 14th and on the 15th of July, these two days show an increase in the CO_2 concentration to 600 ppm (fig. 6.17). the month of August has shown an increase in relative humidity at one time and an increase in temperature at another time. For example, on the 3rd of August was the highest recorded relative humidity percentage of 55.6 (%) that was corresponding to an ambient temperature of 26 °C, and on the 26th of July was the highest indoor ambient temperature recorded of 30.1 °C that corresponded with a relative humidity of 39 (%).

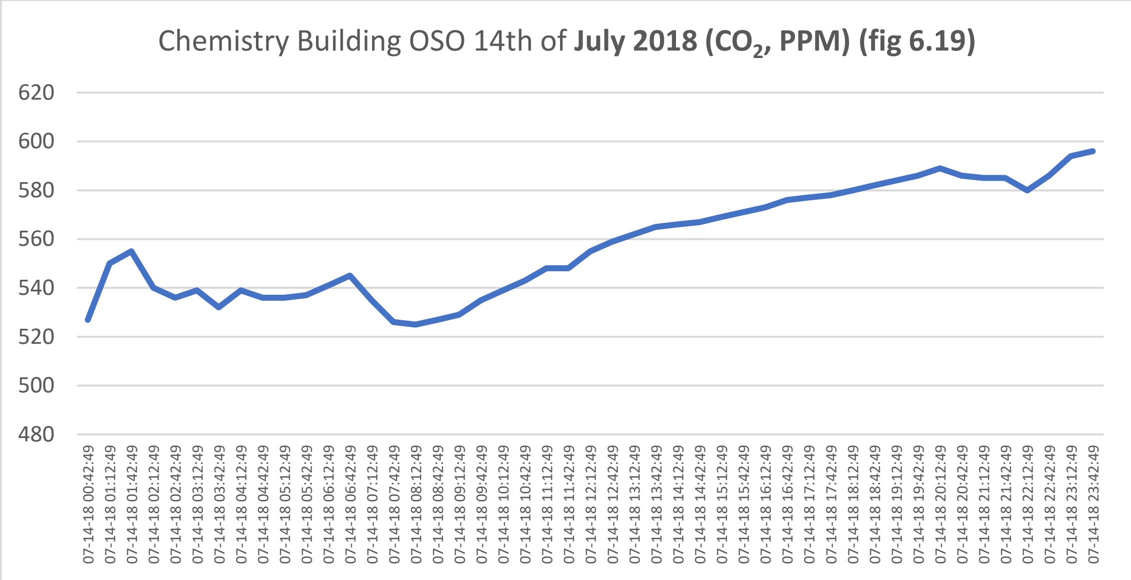

Figure 6-19 Chemistry Building OSO 14th of July 2018 (CO2, PPM)

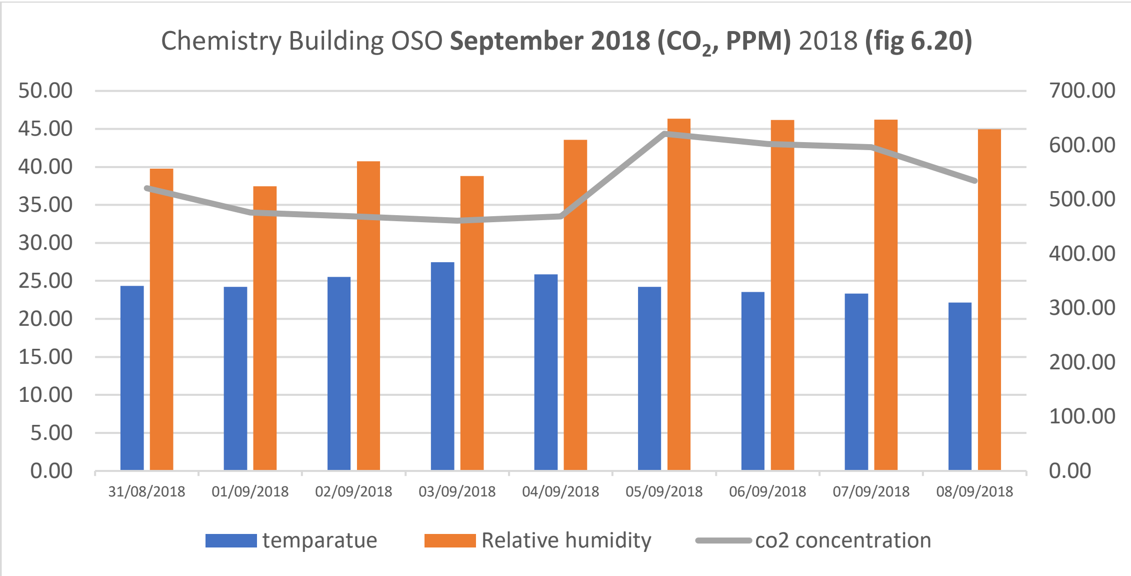

Figure 6-20 Chemistry Building OSO September 2018 (CO2, PPM) 2018

6.2.4 September 2018

When analysing the data from the first eight days of September, most of the data are very similar to other months. However, from the 4th of September to the 6th of September there is a significant increase in CO_2 concentration. In (fig. 6.19) the concentration of CO_2 rises from 600 ppm to 1100 ppm. This concentration is the highest acceptable concentration of CO_2. This increase is not common compared to other data taken from previous months and what is worth noting is that CO_2 concentration is usually high during the heating season and not in other periods like summer or spring.

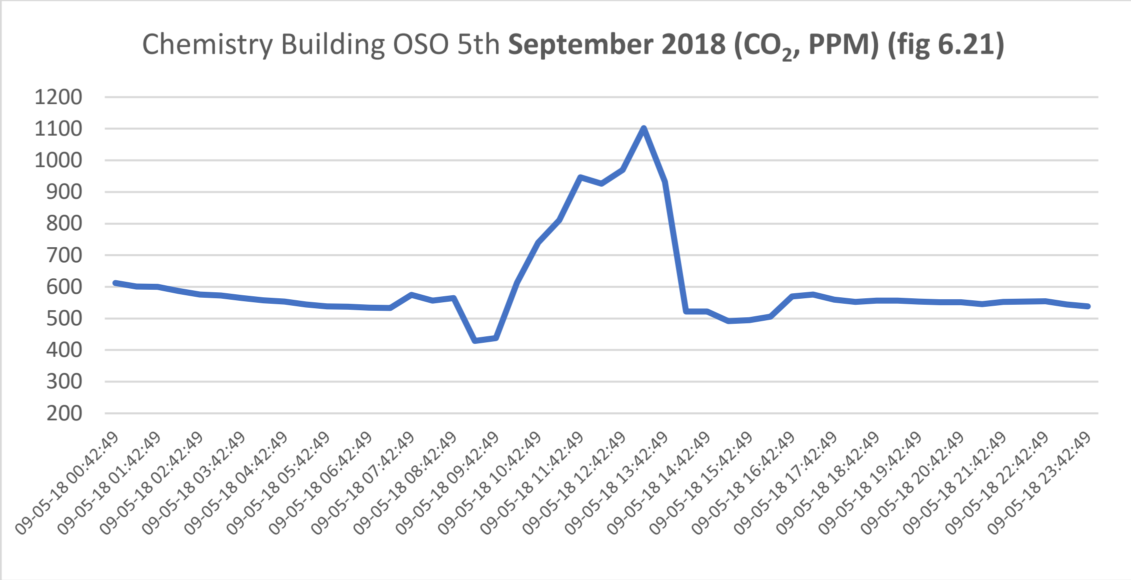

Figure 6-21 Chemistry Building OSO 5th September 2018 (CO2, PPM)

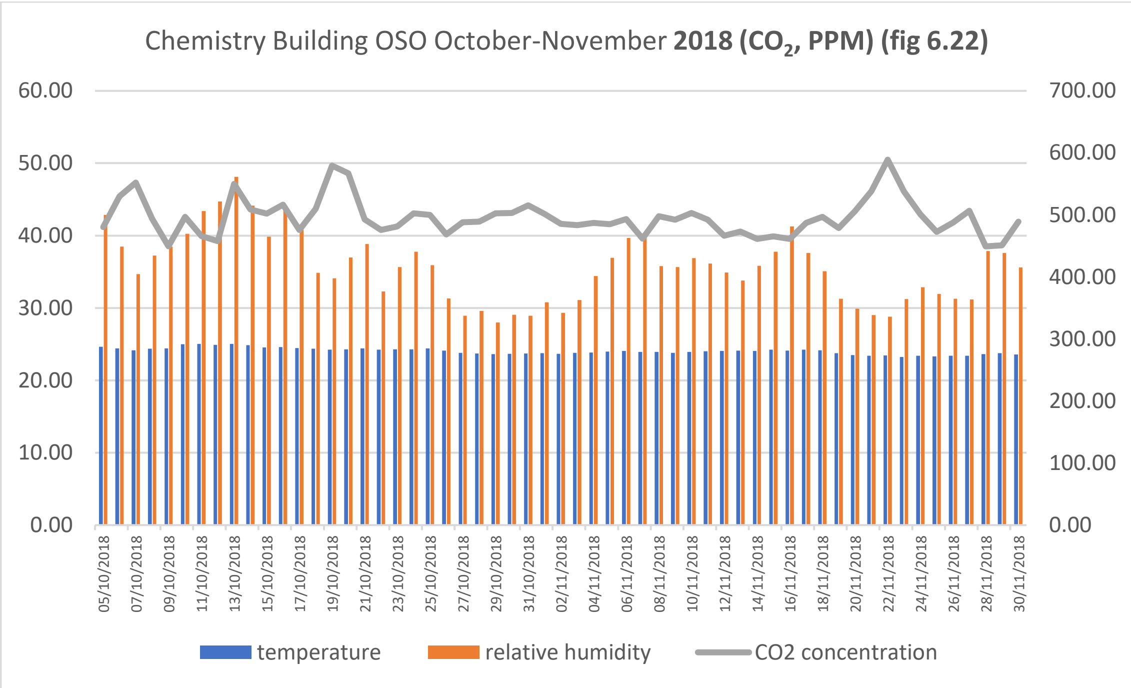

Figure 6-22 Chemistry Building OSO October-November 2018 (CO2, PPM)

6.2.5 October- November 2018

The data recorded during the month of October and November are very similar to each other. The average concentration of CO_2 is around 500 ppm. On some occasions, the concentration of CO_2 rises from 500 to 600 ppm and it appears that on these occasions the relative humidity decreases significantly. The data from the 19th of October, demonstrate that the relative humidity is very low (average of 34 %) and the CO_2 concentration on that day have reached 705 ppm. When comparing this result from another time like for example on the 12th of October, demonstrate that the relative humidity is close to 44 (%) and the concentration of CO_2 was 457 ppm. It could be inferred that on the 19th of October the employees were occupying the OSO space and therefore, their presence has increased the level of CO2 and it could be also inferred that low levels of CO_2 occur when the windows are closed. On the other hand, when the data from the 12th of October was examined, it showed that the average CO_2 concentration is much lower and the relative humidity is much higher. The reason could because of the absence of people inside the space and that the windows are kept open to preserve energy. The same phenomenon could be observed on the 21st of November where the average relative humidity is close to 29 (%) with the lowest level of relative humidity was 27.2 (%) and the average CO_2 concentration was 538 ppm with the heist recorded concentration of CO_2 was 625 ppm.

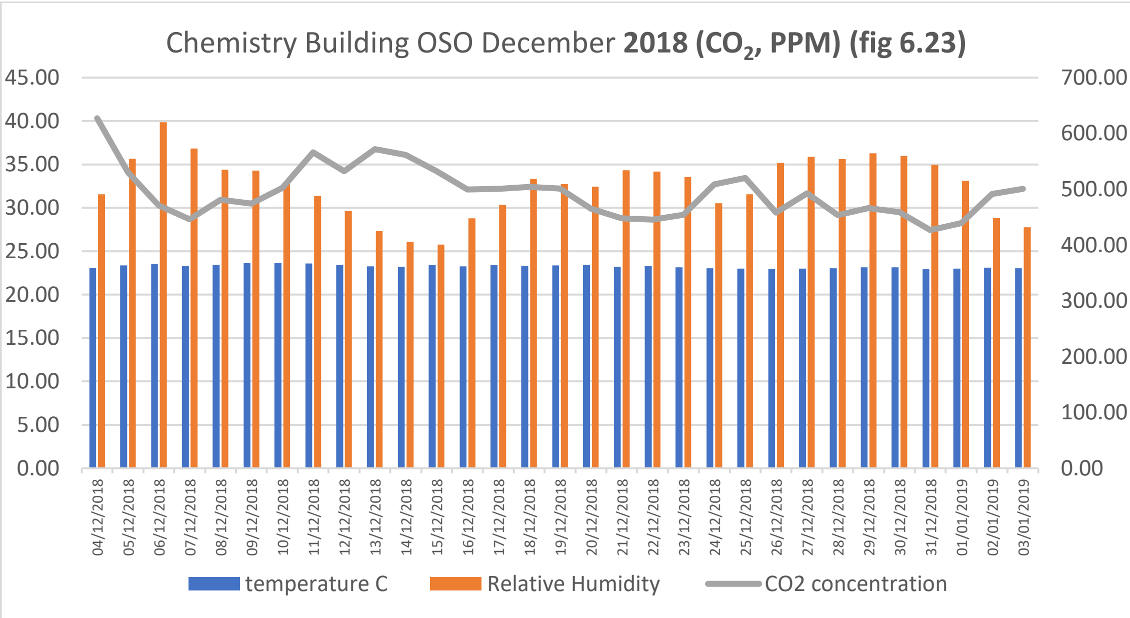

Figure 6-23 Chemistry Building OSO December 2018 (CO2, PPM)

6.2.6 December 2018

There are a few interesting trends that are very unique in the month of December. Looking at the chart in (fig. 6.24) shows that the Concentration of CO_2 starts at a high level around 600 ppm and then it starts to gradually decrease towards the end of the month. Of course, there are two occasions in the month of December in which the Chemistry building was empty all the time. In fact, the lowest recorded CO_2 concentration is around 388 ppm. This reading was taken on the 21st of December which corresponds to the holiday vacation. Another time this concentration level was reached was on the 31st of December. The average recorded CO_2 concentration was 426 ppm (fig 6.24)

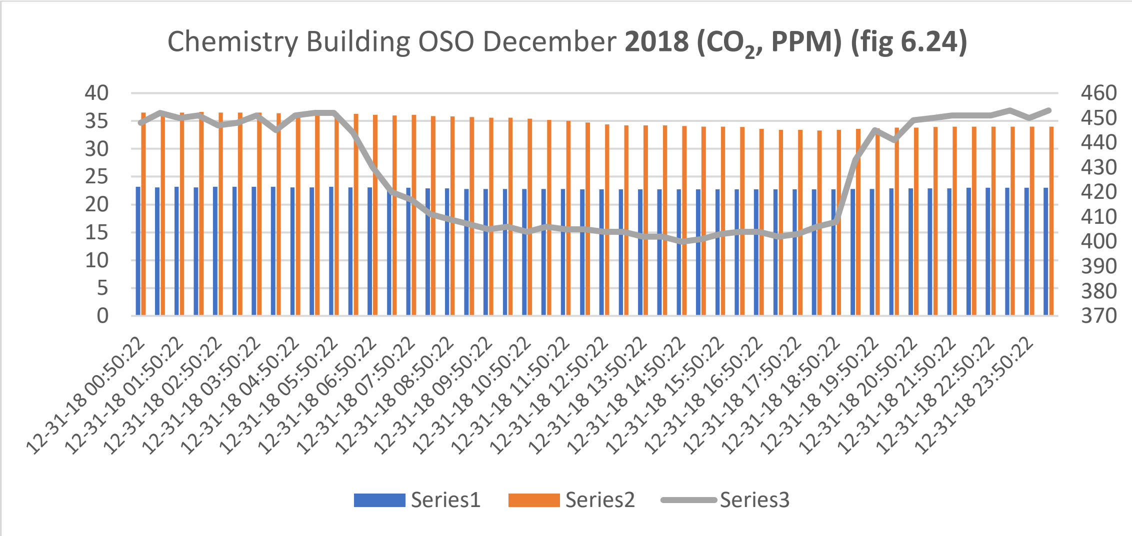

Figure 6-24 Chemistry Building OSO December 2018 (CO2, PPM)

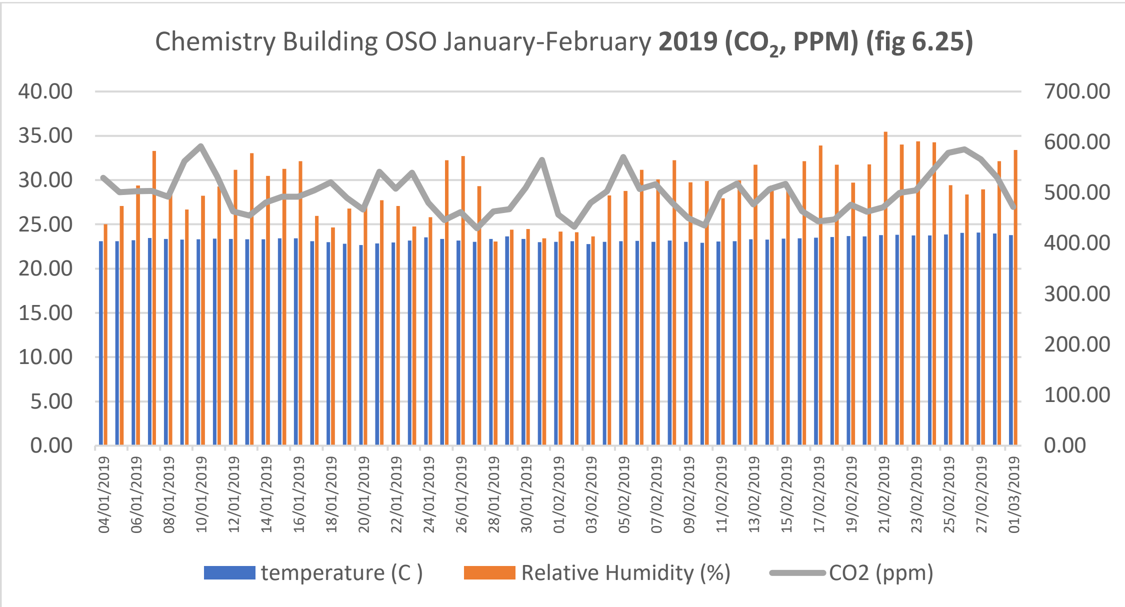

Figure 6-25 Chemistry Building OSO January-February 2019 (CO2, PPM)

6.2.7 January – February 2019

Most of the data recorded during the month of January are consistent with very little fluctuation in the recorded data. In most cases during the weekdays, the CO_2

concentration is constant throughout the first few hours of the day. Afterwards, when the employees and students come to the building the concentration of CO_2 starts to shift due to the constant movement of people through the space. There are two time periods where the peak concentration of CO_2 is reached and that is around 10:30 AM and 4:30 PM. At these times the concentration of CO_2 is at its peak. The only exception has occurred during the 10th of January on that day the level of CO_2 was high during most hours of the day. The average concentration was around 600 ppm with the highest recorded concentration was 714 ppm (fig. 624).

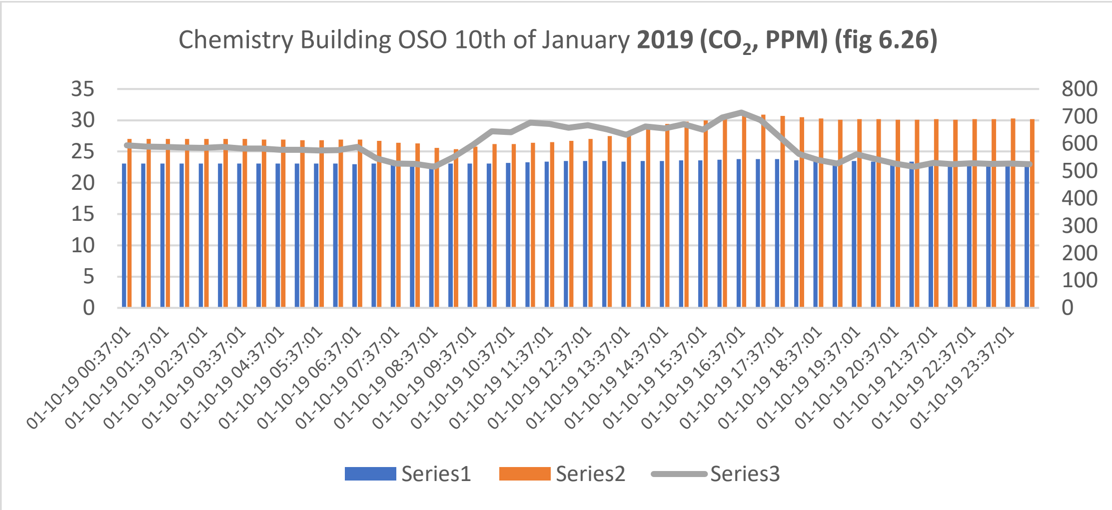

Figure 6-26 Chemistry Building OSO 10th of January 2019 (CO2, PPM)

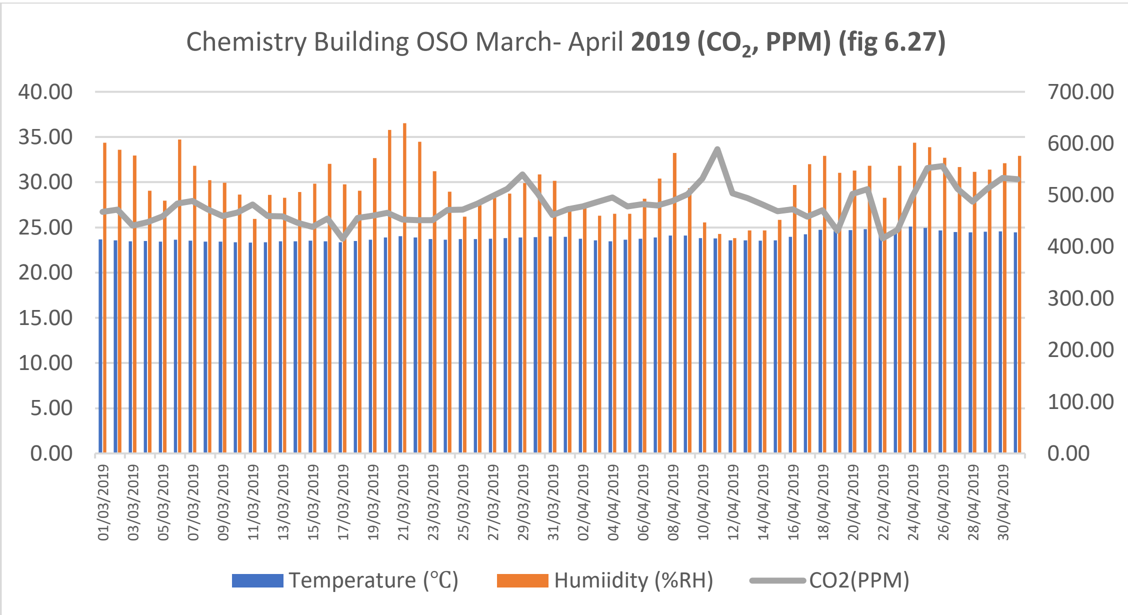

Figure 6-27 Chemistry Building OSO March- April 2019 (CO2, PPM)

6.2.8 March -April 2019

The readings during the month of March does not show any distinct pattern that is similar to other months. The concentration of CO_2 is lower on average than the readings taken in the month of January to February 2019. The average readings of CO_2 were 450 ppm on most days of the month. On some occasions, the CO_2 concentration is even lower than 400 ppm. The temperature readings were also stable and show no distinct pattern. The month of April has revealed on many occasions where there are odd circumstances that either increases the level of CO_2 dramatically or even decreases it. On one occasion the CO_2 concentration has risen from 467 to 814 ppm which shows almost double the concentration of CO_2. This reading was taken on the 11th of April 2019. What is odd about this reading is that the rise in CO_2 concentration happened after the normal working hours on the 10th of April 2019. It started from 464 ppm at 7:00 PM then it kept rising until it reached its peak at 12:30 AM the next day at 814 ppm. Generally, the CO_2 concentration tends to rise after the workers leave the OSO space and that could be attributed to the MVHR working at energy conservation mode. During this stage, the relative humidity is averaging at 26 (%) and the ambient temperature is around 23 °C. This phenomenon has happened again on the 25th and the 26th of April 2019. On a different occasion, it showed a different pattern occurring in the same month, the reading from the 19th of April the complete opposite happened. The concentration of CO_2 has decreased from 480 ppm to 380 ppm. What is different is that these low concentration did not occur regularly, instead, these reading have lasted several hours. The relative humidity is around 30 to 32 (%) and the average temperature is around 24 °C.

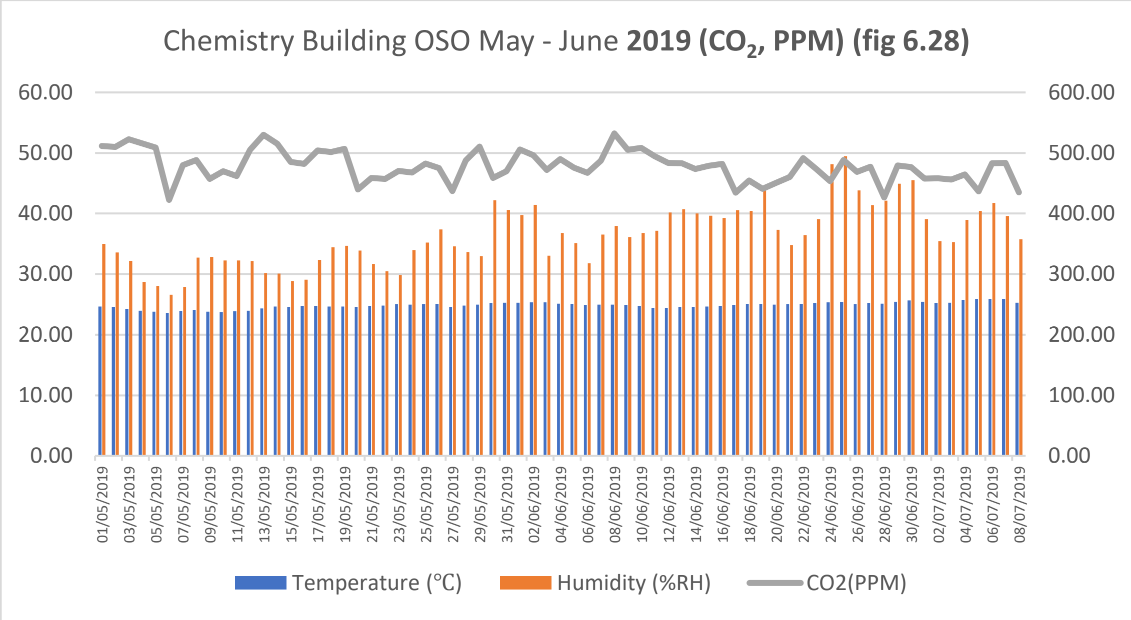

Figure 6-28 Chemistry Building OSO May - June 2019 (CO2, PPM)

6.2.9 May – June 2019

In May, it could be observed that the increase in the level of relative humidity starts in the low thirties at the begging of the month of May to the mid-forties at the later days in June where the highest relative humidity level was recorded on the 24th of June was 50.1 (%). There are very few occasions where the concentration of CO_2 increases above 550 ppm

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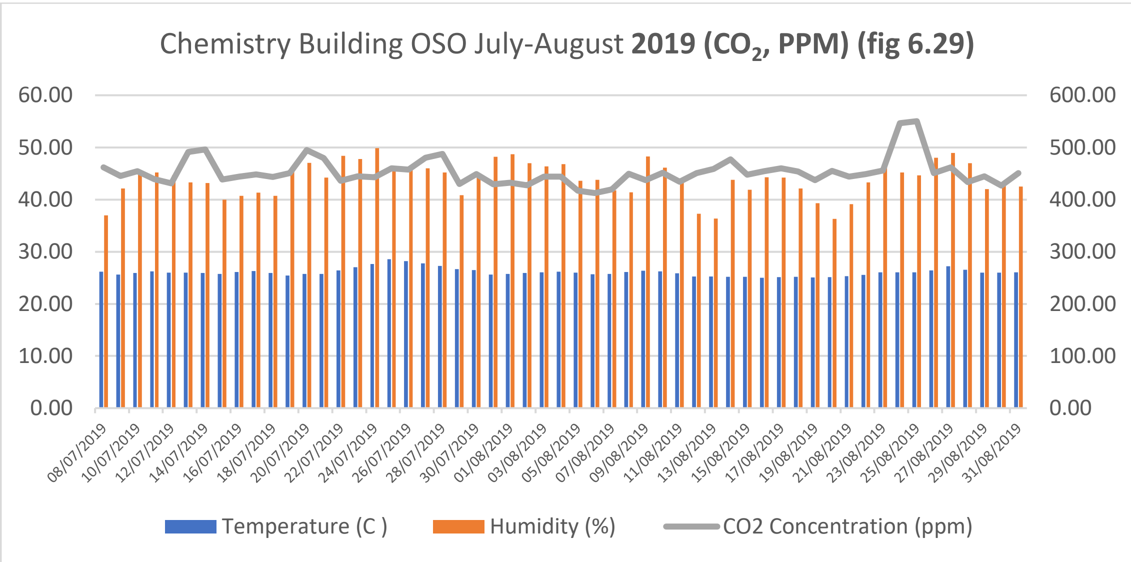

Figure 6-29 Chemistry Building OSO July-August 2019 (CO2, PPM)

6.2.10 July-August 2019

When analysing the data for the CO_2 concentration for the month of July, it will show that the average concentration of CO_2 is not very high. Taking the average of CO_2 for most of the days in the month it should be noticed that the average concentration of CO_2 is around 455 ppm. The average temperature and humidity are very high. by looking at the temperature, for instance, the average temperature throughout the month is around 26 °C. the highest temperature recorded inside the OSO was 30.4 °C while the highest recorded relative humidity level was 55.3 (%). The reason is likely because the windows and doors are open to the winter garden. In the month of September, the temperature and the relative humidity is not too high compared to the month of July. The ambient temperature is close to 26 °C and the relative humidity is close to 43 (%) although on some occasions it could be seen that the relative humidity does rise to 53 (%). The CO_2 concentration is very similar to the month of July, but on some occasions, the CO_2 concentration increases to 624 ppm.

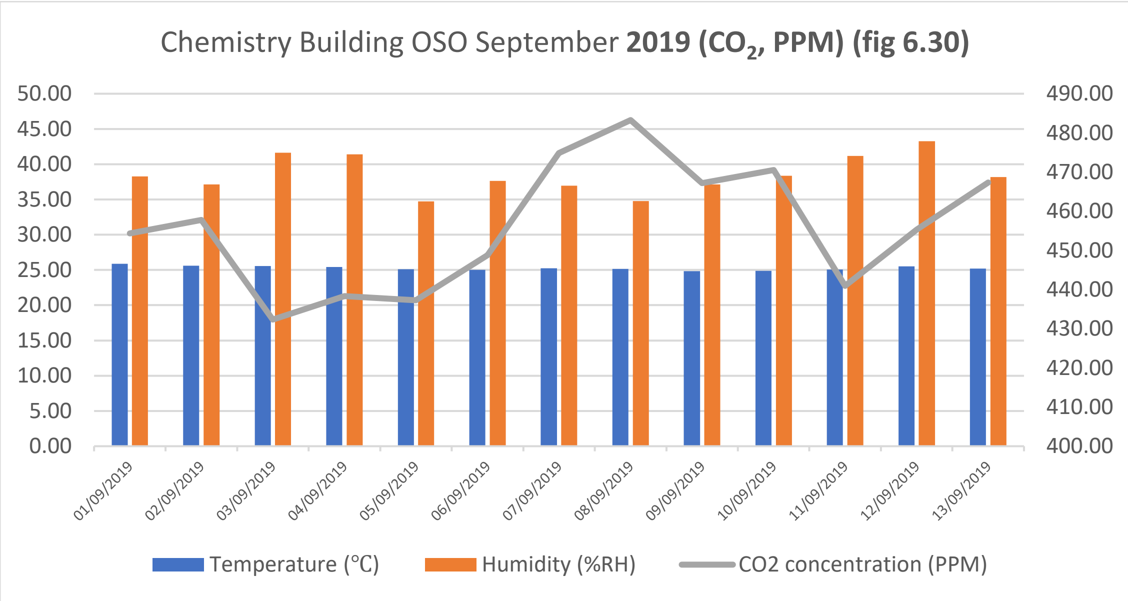

Figure 6-30 Chemistry Building OSO September 2019

6.2.11 September 2019

In the month of September, one could notice that the temperature starts to decrease slowly from 26 to 25 °C and the relative humidity is decreasing from 45 to 38 (%). The average CO_2 concentration is around 440 to 450 ppm.

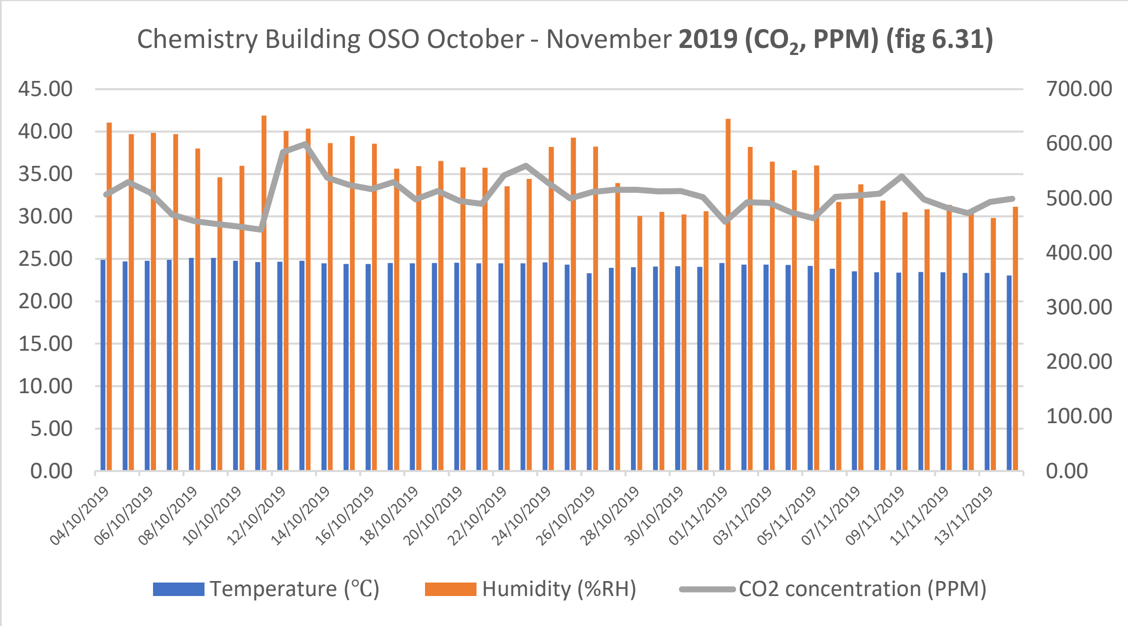

Figure 6-31 Chemistry Building OSO October - November 2019 (CO2, PPM)

6.2.12 October – November 2019

The average concentration of CO_2 in October is slightly higher than in September. As can be seen from the chart (fig 6.31) the concentrations of CO_2 are between 450 – 500 ppm. The relative humidity starts to decrease gradually. At the beginning of the month, the relative humidity is closer to 40 (%), however, at the end of the month, the relative humidity is closer to 30 (%). In the month of November, the trend continues with a decrease in relative humidity. The relative humidity at the beginning of November is in the mid-thirties (30-35 %), and at the end of the month, the relative humidity is closer to 28 (%). The ambient temperature also decreases from 24 to 23 °C.

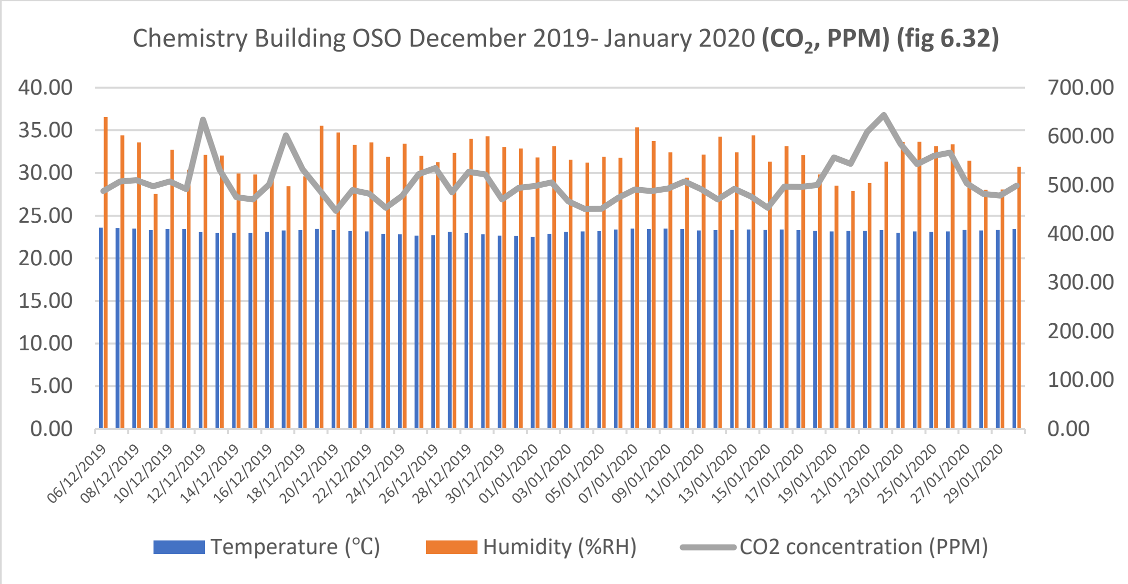

Figure 6-32 Chemistry Building OSO December 2019- January 2020 (CO2, PPM)

6.2.13 December 2019 – January 2020

The month of December is a typical heating period where the concentration is slightly higher than the other month of the year due to the fact that the doors and windows are mostly closed during working hours. On one occasion on the 12 of December, the concentration of CO_2 was higher than usual and resembles the same phenomenon that happened on the 11th of April 2019 when the CO_2 concentration started to rise during the light hours of the day and continued until the next morning. Fig (6.33) shows the rise in CO_2 levels between December 12 and December 13. The rise in the concentration starts at 12:00 PM with a concentration of 467 ppm and continues until it reaches 957 ppm around 8:00 PM the same day. the relative humidity had also risen with the rise of CO_2. The relative humidity started at 29 (%) and then it has risen until it reached 36.6 (%).

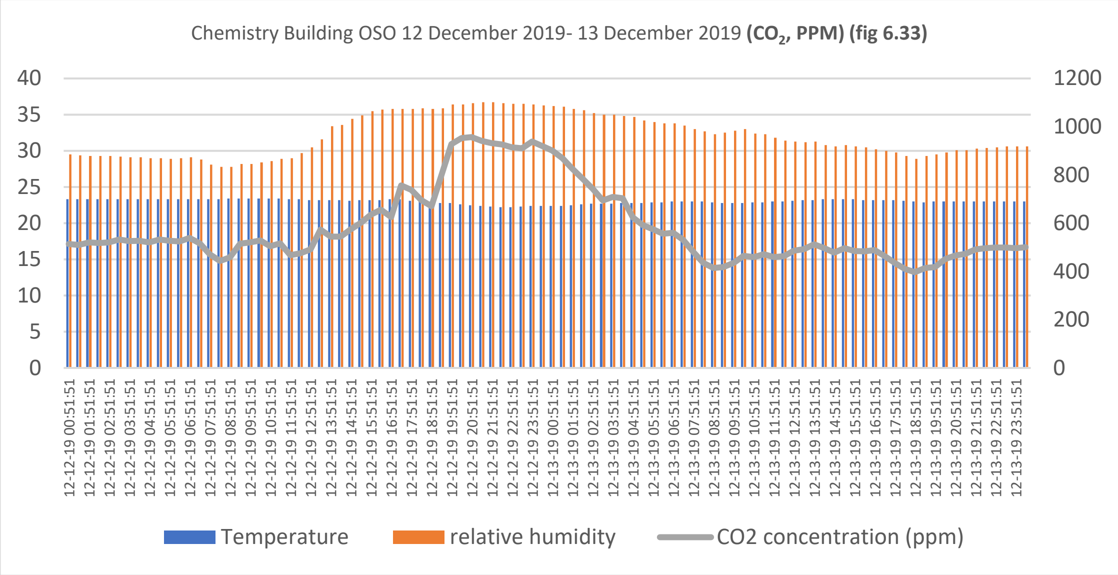

Figure 6-33 Chemistry Building OSO 12 December 2019- 13 December 2019 (CO2, PPM)

6.3 Chemistry Building FFO PM & VOC

The reason why the FFO was included in the data collection is because of the result from the survey conducted inside the building. This survey has included 64 people who were working and studying inside the GSK chemistry building. The result of the survey suggested that there was a lack of thermal comfort in the laboratories close to these office spaces. The recordings have started on the 8th of July 2019 and continued until the end of December 2019. The room is much smaller than the OSO and it hosts 12 graduate students. The MVHR is base on an extract fan located at 3.5 meters above the floor and it draws air from the FFO and the laboratory adjacent to it.

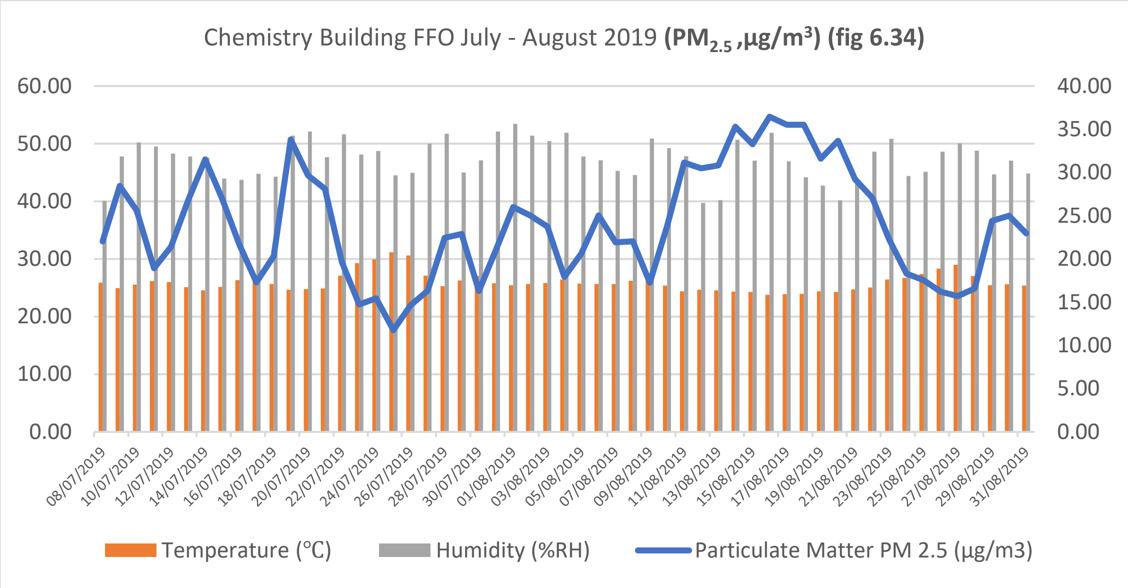

Figure 6-34 Chemistry Building FFO July - August 2019 (PM2.5,µg/m3)

6.3.1 July – August 2019

When analysing the data for the FFO it shows that that the concentration of $PM_{2.5}$ is much higher than those concentration recorded in the OSO. The average concentration of $PM_{2.5}$ in the month of July is 22 µg/m^3. This could be because there is a significant number of people working per area compared to the OSO. The FFO has 12 students working in an area of 48 m^2, while the OSO is much bigger in terms of space. Not only that, but the FFO has fewer air inlets and outlets. Looking at figure (6.34) shows that the range of $PM_{2.5}$ concentration is more susceptible to the presence of people inside the space. On the 9th of July for example, at the beginning of the day at 12:00 AM the concentration of $PM_{2.5}$ is very high at 35 µg/m^3. The $PM_{2.5}$ levels remain like that for a long period of time and then it starts to drop to 21 µg/m^3 around 12:00 PM and then to 17 µg/m^3 around 2:00 PM. This suggests that the presence of students inside the space might have an effect on the concentration levels of $PM_{2.5}$. During the weekend like, for example, the 13th of July, the concentration of $PM_{2.5}$ starts at 21 µg/m^3, rises to 35 µg/m^3 at 4:30 AM, and then drops to 21 again at 1:00 PM. What is also interesting is that the ambient temperature is also high in the month of July. On the 25th of July, the highest recorded ambient temperature inside the FFO was 33.7 °C. the highest relative humidity level was recorded at 60.3 (%) on the 19th of July.

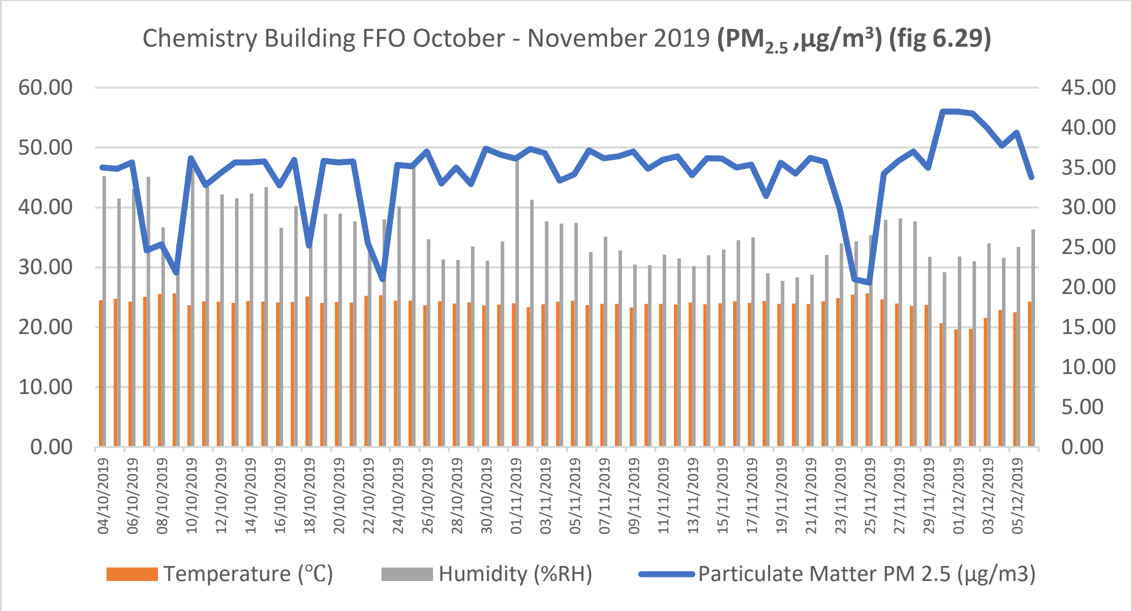

Figure 6-35 Chemistry Building FFO October - November 2019 (PM2.5,µg/m3)

6.3.2 October- November 2019

In the month of October, the concentration of $PM_{2.5}$ is always high with little fluctuation in the level of concentration. For example, on the 5th of October, the concentration of $PM_{2.5}$ have started at 35 µg/m^3 at the beginning of the day and it remains at the same level of concentration throughout the day with little to no changes in the level of concentration. On the 8th of October, the conditions are different, the concentrations of $PM_{2.5}$ varies because of the presence of students and researchers inside the FFO. The $PM_{2.5}$ concentration starts at 35 µg/m^3 and then it starts to decrease until it reaches 17 µg/m^3 at 5:30 PM. When comparing the ambient temperature recordings from the FFO to the OSO space it could be realized that the ambient temperature in the FFO space varies more frequently than the OSO. For instance, on the 18th of October, the ambient temperature ranges from 23 to 25 on the same day. One thing to note about the FFO is that the door to the office is left open most of the time because the students are moving constantly from in and out of the office. When analysing the data from the month of November it could be realised that the pattern of readings is similar to the month of October with less fluctuation. There are, however, few exceptions to that trend. On the 24th of November, the concentration of $PM_{2.5}$ was 21 µg/m^3 the whole day. Even though it was a weekend day, the same thing did not occur at the previous weekend in the same month. Another exception happened on the 30th of November when the concentration of

$PM_{2.5}$ was 47 µg/m³. This concentration lasted three consecutive days with the same concentration which is unprecedented.

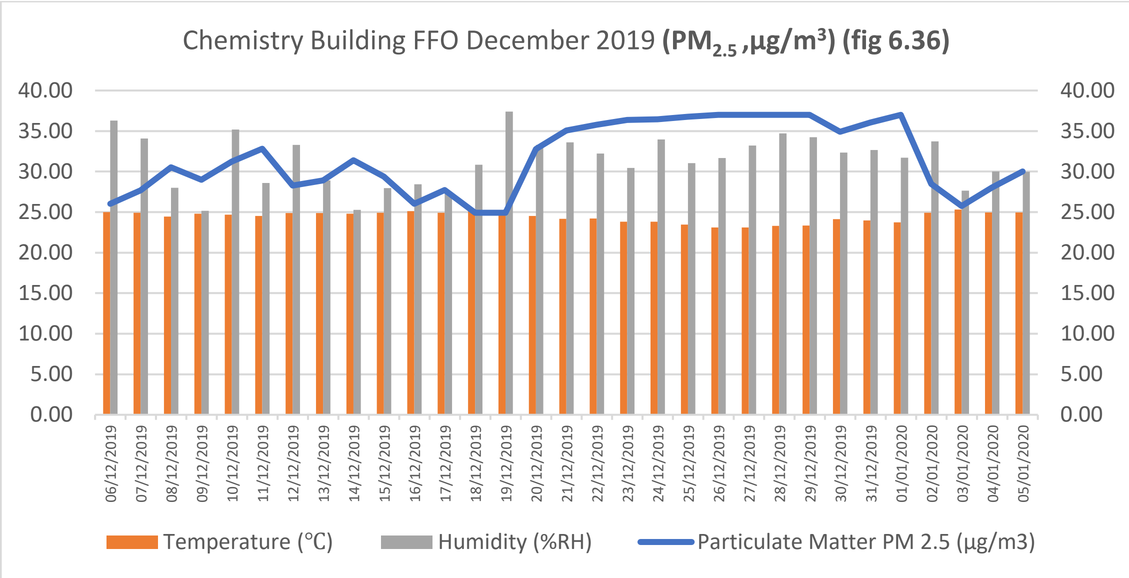

Figure 6-36 Chemistry Building FFO December 2019 (PM2.5,µg/m3)

6.3.3 December 2019

At the beginning of the month, the concentration of $PM_{2.5}$ varies within the same day, unlike the readings that were taken during the previous two months where the concentration does not vary significantly within the same day. On the 25 of December, the level of $PM_{2.5}$ remained at 37 µg/m³ for six consecutive days. The levels of humidity are generally low in the month of December. On many days the average level of relative humidity is at 25 (%), but on most days it’s between 30 – 35 (%).

6.4 Chemistry Building FFO CO2

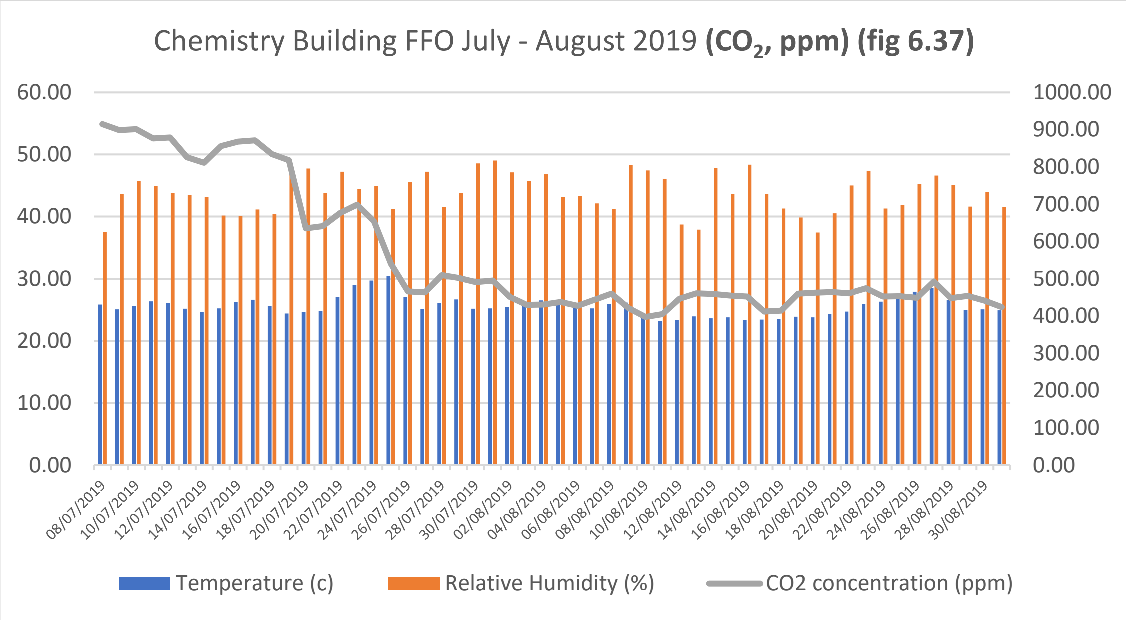

Figure 6-37 Chemistry Building FFO July - August 2019 (CO2, ppm)

6.4.1 July – August 2019

At the beginning of the month of July, the concentration of CO_2 is considerably high. For example, in the first readings taken on the 8th of July, the highest CO_2 reading was 1795 ppm. This reading is an anomaly compared to the rest of the readings. Most of the readings on the 8th of July is around 850 – 992 ppm. From the 8th of July onward until the 20th of July the concentration of CO_2 is very high compared to the rest of the readings taken in the month of July (850 – 990 ppm). These high levels of CO_2 concentration indicate a significant presence of people coming in and out of the FFO. The high levels of CO_2 do not seem to correlate with the ambient air temperature inside the room. In fact, during the first ten days when the CO_2 concentration was high, the ambient air temperature was not significantly high. However, the highest ambient air temperature recorded was on the 25th of July which was 33.8 °C and the CO_2 concentration was around 535 ppm. The readings in the month of August is much lower than the beginning of the month of July. This could be observed from the chart in (fig. 6.37) where at the beginning of the month of July the CO_2 concentration was very high and then the levels of CO_2 will gradually decrease. For example, on the first day of August, the concentration of CO_2 is close to 495 ppm and on the 10th of August is close to 397 ppm.

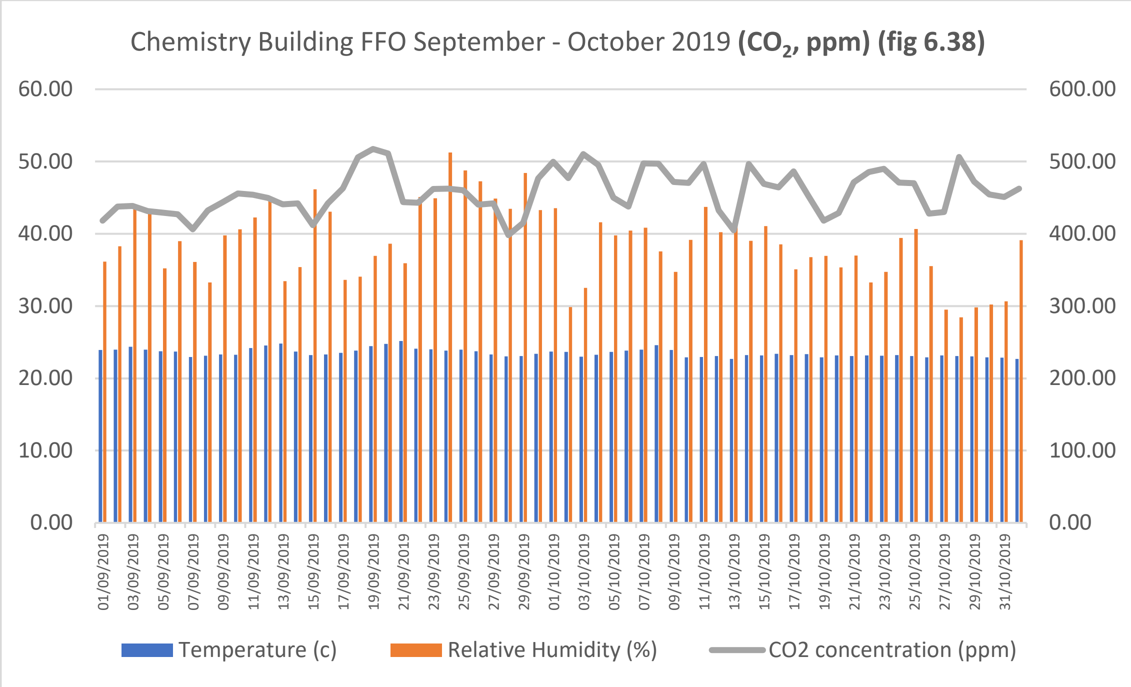

Figure 6-38 Chemistry Building FFO September - October 2019 (CO2, ppm)

6.4.2 September- October 2019

The month of September does not show any major fluctuation in the levels of CO_2 concentration. The average levels of CO_2 concentration in the FFO are between 420 – 500 ppm. The data shows that most of the working days have the same pattern of CO_2 concentration. The CO_2 concentration starts to increase at 8:00 AM in the morning and peaks during the hours from 12:00 PM to 1:00 PM, after that the levels of CO_2 starts to decline from their peak concentration to their lowest concentration at 6:00 PM in the evening. In the month of October, the CO_2 concentration follows a similar pattern that happened in September, with the exception that the concentration in October is sometimes higher during the peak hours of the working days. For instance, on the 11^{th}, 14^{th}, and 28^{th} of October the highest concentration of CO2 during the peak hours is around 700 ppm.

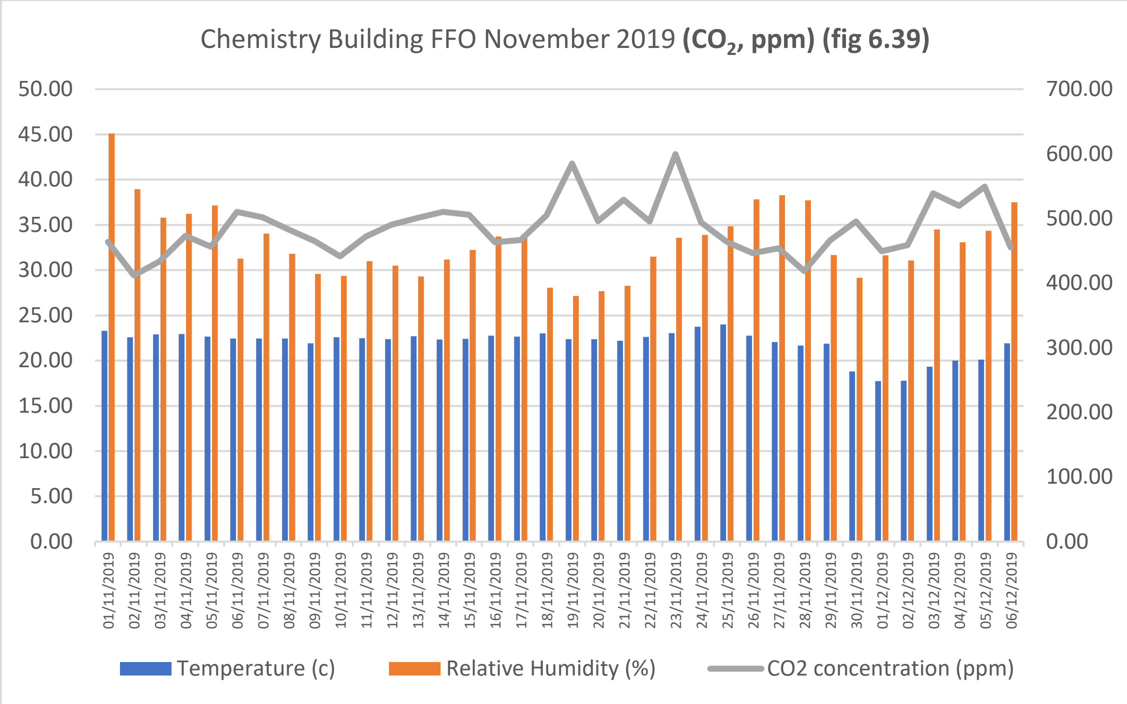

Figure 6-39 Chemistry Building FFO November 2019 (CO2, ppm)

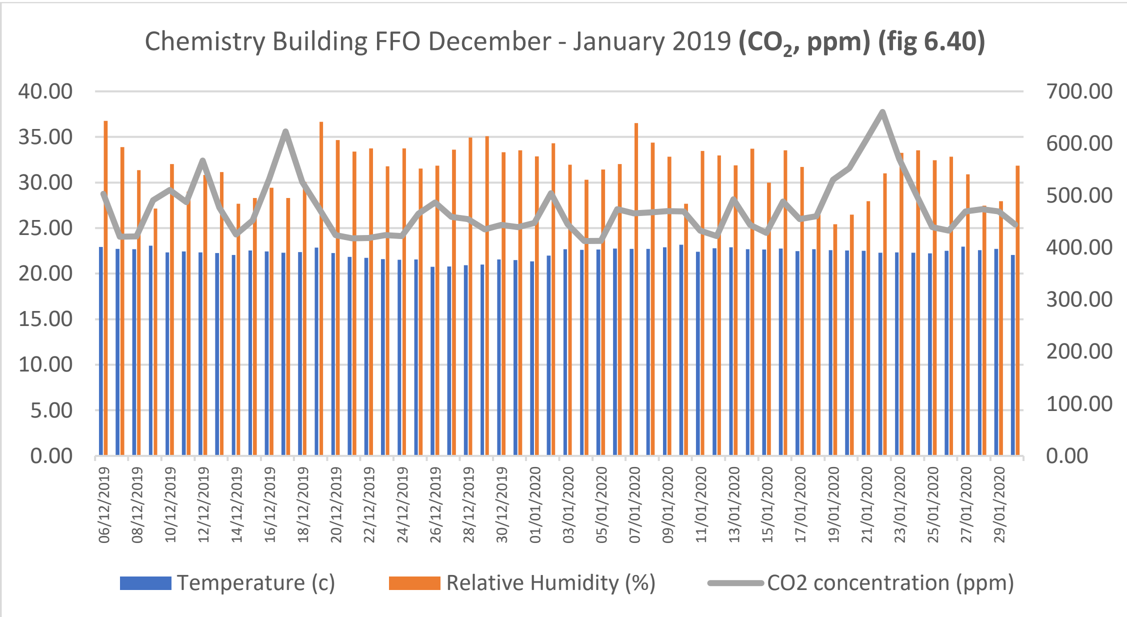

Figure 6-40 Chemistry Building FFO December - January 2019 (CO2, ppm)

6.4.3 November – December 2019

The CO_2 readings in the month of November show some unique patterns. Two unique patterns emerge that are consistent with the heating season. The first pattern is the higher levels of CO_2 concentration that can be seen on the 11th to 15th of November. During this period the CO_2 concentration is higher than 650 ppm. Another pattern is the lower level of relative humidity starting from the 18th of November until the 22nd of

November. During these dates, the relative humidity is lower than 30 (%), and on many occasions, the levels of humidity are even lower than 25 (%). The month of December shows a similar characteristic to the month of November. The CO_2 concentration is higher than in other months, and the relative humidity is lower in the month of December than in other months. For example, on the 8th of December, the lowest concentration of CO_2 has been recorded at 385 ppm and the highest concentration was on the 16th of December (857 ppm). The lowest concentration for relative humidity was on the 15th of December was 20 (%). The high levels of CO_2 were also recorded on the 21st of January 2020 around 866 ppm.

6.5 Eco House PM & VOC

The Eco-house is one of the energy efficiencies houses that was built at the University of Nottingham. They are homes that were built with a low-carbon standard set by the UK government. The house uses a radiant floor heating system that generates heat within a pipe system laid underneath the flooring of the house and it depends on natural ventilation through the sunroom and the other regular windows especially in the cooling season. The monitoring of the pollutants was set inside the kitchen area where most of the pollutants might originate. The number of people occupying the EHS is very limited to the number of student and researchers working inside the house.

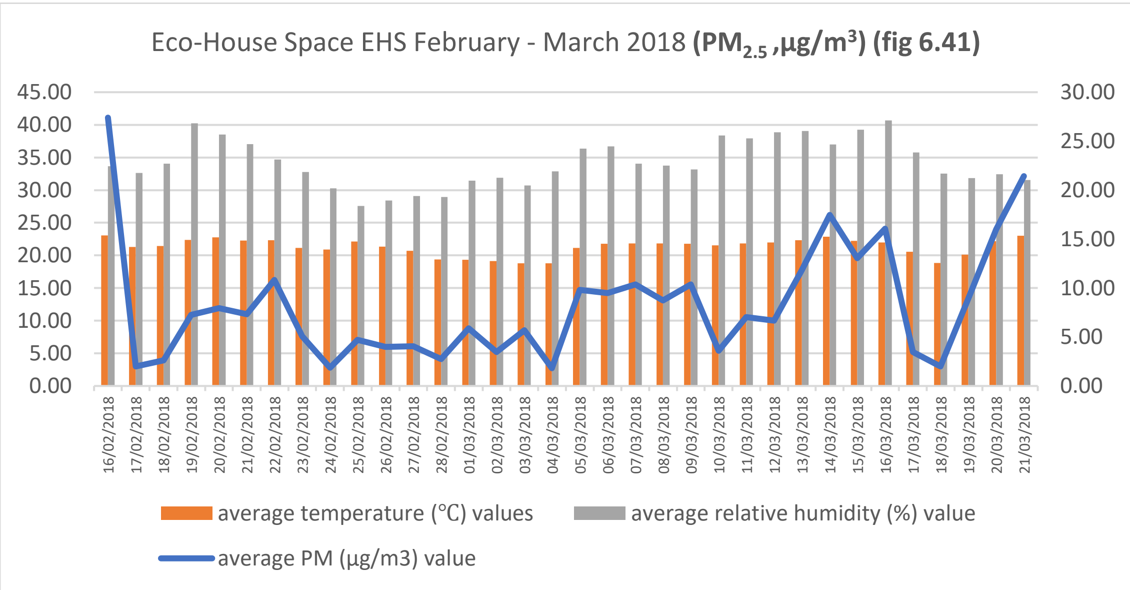

Figure 6-41 EHS February - March 2018 (PM2.5,µg/m3)

6.5.1 February-March 2018

In the heating season, the levels of $PM_{2.5}$ concentration shows varied levels. At the start of the day, the levels are very low between 2-4 µg/m^3. However, when people start to come to the EHS the levels of $PM_{2.5}$ starts to increase dramatically. On the 19th of February, the levels of $PM_{2.5}$ starts at 2 µg/m^3 until 10:00 AM when students and employees start to arrive at the building the $PM_{2.5}$ levels start to increase until it reaches 34 µg/m^3 at 1:00 PM. Since the sensors were located in the kitchen, this increase in $PM_{2.5}$ concentration is mostly attributed to the frequent visits to the kitchen area where most of the workers would prepare food and sit there to chat and have their afternoon break. The pattern does not occur at the weekend where the levels of $PM_{2.5}$ remains the same throughout the day. This pattern persists throughout the month of February with higher increases of $PM_{2.5}$ that could reach up to 44 µg/m^3. Because the house is ventilated mainly with natural ventilation, the ambient temperature inside the EHS is less stable than other controlled MVHR space. For example, on the 28th of February 2018, the ambient temperature is less than 19 °C in most of the day.

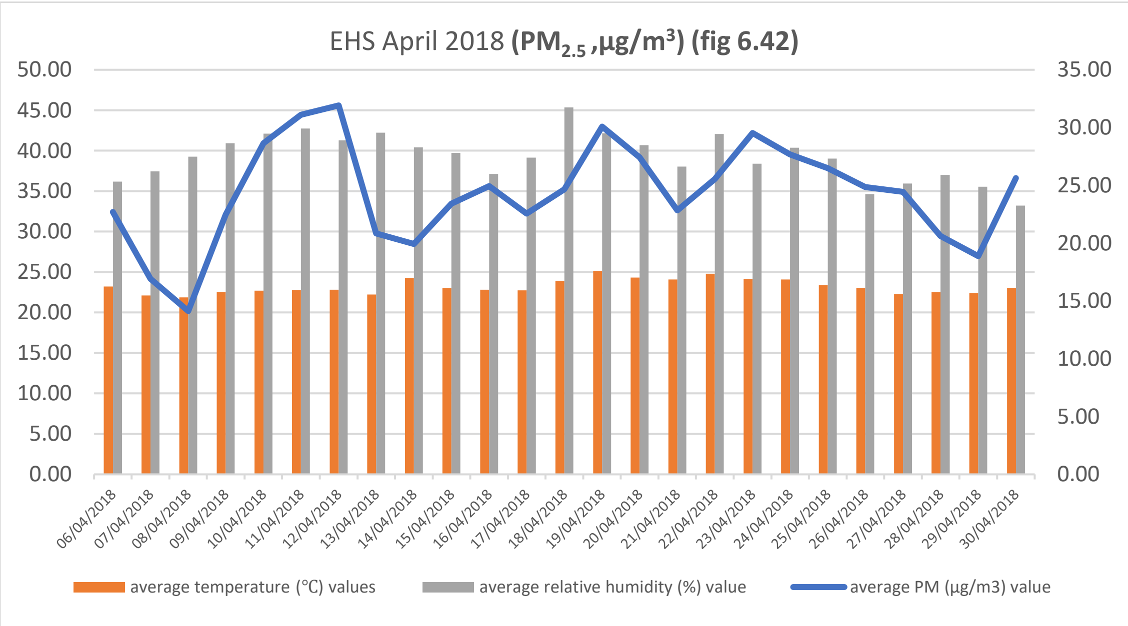

Figure 6-42 EHS April 2018 (PM2.5,µg/m3)

6.5.2 April 2018

The month of April comes after the cooling season and that is shown in the recordings of the $PM_{2.5}$ levels. Compared to the month of February and March, the readings of $PM_{2.5}$ is higher even in the early hours of the day. One example could be seen from the data taken on the 16th of April. At the beginning of the day, the $PM_{2.5}$ was 15 µg/m^3 at 12:00 AM. The level of $PM_{2.5}$ then will increase until it reaches 63 µg/m^3 at 7:30 AM. This is not the only incident where the level of $PM_{2.5}$ reaches 60 µg/m^3. In fact, most of the working days in the month of April has the same pattern, and in most cases, the highest increase occurs in two distinct times. The first is around 7:00 AM in the morning which is uncommon because most of the rise in $PM_{2.5}$ take place in the afternoon where most of the occupants are taking moving around the house and taking their afternoon break. The other time where most of the increase in $PM_{2.5}$ take place around 1:00 PM. The ambient temperature is more stable in the month than in previous months. The relative humidity has increased from 25 -30 (%) in the previous months of February and March to 35 – 40 (%).

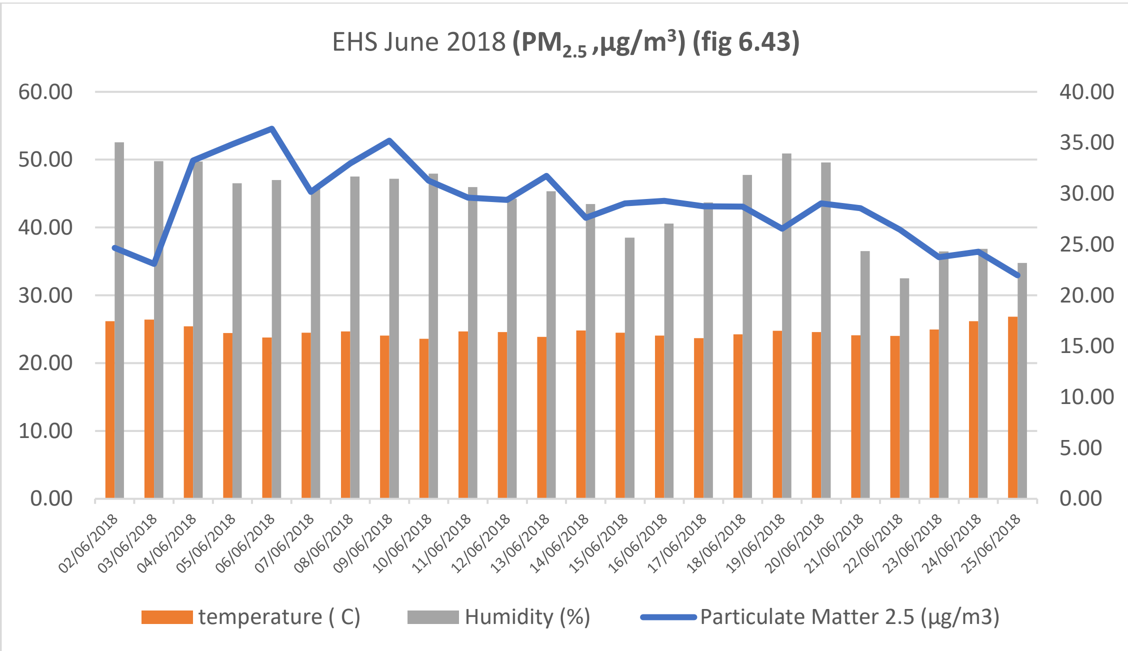

Figure 6-43 EHS June 2018 (PM2.5,µg/m3)

6.5.3 June 2018

During the cooling season month like June, July, and August the windows are kept open most of the time the researchers and students are occupying the space. When looking at the chart (fig 6.37) it could be seen that the relative humidity especially at the beginning of the month where the relative humidity is considerably high at 50 – 55 (%). The house ambient temperature is very moderate at 23 – 25 °C. On one occasion the ambient temperature has reached 28.6 °C on the 24th of June and on many occasions the ambient temperature has reached 27 °C. Not only that but also the $PM_{2.5}$ have reached high levels of 60 µg/m^3. These data could be explained by the open windows that were open during the month of June. It is worth noting that the levels of $PM_{2.5}$ have been consistent throughout the whole month with data showing that the levels are around 25 – 30 µg/m^3. This could suggest that the presence of workers and student is less frequent compared to other months like April and May.

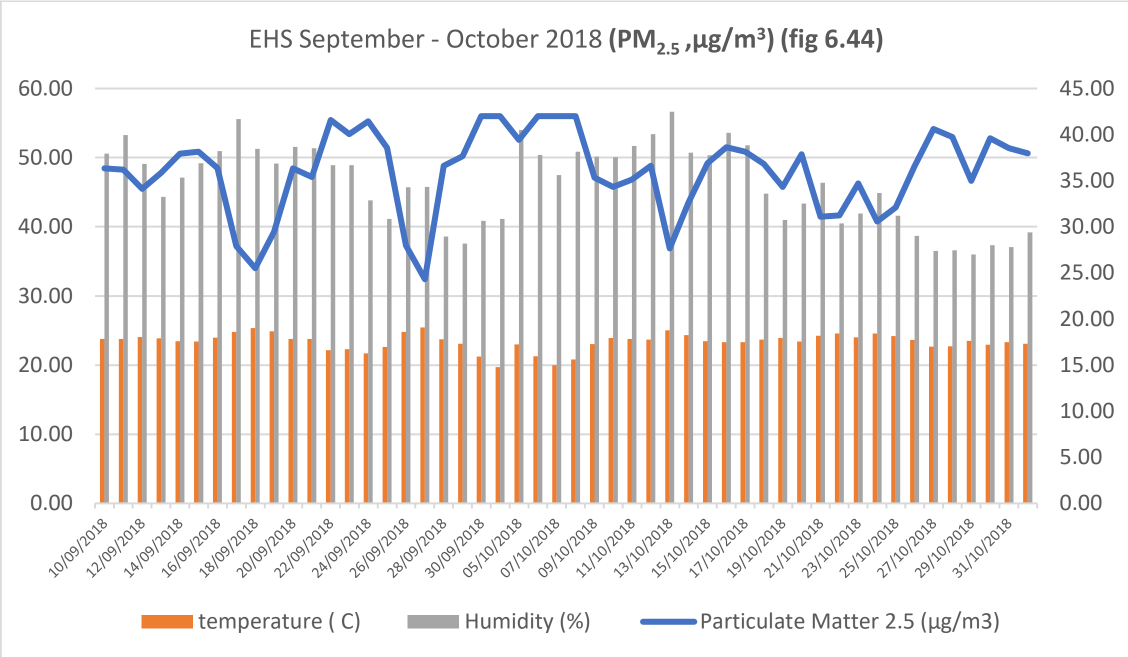

Figure 6-44 EHS September - October 2018 (PM2.5,µg/m3)

6.5.4 September – October 2018

The month of September has exhibited even higher recordings from the month of June. For example, the relative humidity levels are very high as seen on the 17th of September where the relative humidity has reached 67 (%). However, that reading was not the only time when the relative humidity has reached high levels of 60 (%) and above. The $PM_{2.5}$ concentration is high most of the month of September. The level ranges from 17 – 42 µg/m^3. Looking at the data indicates that the ambient temperature is decreasing the closer it gets to October. At the beginning of September, the average ambient temperature is close to 23 °C, and at the end of the month, the ambient is getting closer to 19 °C. the month of October is similar to the month of September in terms of $PM_{2.5}$ concentration. However, the relative humidity is gradually decreasing at the end of the month of October as can be seen from fig (6.38).

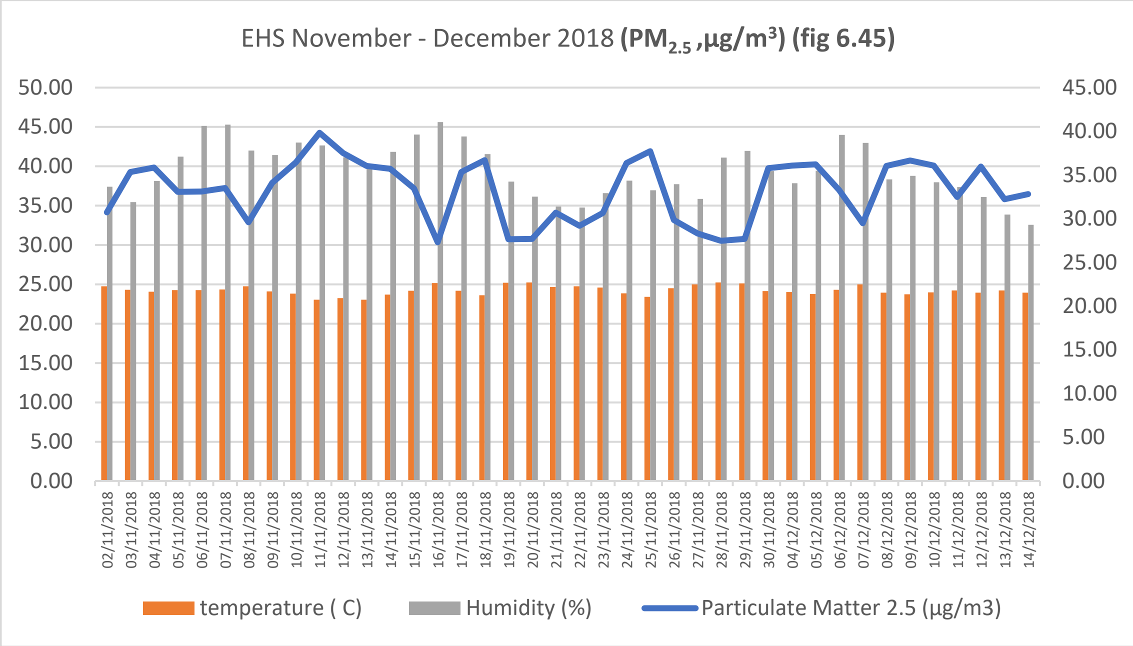

Figure 6-45 EHS November - December 2018 (PM2.5,µg/m3)

6.5.5 November- December 2018

The previous levels of relative humidity from the month of October continues through the month of November around 33- 45 (%). Even the levels of $PM_{2.5}$ concentration is similar but slightly higher. On most days, the level of $PM_{2.5}$ is around 37 $\mu g/m^3$. What could be derived from the data recorded in the month of November is that the levels of $PM_{2.5}$ are constant with the exception of when students and workers use the kitchen area during the break hour. Around 12:00 PM a drop in $PM_{2.5}$ can be seen from 37 – 21 $\mu g/m^3$ and on some occasions 17 $\mu g/m^3$. The ambient temperature inside the EHS during the month of November is expected to be low if the windows are open and warm when the windows are closed. However, the ambient temperature is higher than expected which could only be seen in the cooling season. On many occasions, the ambient temperature has reached 27 °C. Additionally, the ambient temperature has reached more than 28 °C.

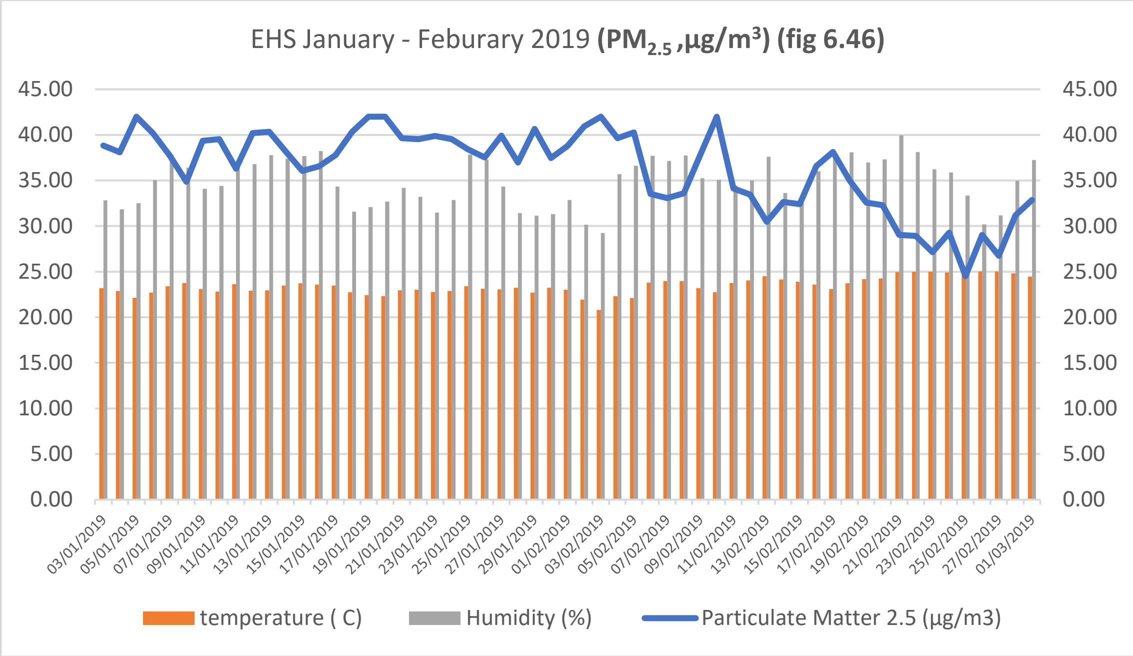

Figure 6-46 EHS January - February 2019 (PM2.5,µg/m3)

6.5.6 January- February 2019

Looking at the chart from (fig 6.46) shows that level of $PM_{2.5}$ is high through most of the month and it follows the same pattern seen in both November and December in which the $PM_{2.5}$ concentration is constant throughout the day and only changes with the movement of people inside the EHS and this could be explained with the frequent opening of the kitchen door that leads to the outside of the house. The door area of 2 meters by 1 meter is a great source of air movement inside the space even if it only happens for a brief moment. The thermal condition inside the EHS is consistent most of the month with the exception of the 3rd of January in which the ambient temperature was 19 °C and the relative humidity is around 28 (%). This may not be caused by the infiltration of outside air to the building otherwise the relative humidity would be much higher than that. This could be because the radiant floor may not have been working properly that day which affected the ambient air temperature and not so much the relative humidity.

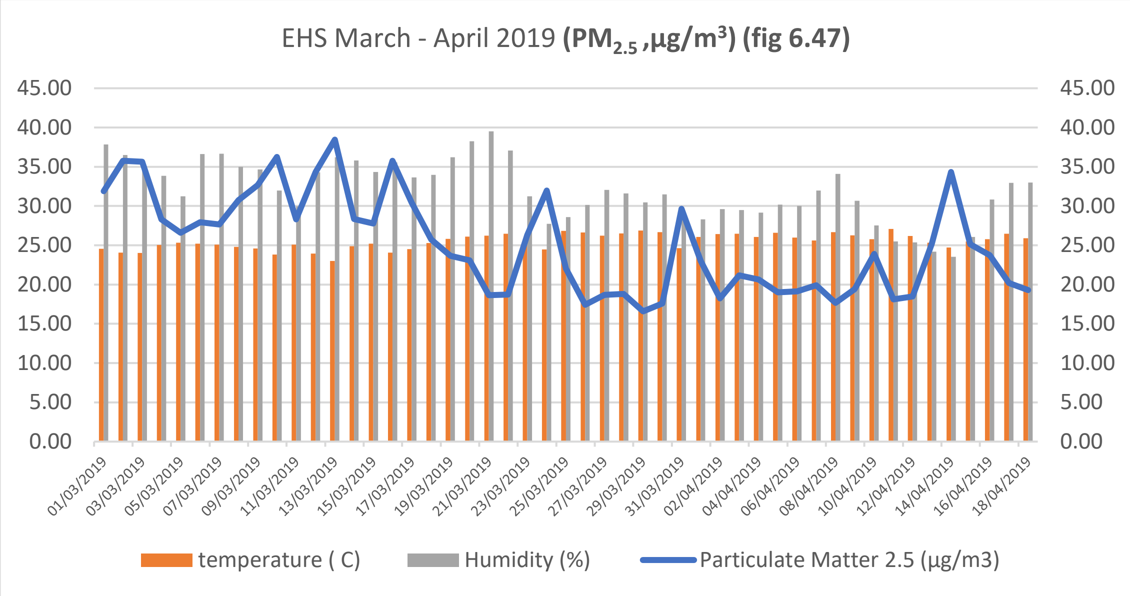

Figure 6-47 EHS March - April 2019 (PM2.5,µg/m3)

.5.7 March – April 2019

The concentration of $PM_{2.5}$ starts to decrease from 42 – 35 µg/m^3. It could be noticed that during the first days of the month the $PM_{2.5}$ starts at 35 µg/m^3 and it is lower when students and worker are present with the house. Nevertheless, at the end of the month of March, the levels of $PM_{2.5}$ will average around 17- 20 µg/m^3. Not only that but also the relative humidity starts to decrease from 30 – 40 (%) at the beginning of the month to 28 – 33 (%) at the end of the month. In the month of April, the average $PM_{2.5}$ is around 17 µg/m^3 in most of the data collected. This shows that opening the windows and doors lowers the level of $PM_{2.5}$ significantly from 42 µg/m^3 on average in most cases in the winter to 17 µg/m^3 in the spring season. The thermal conditions have also changed during the month of April. For example, the ambient temperature is on average around 25 – 27 °C. On many occasions, the ambient temperature has reached 28 °C and on some occasions, it reached 29 °C. it is worth noting that the higher levels of ambient temperature could be attributed to the use of kitchen appliances during break hours because in most cases the rise in ambient temperature happens around 2:00 PM in the afternoon.

6.6 Eco House CO_2 Readings

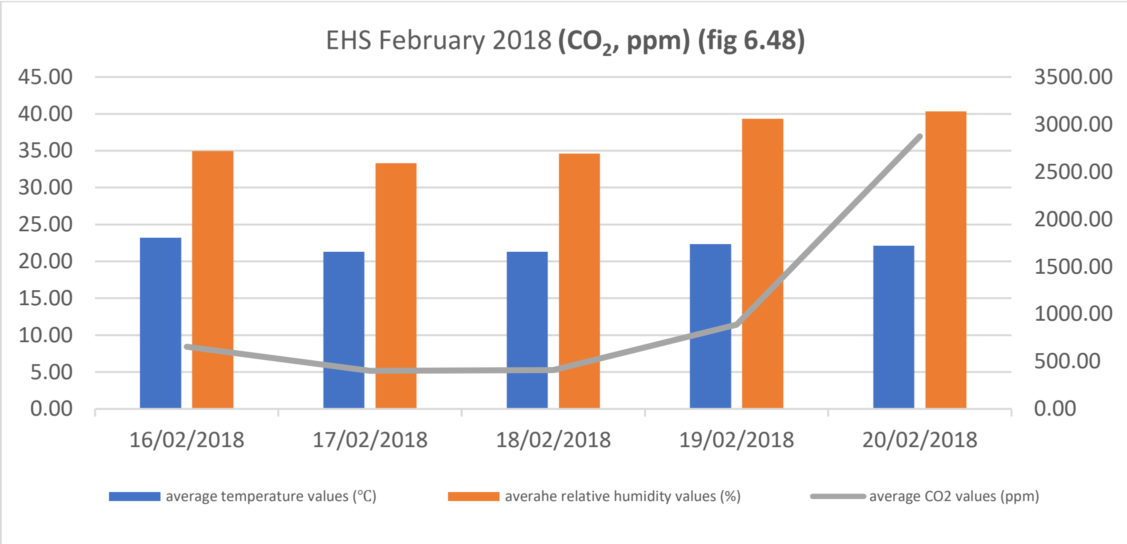

Figure 6-48 EHS February 2018 (CO2, ppm)

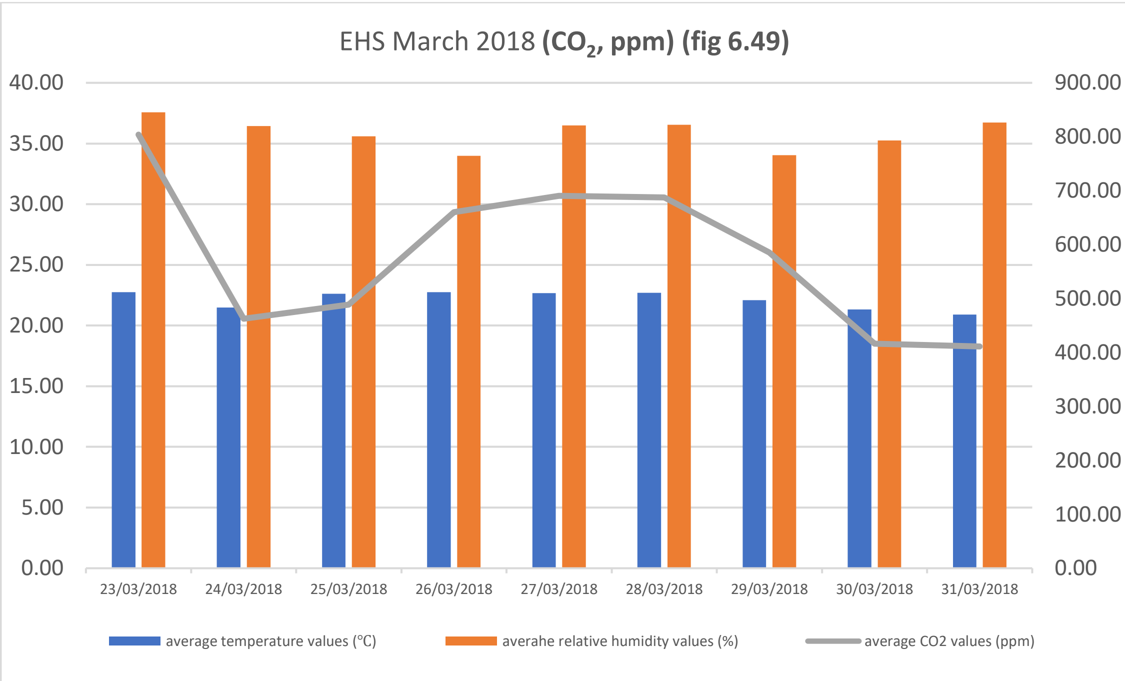

Figure 6-49 EHS March 2018 (CO2, ppm)

6.6.1 February – March 2018

The data collected from the month of February reveals a very high concentration of CO_2 as can be seen from (fig 6.49). the highest recorded CO_2 concentration was more than 4500 ppm. this concentration could be dangerous if it happened consistently inside that space. Fortunately, this data was not consistent and it was only recorded on the 20 of

February 2018. However, the concentration of CO_2 has reached the 1000 ppm threshold many times.

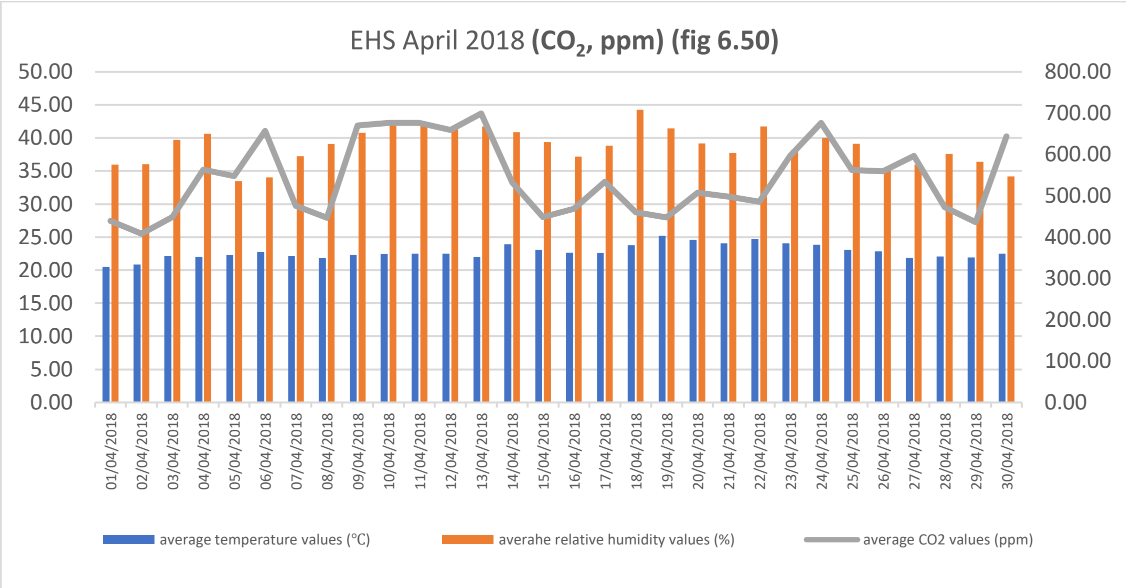

Figure 6-50 EHS April 2018 (CO2, ppm)

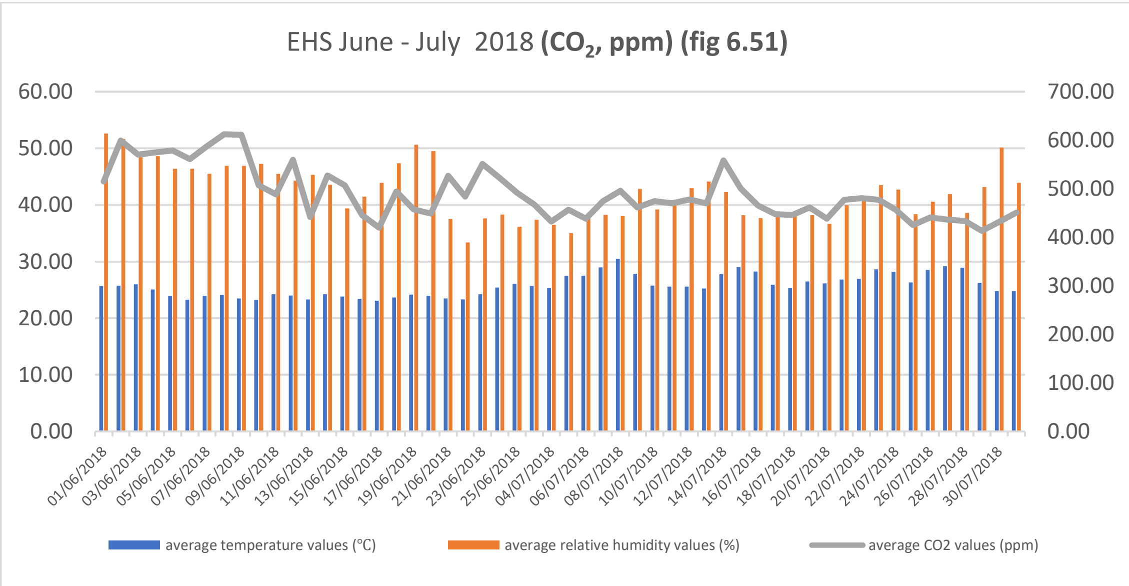

Figure 6-51 EHS June - July 2018 (CO2, ppm)

6.6.2 April 2018

The month of April shows a moderate level of CO_2 during the weekdays. On most working days the level of CO_2 starts at around 400 ppm at 12:00 AM and then when students and employees start to walk into the office the levels of CO_2 starts to increase.

This is because the level of CO_2 is very susceptible to the presence of people. Between the hours 12:00 PM and 4:30 PM, the highest recording occurs for CO_2. These level can be between 600 ppm to 1200 ppm.

6.6.3 July- August 2018

During the cooling month of July and August. The levels of CO_2 are almost the same throughout the whole period. This might indicate that the student and some researchers are not frequenting the house very often. There is, however, an unusual phenomenon recorded in the month of July. The ambient temperature in the month of July is at 30 °C even at the start of the day from 12:00 AM. What is unusual in the data is that the ambient temperature starts to decrease once students return to the EHS. Figure (6.52) shows the rise in temperature around 30 °C throughout the day even at night times on the 7th of July 2018.

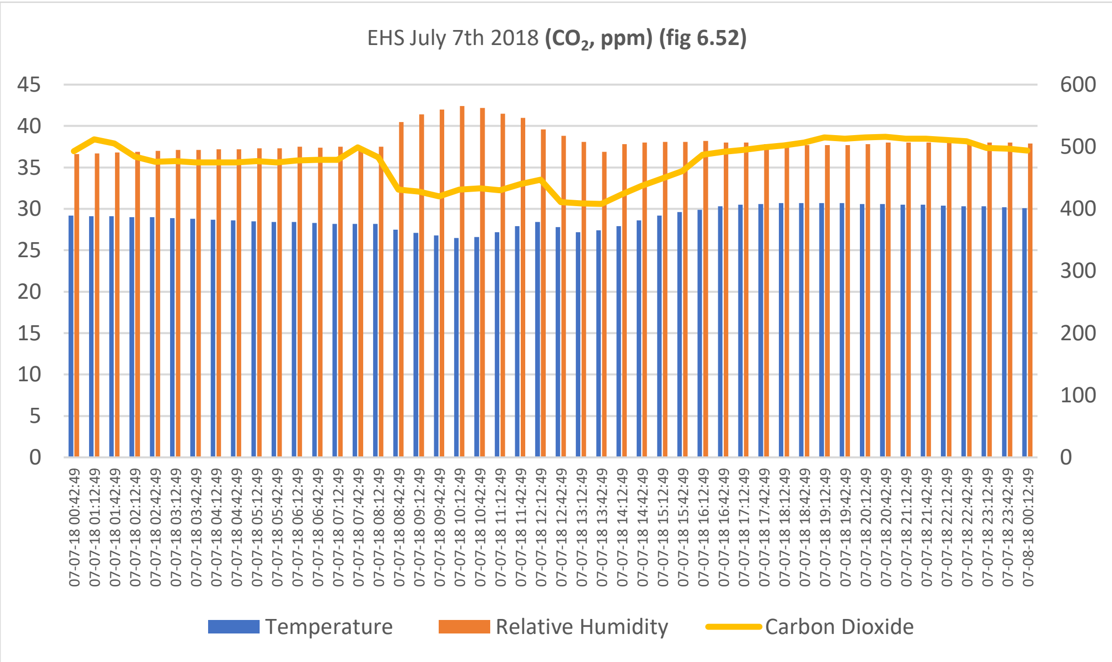

Figure 6-52 EHS July 7th 2018 (CO2, ppm) (fig 6.52)

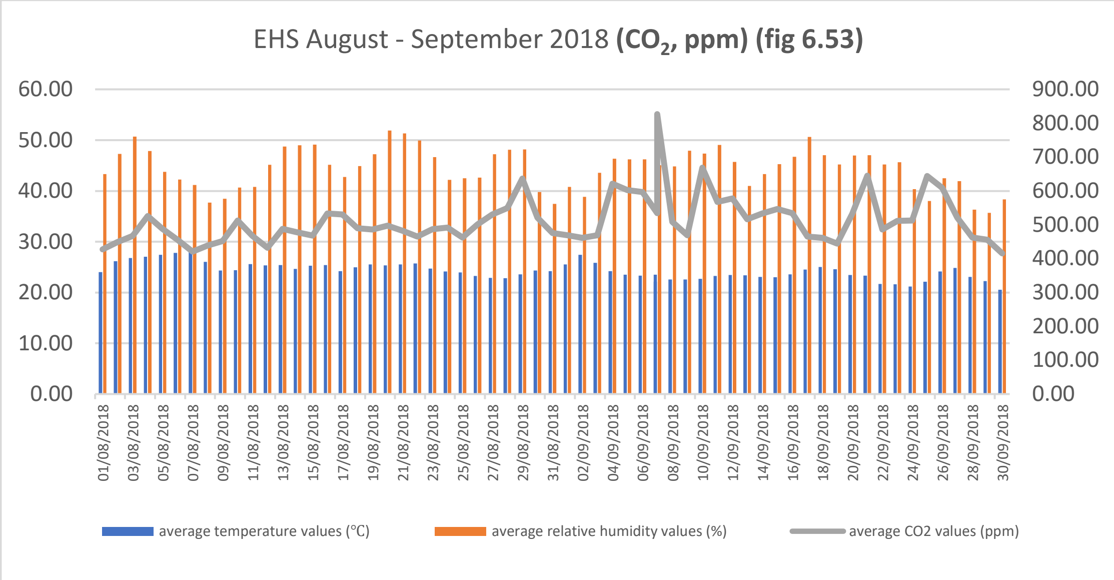

Figure 6-53 EHS August - September 2018 (CO2, ppm)

6.6.4 September 2018

When looking at the chart in (figure 6.53) it shows a spike increase in CO_2 concentration especially on the 7th of September with the highest increase of CO_2 reading of 1211 ppm. Moreover, the month of September has witnessed many peak levels of CO_2 concentration in the middle of the day that is higher compared to previous months. That is because during the month of September the employees will start to close the windows on some days. After the 23rd of September, a decrease in ambient indoor temperature can be observed from the data from 23 °C to 21 °C during the following days after the aforementioned date.

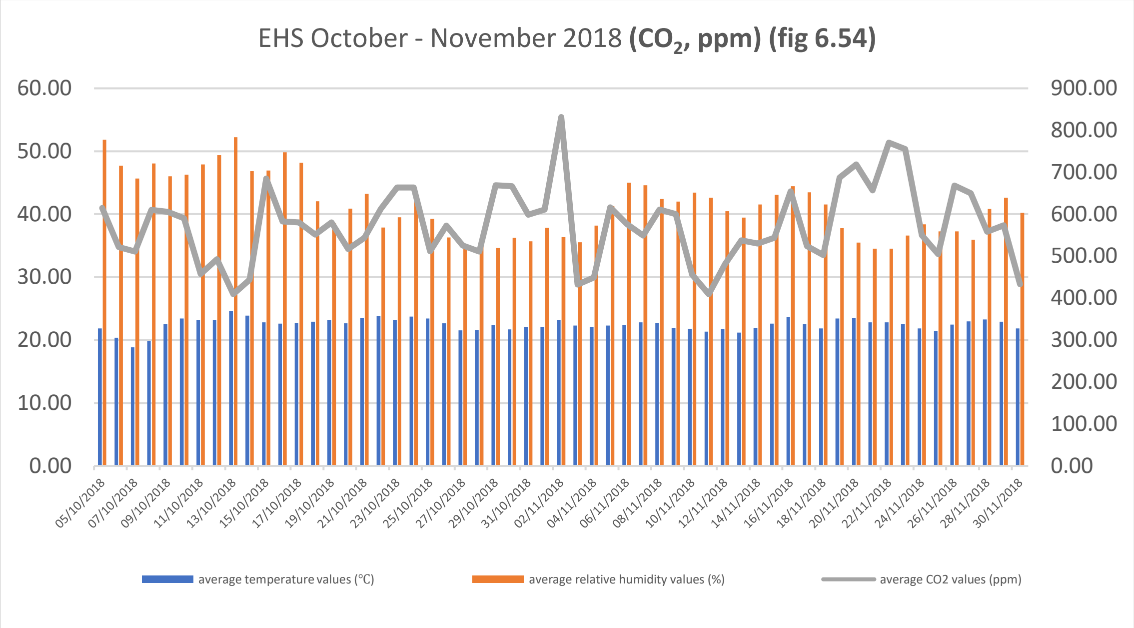

Figure 6-54 EHS October - November 2018 (CO2, ppm)

6.6.5 October 2018

The data from the month of October is somewhat similar to the data from the month of September. However, there are some differences in the data from the month of October in which the concentration of CO_2 has kept on increasing except for the 15th of October when a significant increase in CO_2 concentration reaches 1477 ppm. All the other data recorded data during that month was much lower (400 – 800 ppm). What does increase consistently throughout the month of October is the relative humidity. On the 13th of October, the relative humidity remained around 50 (%) throughout most of the day. in contrast, on the 28th of October, the relative humidity was 34 (%) throughout most of the day.

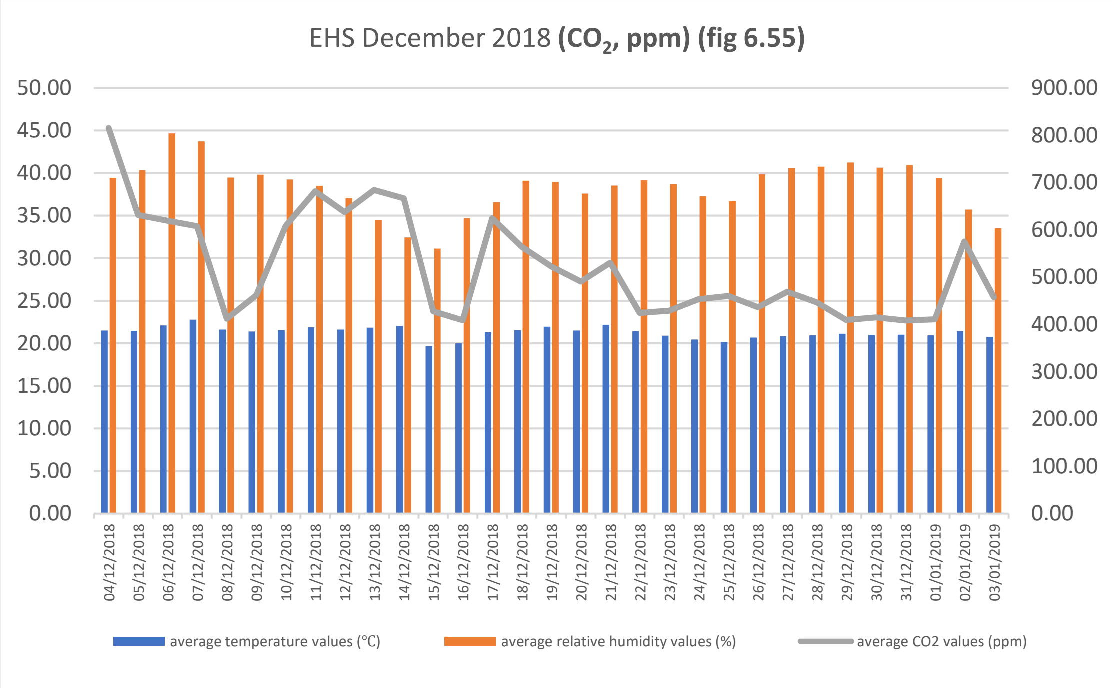

Figure 6-55 EHS December 2018 (CO2, ppm)

6.6.6 November – December 2018

The month of November is very similar to the month of October in which the concentration of CO_2 is low during the weekend days and higher during the working days when students and employees are presents inside the house. For example, on a typical weekend like on the 11th of November, the average CO_2 concentration was around 409 ppm and the temperature was 21 °C. However, on a typical weekday like on the 16th of November, the average CO_2 concentration was between 654 ppm as the lowest reading to 1032 ppm as the highest reading and the average ambient indoor air temperature was 23 °C. In fact, when looking at the data in the month of December they show that there are some changes that could occur in the same day. Like for example, on the 17th of December at the beginning of the day, the CO_2 concentration was 425 ppm and the ambient temperature was at 20 °C at 12:00 AM. At 5:30 PM the ambient temperature was 23.8 °C and the CO_2 concentration was 985 ppm.

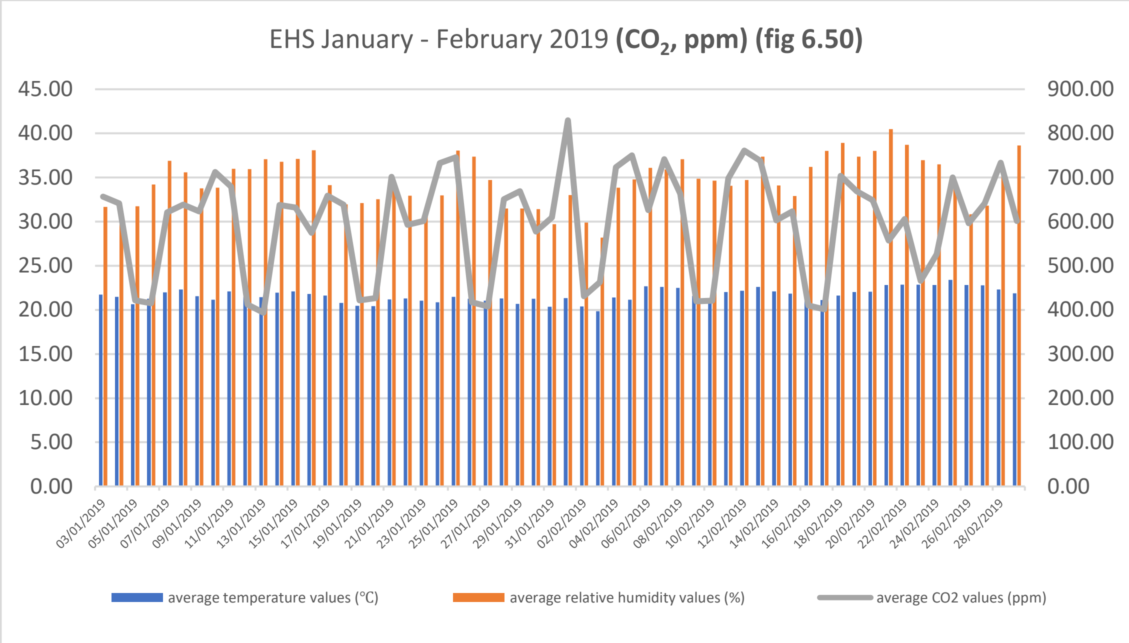

Figure 6-56 EHS January - February 2019 (CO2, ppm)

6.6.7 January – February 2019

When comparing the month of January to the month of December sees similar trends at the beginning of the month. During the autumn and winter months, from September to February, weekdays have high peak CO_2 concentration around 700 – 1000 ppm and between 400 – 450 ppm during the weekend days. In fact, on the 11th and the 12th of January, the CO_2 concentration was around 389 ppm the whole day. In the middle of the month of January, very high concentration of CO_2 occurs during peak times like for example on the 24th and the 25th of January when the concentration of CO_2 reached 1269 and 1364 ppm respectively. This phenomenon is even greater in the month of February. For example, on the 13the of February the highest ever CO_2 concentration was recorded during that month was 1556 ppm at 3:00 PM.

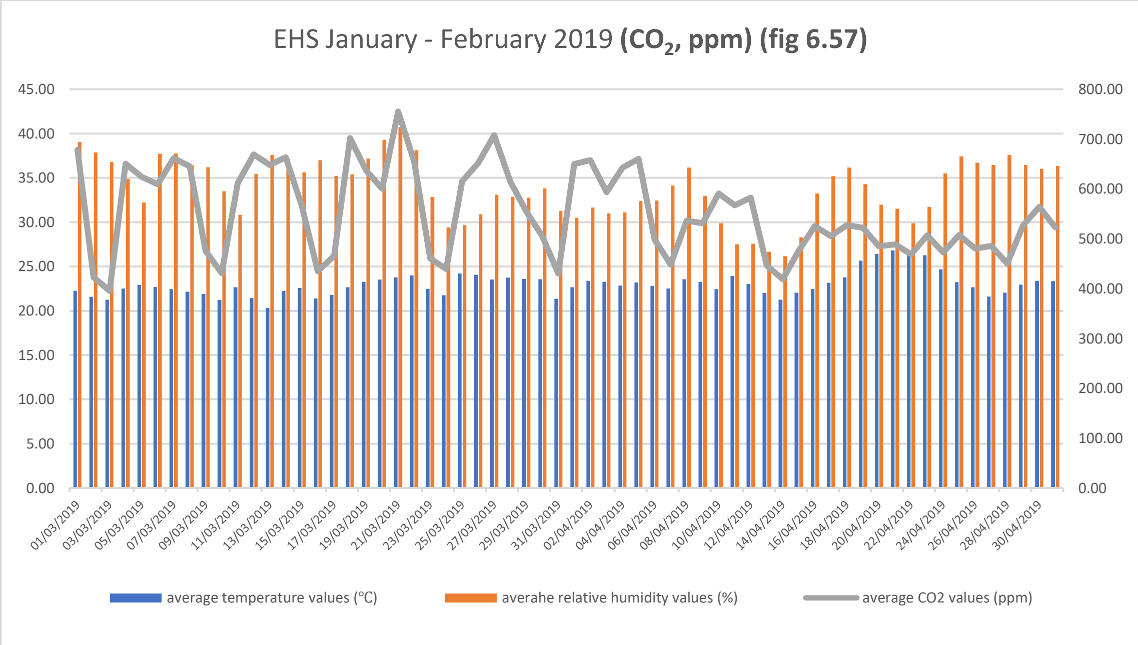

Figure 6-57 Eco-House EHS January - February 2019 (CO2, ppm)

6.6.8 March – April 2019

During the month of March, the concentration of CO_2 is not significant and there is no high concentration of CO_2. What is unique about the data recorded is the ambient indoor air temperature. The data at the beginning of the month shows stable recordings of ambient air temperature like on the 3rd of March the whole day has the same ambient temperature at 21 °C. However, on some days the changes in ambient indoor temperature are more drastic. For example, on the 11th of March, the ambient temperature has gone from 20.3 °C at 6: 45 AM to 25.6 °C at 1:45 PM on the same day. what is also interesting is that the CO_2 concentration at 6:45 AM was 417 ppm and at 1:45 PM it went to 942 ppm. Another similar example can be seen in the readings from the 25th of March. At 6:49 AM the ambient temperature was 21 °C and at 3:19 PM the ambient temperature was 27 °C. In addition, the CO_2 concentration is also similar to that recorded on the 11th of March in which at 6:49 AM the CO_2 concentration was 422 ppm and at 3:19 PM the CO_2 concentration was 1169 ppm. It is also worth noting that in both times the relative humidity remained the same at 30 (%).

6.7 Discussion

6.7.1 The New Sustainable Chemistry Building: OSO

When analysing the data in the chemistry building. The air supplied inside both the OSO and the FFO come from the MVHR. Therefore, the thermal condition is kept sustained especially during winter period. The ambient temperature during winter months is higher than in spring and summer months. The relative humidity during these months is kept moderate because there is no mixing of air between the OSO and the winter garden. Furthermore, the windows and door are kept close most of the time. After the winter months, many changes can be observed from the data. First, a decrease in the $PM_{2.5}$ levels from 10 μg/m^3 to 5 μg/m^3. Another change can be seen in relative humidity and ambient air temperature levels where a rise in both of them take place and that is because the air inside the OSO is being mixed with the air coming from the winter garden. The OSO is influenced heavily by the air coming from the winter garden and not from other sources because the OSO is secluded inside the building and does not have any other opening to the outdoor air. The effect of air mixing is not restricted to air temperature and relative humidity. The pollutant concentration is also affected by the air mixing between the OSO by which the air from the winter garden is diluting some of the indoor air pollutants from OSO. In general, the months of June, July, and August reveal a trend that is opposite to the winter months. During the summer months, the $PM_{2.5}$ level is almost half of that during the winter months around 5 μg/m^3, while in the winter months the average $PM_{2.5}$ is around 10 μg/m^3. The summer months also reveal an increase in the ambient temperature which shows that overheating can be an increasing issue that exists in low-carbon building. When the winter months starts again the same data recorded from the month of November, December, January, and February in 2018 are also seen in the data recorded in 2019 with some minor differences.

The CO_2 concentration is very much susceptible to people's presences inside the space; therefore, the concentration of CO_2 can change dramatically during the day when compared to particulate matter. The changes in CO_2 concentration can be evidently seen when students and employees to occupy the indoor space. On most occasions, a rise in CO_2 concentration when students and employees enter the OSO. A steady increase in CO_2 concentration happens until it reaches its peak in the afternoon and then the concentration starts to decrease gradually until it reaches its lowest point when students and employees leave the building in the evening. The month of June and July shows very little changes in the concentration of CO_2 and that could be because of the absence of students from the building. This could also explain why there are more frequent changes in the ambient temperature and relative humidity levels and fewer changes in the concentration of CO_2. Also similar to the data taken for the particulate matter, there are also seasonal changes in CO_2 concentration that correspond to the specific changes in every month of the year. For instance, the winter months shows a high concentration of CO_2 but low levels of relative humidity with very little changes in ambient air temperature. On the contrary, the summer month shows high ambient air temperature and relative humidity but low CO_2 concentration.

6.7.2 The New Sustainable Chemistry Building:

The data from the FFO was recorded after analysing the data taken from the survey. The majority of the result from the survey has indicated that the thermal condition in the laboratories is uncomfortable. Most participants have indicated that the laboratories are either too hot or too cold. These significant variants in the ambient air temperature have revealed that some compromises have been made to MVHR design that resulted in reduced air quality and thermal condition. This is evident from the data collected from the FFO located next to the laboratory. The month of June, July and August have revealed that the $PM_{2.5}$ concentration is much higher than the concentration recorded in the OSO. The concentration ranged during the summer month was from 17 – 35 $\mu g/m^3$. What is also different from the OSO data is that the ambient air temperature and relative humidity changes more frequently. What can be inferred is that the MVHR plays a significant role in the preservation of indoor air quality. Human impact is also significant in indoor air quality. From the data recorded in both the OSO and the FFO, it could be concluded that the act of opening windows and doors and the movement of people along with the presence of people themselves play a vital role in the presence of indoor air pollutants. During the holiday vacation, the data collected from both the OSO and the FFO reveal no significant changes in the pollutant concentration which is anticipated. This could be seen during the month of December and January where on the 15th and 16th of December there is a rise in both CO_2 and $PM_{2.5}$ concentration and then there is a dramatic decrease in both pollutants during the holidays. The CO_2 concentration recorded in the FFO is much higher than the concentration recorded in the OSO. The ambient temperature in the summer months is very high inside the FFO. When conducting the survey inside the offices, many students have said that the sun rays coming from the windows is affecting the ambient air temperature. After the summer months, the fluctuation in the levels of CO_2 concentration does not occur very often. The average levels of CO_2 concentration in the FFO are between 420 – 500 ppm. The data shows that most of the working days have the same pattern of CO_2 concentration. During a typical working day, an increase in CO2 starts at the early hours of the morning and peaks during the afternoon and then declines until it reaches the lowest point in the evening.

6.7.3 The Eco-House Space; (EHS)

The EHS shows similar data result to the FFO in which the space inside the EHS in which the air inside the EHS is not managed manly by the HVAC system. The house uses a radiant floor heating system for air condition. The radiant floor system does not interfere with the ventilation system and only operate in the winter season. Therefore, the building relies mostly on natural ventilation and this is shown from the data taken of the building. Data from the winter season is very unique. The reason being is that the concentration of pollutants is sometimes affected by the presence of people inside the space and it is also affected by the opening of windows and doors momentarily. The door next to the kitchen, where the data was collected, is open to the outdoor and when people enter the kitchen a large amount of air is introduced into the kitchen which will mix with air inside the space allowing for the pollutants to be diluted. After the winter months, the levels of $PM_{2.5}$ was very high reaching as high as 60 µg/m^3. Not only that but also the ambient temperature and relative humidity also changes. These changes mainly have to do with the intrusion of outdoor air. Within the same day the ambient air temperature changes from 21 to 24 °C. The relative humidity does also change as can be seen in one of the data taken from the 20th of April in which the relative humidity changed from 60 to 38 (%) on the same day. The summer months show even higher readings in all pollutant categories, ambient temperature, and relative humidity. The ambient temperature has reached as high as 28 °C and the relative humidity reached 57 (%), and lastly, the $PM_{2.5}$ was high as well reaching 76 µg/m^3, however, the levels of $PM_{2.5}$ is not consistent throughout the month and averaging around 25 µg/m^3 during the rest of the month.

Characteristically the concentration of CO_2 in the Eco-House during the month of February is very high compared to the months that will follow after that. This increase in CO_2 concentration occurs only during the working days where there are people working inside the EHS. This trend, however, continues until the middle of April where a gradual decline in CO_2 concentration from 1000 ppm to 700 ppm on average take place. As expected, the month of July and August shows the opposite trend. The CO_2 concentration is decreasing while the relative humidity and ambient indoor air temperature are increasing reaching up to 32 °C in the middle of July. After the summer months, the concentration of CO_2 starts to rise up again but very slowly which starts in the month of September and continues on to the month of October. The month of October is a transitional period where there is no significant increases in ambient indoor temperature nor there is any increases in CO_2 concentration. Instead, there is a consistent increase in the levels of relative humidity. The reason might be because during that time the windows are open most of the time and that would allow the outdoor air to mix with the indoor air of the EHS. This could be evident from the drastic low ambient indoor air temperature recorded on the 7^{th} and 8^{th} of October in which the ambient indoor temperature has reached 17 and 18 °C respectively.

6.8 Conclusion

From the data gathered from the two low-carbon buildings, it is concluded that the indoor air quality inside the Chemistry building has been acceptable in some parts of the building but not in all area in the building. the data was taken from three working areas in the University of Nottingham Park and Jubilee campus region. The first working space was the OSO where the MVHR system was designed to meet the needs of the occupants inside that space. On most days of the year, the MVHR has supplied the room with an adequate amount of fresh air that satisfied most of the occupants in that area. However, the issue of overheating has persisted in all three working areas of this research even in the OSO area. In the winter month, it is hard to keep the windows open for a long period of time, and therefore, the air inside the space can become stuffy according to some of the responses from some of the participants in the survey, and that is evident in the data taken. But it is worth noting that not all have felt the same way because the relative humidity inside the working area in the wintertime is moderately low at 30 (%) in most cases. The other working areas were not equipped with the same MVHR system as in the OSO. The FFO for instance, have relied heavily on the extract fan. This has created some issues in the summer when many students have complained about the sun rays entering the office and overheating the office. The Eco-House have the same issue during the summer because there is only one extract fan in the kitchen area. The Eco-House relies mostly on the natural ventilation from the windows during the spring and summer months. In both situations in the FFO and the EHS, the fluctuation in relative humidity, pollutant concentration, and ambient indoor temperature is very clear. These changes could happen on the same day, especially during the summer period. It can be concluded that low carbon buildings have gone a long way through the process of development, but they are still some design elements that need to be tackled in order to ensure better indoor air quality. One of these issues is the issue of overheating, and that is especially true in the cold regions that are similar to the United Kingdom. The other issue is the design of the MVHR system. In both situations, the FFO and the EHS, the absence of a well-designed MVHR system is evident and it created an unstable indoor air environment.

7. Chapter seven

7.1 survey questionnaire

a survey questionnaire was developed to compare people's responses to the data collected from the building. The Carbon Neutral Building is occupied by both student and employees. A quantitative method of questionnaire was used to gather as much information as possible from most of the users inside the building. The survey consists of 15 multiple response questions that will inquiry about some of the most important issues related to indoor air quality like (sick building syndrome, nasal or respiratory diseases, and the air perception inside the space). At the end of the survey, there is an open-ended question was included to give the participants the chance to share any thoughts about the indoor air quality conditions and to convey that in a descriptive manner that helps better understand the situation from a humanistic point of view. The number of participants who completed the questionnaire was 64 participants.

Table 7-1 Chemistry Building Survey Question 1

Q1: Please indicate if you frequently have any of the following complaints concerning the indoor air quality in the GSK building (check all that apply).				
		Responses		
		N	Percent	Percent of Cases
question 1[a]	temperature too cold	35	29.7%	54.7%
	temperature too hot	38	32.2%	59.4%
	stuffy air	10	8.5%	15.6%
	moldy odors	1	0.8%	1.6%
	other odors	4	3.4%	6.3%
	dusty	4	3.4%	6.3%
	too dry	4	3.4%	6.3%
	too humid	3	2.5%	4.7%
	drafty	2	1.7%	3.1%
	no complaints	17	14.4%	26.6%
Total		118	100.0%	184.4%
a. Dichotomy group tabulated at value 1.				

Table 7-2 Chemistry Building Survey Question 2

Q2: Please indicate if you have the following habits (check all that apply).		Responses		
		N	Percent	Percent of Cases
Question 2[a]	wear contact lenses	10	12.0%	15.9%
	operate video display	27	32.5%	42.9%
	use any chemical substance	25	30.1%	39.7%
	smoke tobacco products	4	4.8%	6.3%
	none of the above	17	20.5%	27.0%
Total		83	100.0%	131.7%

a. Dichotomy group tabulated at value 1.

Table 7-3 Chemistry Building Survey Question 3

Q 3: Please indicate if you have ever been diagnosed with any of the following symptoms since you started studying or working in the GSK building (check all that apply).		Responses		
		N	Percent	Percent of Cases
Question 3[a]	Allergic Rhinitis	3	4.5%	4.7%
	Asthma	1	1.5%	1.6%
	Allergies	3	4.5%	4.7%
	Sinusitis	2	3.0%	3.1%
	Other chest conditions	1	1.5%	1.6%
	None	57	85.1%	89.1%
Total		67	100.0%	104.7%

a. Dichotomy group tabulated at value 1.

Table 7-4 Chemistry Building Survey Question 4

Q 4: Please indicate if you have experienced any of the following symptoms in the GSK building (check all that applies)				
		Responses		
		N	Percent	Percent of Cases
Question 4[a]	Frequent cough	9	7.1%	14.1%
	Multiple colds (more than four)	11	8.7%	17.2%
	Shortness of breath	1	0.8%	1.6%
	Migraines	10	7.9%	15.6%
	Burning or irritated eyes)	9	7.1%	14.1%
	Nasal congestion	11	8.7%	17.2%
	Sinus infections	5	3.9%	7.8%
	Sore throat	13	10.2%	20.3%
	Hoarse voice	5	3.9%	7.8%
	Headaches	20	15.7%	31.3%
	Sneezing attacks	5	3.9%	7.8%
	None of the above	25	19.7%	39.1%
	Other (please specify)	3	2.4%	4.7%
Total		127	100.0%	198.4%
a. Dichotomy group tabulated at value 1.				

Table 7-5 Chemistry Building Survey Question 5

Q 5: Do you have any health problems or allergies that might account for the above symptoms?				
		Responses		
		N	Percent	Percent of Cases
Question 5[a]	yes	13	20.3%	20.3%
	no	51	79.7%	79.7%
Total		64	100.0%	100.0%
a. Dichotomy group tabulated at value 1.				

Table 7-6 Chemistry Building Survey Question 6

Q 6: Please rate the indoor air quality in the GSK building.				
		Responses		
		N	Percent	Percent of Cases
Question 6[a]	good	31	48.4%	48.4%
	average	33	51.6%	51.6%
Total		64	100.0%	100.0%
a. Dichotomy group tabulated at value 1.				

Table 7-7 Chemistry Building Survey Question 7

Q 7: If you think that there have been some indoor air quality problems in this building, do they change with the specific seasons of the year?				
		Responses		
		N	Percent	Percent of Cases
Question 7[a]	yes	27	42.2%	42.2%
	no	11	17.2%	17.2%
	Do not know	26	40.6%	40.6%
Total		64	100.0%	100.0%
a. Dichotomy group tabulated at value 1.				

Table 7-8 Chemistry Building Survey Question 8

Q 8: If you ticked "Yes" to #7, please answer when does indoor air quality problems seem to be most serious?				
		Responses		
		N	Percent	Percent of Cases
Question 9[a]	Morning	1	2.0%	2.0%
	Afternoon	11	21.6%	22.4%
	All day	9	17.6%	18.4%
	No noticeable trend	29	56.9%	59.2%
	Specific time____	1	2.0%	2.0%
Total		51	100.0%	104.1%
a. Dichotomy group tabulated at value 1.				

Table 7-9 Chemistry Building Survey Question 9

Q 9: How long do you usually spend in the GSK building on average per day for working or studying?				
		Responses		
		N	Percent	Percent of Cases
Question 10[a]	4 to 8 hours	39	60.9%	60.9%
	More than 8 hours	25	39.1%	39.1%
Total		64	100.0%	100.0%
a. Dichotomy group tabulated at value 1.				

Table 7-10 Chemistry Building Survey Question 10

Q 10: Are any of the following items located within your workroom or area? (Check all that apply)				
		Responses		Percent of Cases
		N	Percent	
Question 11[a]	Photo copier	17	16.0%	30.4%
	Laser printer	25	23.6%	44.6%
	Windows	42	39.6%	75.0%
	Plants	22	20.8%	39.3%
Total		106	100.0%	189.3%
a. Dichotomy group tabulated at value 1.				

Table 7-11 Chemistry Building Survey Question 11

Q11: Has there been any renovation or related activities occurring in or near your work environment? (i.e., new carpet, painting, new office furniture HVAC works, etc.)				
		Responses		Percent of Cases
		N	Percent	
Question 12[a]	no	59	95.2%	95.2%
	yes	3	4.8%	4.8%
Total		62	100.0%	100.0%
a. Dichotomy group tabulated at value 1.				

Table 7-12 Chemistry Building Survey Question 12

Q 12: Has there been any evidence of water leaks or visible signs of moisture in and around your area				
		Responses		Percent of Cases
		N	Percent	
Question 13[a]	yes	16	25.0%	25.0%
	no	48	75.0%	75.0%
Total		64	100.0%	100.0%
a. Dichotomy group tabulated at value 1.				

Table 7-13 Chemistry Building Survey Question 13

Q 13: Is your office near a laboratory?				
		Responses		Percent of Cases
		N	Percent	
Question 14[a]	yes	52	85.2%	85.2%
	no	9	14.8%	14.8%
Total		61	100.0%	100.0%

7.2 Eco House Survey Questionnaire

The number of people working in the Eco-House or (Mark's group House) is far less than the number of people working in the Chemistry Building. Only four participated in the survey the same survey that was given to the participants in the Chemistry Building.

Table 7-14 Eco-House survey question 1

Q1: Please indicate if you frequently have any of the following complaints concerning the indoor air quality in Mark's group House (Eo-House) (check all that apply).		
Variable	Number of responses	The percentage from the total group
temperature too cold	0	0 %
temperature too hot	2	50 %
stuffy air	2	50 %
moldy odors	0	0 %
other odors	0	0 %
dusty	0	0 %
too dry	0	0 %
too humid	0	0 %
drafty	0	0 %
no complaints	0	0 %
Total	4	100 %

Table 7-15 Eco-House survey question

Q2: Please indicate if you have the following habits (check all that apply).		
Variable	Number of responses	The percentage from the total group
wear contact lenses	0	0 %
operate video display	3	75 %
use any chemical substance	0	0 %
smoke tobacco products	0	0 %
none of the above	1	25 %
Total	4	100 %

Table 7-16 Eco-House survey question 3

Q 3: Please indicate if you have ever been diagnosed with any of the following symptoms since you started studying or working in Mark's group House (Eco-House) (check all that apply).		
Variable	Number of responses	The percentage from the total group
Allergic Rhinitis	0	0 %
Asthma	0	0 %
Allergies	0	0 %
Sinusitis	0	0 %
Other chest conditions	0	0 %
None	4	100 %
Total	4	100 %

Table 7-17 Eco-House survey question 4

Q 4: Please indicate if you have experienced any of the following symptoms in Mark's group House (Eco-House) (check all that applies)		
Variable	Number of responses	The percentage from the total group
Frequent cough	0	0 %
Multiple colds (more than four)	0	0 %
Shortness of breath	0	0 %
Migraines	0	0 %
Burning or irritated eyes)	0	0 %
Nasal congestion	0	0 %
Sinus infections	0	0 %
Sore throat	0	0 %
Hoarse voice	0	0 %
Headaches	0	0 %
Sneezing attacks	0	0 %
None of the above	4	100 %
Other (please specify)	0	0 %
Total	4	100 %

Table 7-18 Eco-House survey question 5

Q 5: Do you have any health problems or allergies that might account for the above symptoms?		
Variable	Number of responses	The percentage from the total group
Yes	0	0 %
No	4	100 %
Total	4	100 %

Table 7-19 Eco-House survey question 6

Q 6: Please rate the indoor air quality in Mark's group House (Eco-House).		
Variable	Number of responses	The percentage from the total group
Good	1	25 %
Average	3	75 %
Poor	0	0 %
Total	4	100 %

Table 7-20 Eco-House survey question 7

Q 7: If you think that there have been some indoor air quality problems in this building, do they change with the specific seasons of the year?		
Variable	Number of responses	The percentage from the total group
Yes	3	75 %
No	1	25 %
Do not know	0	0 %
Total	4	100 %

Table 7-21 Eco-House survey question 8

Q 8: If you ticked "Yes" to #7, please answer when does indoor air quality problems seem to be most serious?		
Variable	Number of responses	The percentage from the total group
Morning	0	0 %
Afternoon	2	50 %
All day	0	0 %
No noticeable trend	1	25 %
Specific time____	0	0 %
Total	3	75 %

Table 7-22 Eco-House survey question 9

Q 9: How long do you usually spend in Mark's group House (Eco-House) on average per day for working or studying?		
Variable	Number of responses	The percentage from the total group
Less than 2 hours	0	0 %
2 to 4 hours	0	0%
4 to 8 hours	3	75 %
More than 8 hours	1	25 %
Total	4	100 %

Table 7-23 Eco-House survey question 10

Q 10: Are any of the following items located within your workroom or area? (Check all that apply)		
Variable	Number of responses	The percentage from the total group
Photocopier	1	12.5 %
Laser printer	1	12.5 %
Windows	4	50 %
Plants	2	25 %
Total	8	100 %

Table 7-24 Eco-House survey question 11

Q11: Has there been any renovation or related activities occurring in or near your work environment? (i.e., new carpet, painting, new office furniture HVAC works, etc.)		
Variable	Number of responses	The percentage from the total group
No	3	25 %
Yes	1	25 %
Total	4	100 %

Table 7-25 Eco-House survey question 12

Q 12: Has there been any evidence of water leaks or visible signs of moisture in and around your area		
Variable	Number of responses	The percentage from the total group
Yes	1	25 %
No	3	25 %
Total	4	100 %

Table 7-26 Eco-House survey question 13

Q 13: Is your office near a laboratory?		
Variable	Number of responses	The percentage from the total group
Yes	0	0 %
No	4	100 %
Total	4	100 %

7.3 Survey questionnaire Discussion

The findings from the survey give a good indication of the health conditions of the students and employees inside the building. The majority of the occupiers stay more than 6 hours inside the building with 60 % of the participant stay between 4-8 hour per day and around 40 % of them stays for more than 8 hours inside the building. Also, in question 14, the participants indicate that around 85 % of them work at their office that is close to the laboratory. It appears from the finding that there is no specific time when the indoor air quality starts to deteriorate. For example, in question 9, 11 participants (21 %) says that the afternoon is perceived as the worst time for the indoor air quality whereas 9 participants (18 %) says that the indoor air quality condition is worse all day. However, question 1 can give a good reason as to why many say that the afternoon was the worst time for indoor air quality. In question 1, 35 participants (29 %), says that the temperature was too cold especially in the winter, and 38 participants (32 %) says that the temperature is too hot especially in summer. This could be further verified from the open-ended question in which respondents say that the laboratory was the worst room in the building. This is very important because it shows that although this building is designed to be low carbon, there are some areas in the building that did not have adequate thermal condition. As mentioned earlier, the findings from question 14 show that about 85% of the participants are using the laboratory. The data collected from the FFO has confirmed that the indoor air quality in the laboratories is not suitable for most of its users. Lastly, the data also shows that there are no major health issues that were experienced by all participants. For instance, in question 4 when participants were asked about sick building symptoms such as (eye irritations, headaches, frequent cough, nasal congestion or sore throat) neither one of these symptoms was more significant than the other which indicate that air quality could be suitable to some people but others might find it uncomfortable. Another example in question 6 when participants were asked how would you rate the air quality inside the room, 31 participants (48 %) says that the air quality is good, and 33 participants (51 %) says that the air quality is average.

When looking at the data from the Eco-House two of the participants have indicated that the temperature inside the EHS is too hot. That is evident from the data collected, where it shows very high ambient indoor air temperature especially in the month of July. Another complaint that is being shared by the participants is that the air inside the EHS is stuffy. The feeling of stuffy air is mostly attributed to the high concentrations of CO_2, this could also be seen in the data that was collected from the building. In the winter and autumn months, the levels of CO_2 have surpassed the 1000 ppm threshold on many occasions. The lack of air circulation during the winter months can be a strong reason why the levels of CO_2 is very high. The majority of the participants have rated the indoor air quality inside the building as average. The reason why most of the participants have indicated that the indoor air quality inside the EHS is average is because of the high levels of CO_2 and higher ambient indoor air temperature that made the indoor environment uncomfortable. The use of an HVAC system can ameliorate some of the problems that might have affected the indoor air quality.

7.4 Concluding remarks

Many participants are comfortable with the conditions of the indoor air quality inside the sustainable carbon-neutral chemistry building. Although, it is important to point out that most of the participants who are working close to the laboratory have mentioned the thermal conditions of the building can be very uncomfortable on some occasions. It is also worth mentioning that the MVHR system is not the same in all rooms. This could be the reason why some participants were not comfortable with indoor air quality inside the building. The open space office, where the original data was taken, has an MVHR system that works constantly with 10 inlet air registers and two extract fans. This is not the same in all rooms, as there are some rooms on the upper floor that has only one register and one extract fan and less airflow than the open space office. Taking the temperature, humidity, $PM_{2.5}$ and CO_2 measurement from another office on the upper floor has given a better understanding of the condition inside the building. Both buildings have been designed according to low carbon standards that will ensure that these buildings would consume as little energy as possible. However, the indoor air quality inside the building did not achieve the optimum level of indoor air quality. In the first building, the thermal condition issues are very apparent. Even though the employees working in the OSO did not have the same complaint as those who were working in the FFO, still on some occasions the ambient air temperature in the summer has reached a very high level of 30 °C. The situation is even more so in the FFO where not only did the employees have complained about the high temperature, but also from the very low temperature as well in the winter. That is attributed to the design of the MVHR system in the laboratories that depends mainly on the extract system only with no air inlet allowed inside the labs. The situation is different in the EHS although, the workers there have complained about similar issues in regards to the thermal condition. The main conclusion that could be derived from both the survey and the data collection is that the design of the low carbon building needs to give particular importance to the design of the MVHR system. The design of the MVHR systems should accommodate all of the variables that concern the indoor air quality like seasonal changes in the summer and winter, peoples' activity and the management of indoor air pollutants.

8. Chapter eight: Comparative analysis

This thesis was aimed to study indoor air quality in low carbon building. Three methods were utilized to assess the condition of the indoor air quality the first method was the use of CFD with the use of the commercial software ANSYS FLUENT R20^{TM}. Using CFD was important the analyse the movement of airflow in three chosen indoor spaces, the concentration of (PM), the concentration of CO_2, and the ambient temperature. Studying these parameters has given a detailed view of the indoor air condition inside the three indoor spaces. Another benefit of using CFD simulation is to compare the difference between two ventilation systems the first is the MVHR system and the second is the natural ventilation. This comparison between the two ventilation systems will determine which method is the best suitable for producing the best indoor air quality inside the three indoor spaces. The second benefit of using CFD simulation is to study the distribution and concentration of indoor pollutant inside the indoor space. The third benefit is the ability to study the different conditions in three distinct scenarios (winter, summer, and autumn/spring). Studying these three scenarios have shown that the indoor air quality in these three distinct scenarios is vastly different.

The second method used was data collection. In this study, four instruments were chosen to monitoring the indoor air quality inside the indoor space. The first instrument was the Perfect-Prime CO2000 Carbon Dioxide (CO2) which was used to monitor the CO2 concentration. The second device used was the TES 5322 PM2.5 Air Quality Monitor. This instrument was used to monitoring the concentration of PM. The third device was the IGERESS Indoor Air Quality Monitor. This instrument was used as a handheld instrument to check the concentration of PM_{10}, $PM_{2.5}$, formaldehyde, temperature and relative humidity. The last instrument used was the 1-wire temperature and humidity sensor. This instrument was used to monitor the indoor air temperature and relative humidity. The data was taken from the OSO starting in January 2018 and ending in December 2019. Likewise, the data collection from the FFO started in July of 2019 and ended in January 2020. Lastly, the EHS data collection started in February 2018 and ended in April 2019. The benefit of using the data collection method is to describe the existing indoor air quality and analysing the data that is collected. The data that is being monitored is the concentration of PM, the concentration of carbon dioxide (CO_2), the ambient air temperature, the relative humidity ratio. Another benefit of data collection is to compare the data collected with the CFD simulation. Comparing the data collection with the CFD simulation result will verify the CFD model. In addition, The data collection will not just be beneficial for comparing the data collected with the CFD simulation results, but also it will very beneficial to compare the data collection to the survey result.

The third method used was the survey questionnaire. The survey questionnaire consisted of 15 questions. Fourteen of these questions were multiple response-questions and the last question was an open-end question. The importance of the survey questionnaire lays within people's response to the indoor air quality condition inside the indoor space. Indoor air quality is mainly the status of the air inside the interior space that is conditioned for people's use. Therefore, the quality of air from a humanistic point of view is very important. The result from the CFD simulation along with the data collected from the building will be analysed and compared with the result from the survey questionnaire. The CFD result and data collection readings will explain the indoor air quality from a case study perspective, while the survey questionnaire will give human insight into the indoor air condition from a quantitative analyses perspective.

8.2 The CFD and Data collection result

When examining the result from both the data collection reading and the CFD simulation. There are many trends that are very similar to each other. the result will be discussed within the four parameters monitored in the data collection and simulated in the CFD software.

8.2.1 Airflow

The first parameter is the airflow analyses from the CFD simulation. As mentioned before, there are two distinct ventilation methods that exist in the two building.

The first is the MVHR system which is implemented in the carbon-neutral chemistry building. The MVHR system was used in both the OSO and the FFO. The second ventilation system was the natural ventilation system implemented in the Eco-House. Even though both the OSO and the FFO uses the MVHR system as the main source for ventilation. The airflow difference between them is very noticeable. In the OSO there are multiple air registers that are scattered all over the space even inside individual offices. In addition, the OSO has two regions of extract fans that have the ability to pull the air at a velocity of 2.1 m/s. the layout of the airflow inlet and outlet have made it possible for the air to spread evenly throughout the space and allowed the airflow from the MVHR to mix with all regions inside the OSO. On the other hand, the layout of the airflow in the FFO is not similar. Although the FFO is much smaller than the OSO, the airflow from the MVHR does not mix with all regions inside the FFO. The EHS relied mainly on natural ventilation with the aid of extract fans from the kitchen area and the radiant floor to heat up the interior space. Natural ventilation has proven to be insufficient in providing the best airflow inside the EHS. This especially true in the winter season when the airflow is very restricted.

8.2.2 Particulate Matter (PM)

The second parameter is the concentration of PM in both the CFD simulation and the data collected. In general, it is inferred from the data collected that the concentration of PM has several factors that could affect its distribution inside the space. Some of these factors are people’s presence, indoor sources, exterior sources, the type of ventilation, and airflow pattern. The data from the OSO have the lowest concentration of (PM) at all time of the year. The concentration of PM inside the OSO had never passed the 10 $\mu g/m^3$ level during the winter season. The result from the CFD simulation also confirmed that the OSO office had the lowest concentration of PM. In both the data collection and the CFD simulation, it appears that the winter season has relatively the highest concentration of PM followed by the autumn and spring season, whereas the summer season had the lowest concentration of PM which was as low as 2 $\mu g/m^3$. Figure (8-1) shows a comparison between the average concentration of PM from the simulation results with the average concentration from the data collection for the OSO model. The average from the simulation was representative of the result from the three main scenarios (summer , spring/autumn, and winter. These simulation results were compared to the result from the data collection. The data collection average was calculated using the average data collected from three months that are representative of the three main scenarios. The winter scenario was represented by the average data from the month of January, The summer scenario was represented by the average data from the month of June, and the autumn months were represented with the month of either October or march. Figure (8-2) and figure (8-3) shows the same comparison for the other two models FFO and EHS respectively.

Table 8-1 Comparing the average concentration of PM between the data collection and the simulation model for the three main seasons in the OSO the chemistry building

Season	(Winter) (µg/m^3)	(spring/Autumn) (µg/m^3)	(summer) (µg/m^3)
Data collection	7.79	7.17	7.22
Simulation	2.44	1.68	1.67

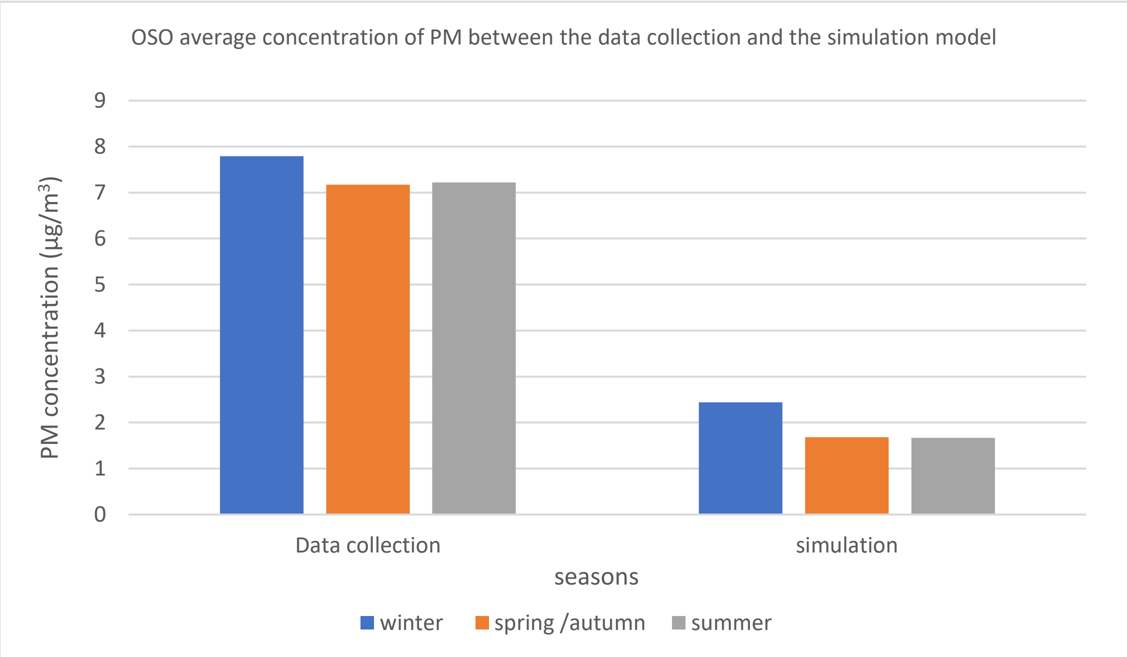

Figure 8-1 chart that Compares the average concentration of PM between the data collection and the simulation model for the three main seasons

The FFO reading did not have the same levels of PM as the OSO even though both of them are located in the same building. The concentration of PM in the FFO is much higher than the concentration in the OSO. There might be a couple of reason as to why these high levels of PM occur in the FFO. The first of which is that the door next to the corridor is kept open almost all the time even in the winter season. There are many people who are crossing through the corridor stirring up the particles from the ground and nearby surfaces. In the corridor also there is a coffee machine that might be a potential source of PM coming toward the interior space. The second reason might be the laboratory next to the FFO. The laboratory has many machines that potentially be a good source for PM coming to the FFO when students are coming in and out of the lab.

Table 8-2 Comparing the average concentration of PM between the data collection and the simulation model for the three main seasons in the FFO the chemistry building

Season	(Winter) (µg/m^3)	(spring/Autumn) (µg/m^3)	(summer) (µg/m^3)
Data collection	31.62	34.20	24.01
Simulation	13.7	9.2	8.5

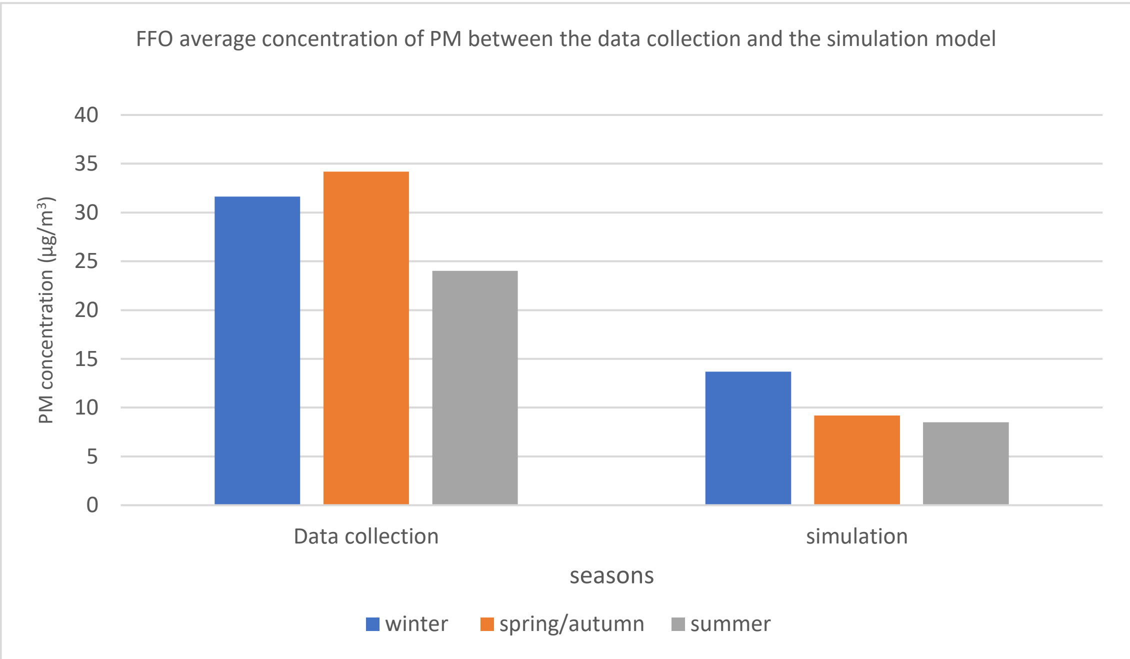

Figure 8-2 chart Comparing the average concentration of PM between the data collection and the simulation model for the three main seasons in the FFO the chemistry building

The data from the EHS shows that the concentration of PM is inconsistent. The reason for the inconsistency in the PM inside the space is the lack of a mechanical ventilation system. because the building relies mostly on natural ventilation the data shows a wide range of PM levels. However, there is a trend that always occurs inside the EHS and that is the presence of people. This also true for the OSO and the FFO, but in the case of the EHS the presence of people is more profound. The reason being is that during the afternoon the student and researcher use the kitchen to prepare meals during the break. When using the kitchen, a considerable increase in the level of PM can be detected. This shows that the kitchen is an important source of pollution. Another way the EHS differs from the chemistry building is that EHS is on a hilltop that is surrounded by grass and trees located outside of the Eco-House. This proximity to the outside green area has the potential to bring in many kinds of PM particles into the interior space.

Table 8-3 Comparing the average concentration of PM between the data collection and the simulation model for the three main seasons in the EHS the chemistry building

Season	(Winter) (μg/m^3)	(spring/Autumn) (μg/m^3)	(summer) (μg/m^3)
Data collection	38.93	27.20	29.2
Simulation	39	4.40	2.90

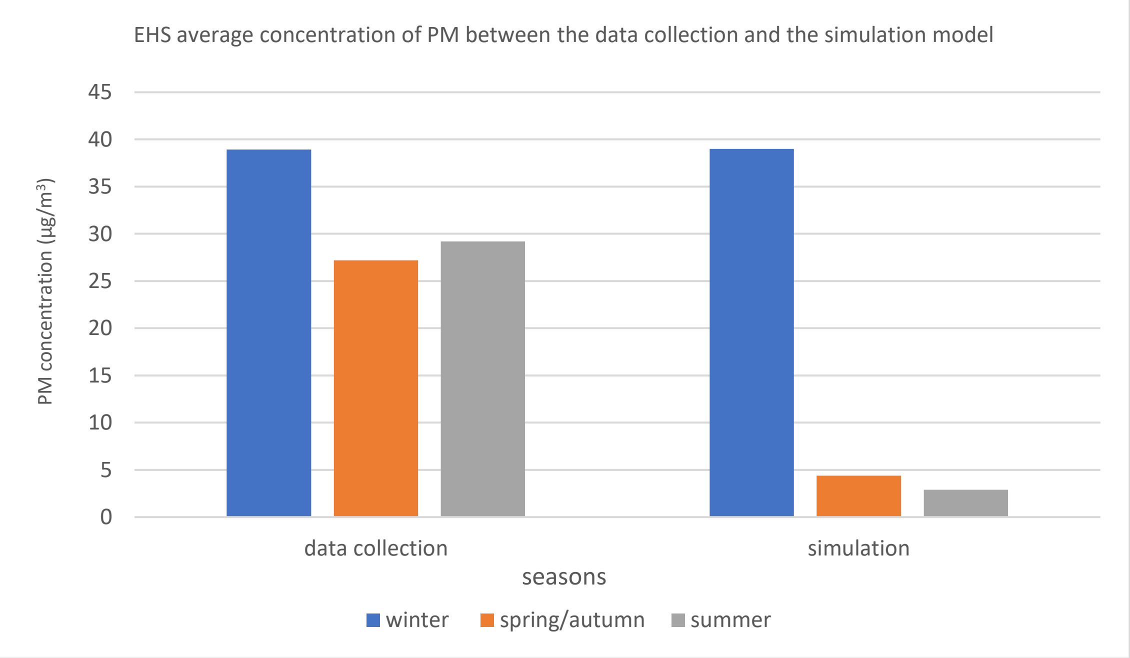

Figure 8-3 chart Comparing the average concentration of PM between the data collection and the simulation model for the three main seasons in the EHS

8.2.3 Carbon Dioxide (CO_2)

From the data collected it can be inferred that carbon dioxide is different from (PM). The major difference is that the presence of people is considered the most influential factor that will determine the concentration of CO2 inside the space. The OSO had the lowest concentration of CO2 in all three indoor spaces. There is however incidence of CO2 reaching levels close to 1000 ppm. However, these reading are very rare and do not represent the majority of the data result. Even though the concentration of PM in the FFO is very high, the concentration of CO2 in the FFO was very similar to the OSO. On the other hand, the CO2 concentration in the EHS is much higher compared to the OSO and the FFO. As mentioned before, the airflow inside the EHS relies on natural ventilation, therefore, there is little chance for the indoor levels of CO2 to diluted by mixing with the outdoor air especially in the winter season. Figure (8-4) shows a comparison between the average concentration of CO_2 from the simulation results with the average concentration from the data collection for the OSO model. The average from the simulation was representative of the result from the three main scenarios (summer , spring/autumn, and winter. These simulation results were compared to the result from the data collection. The data collection average was calculated using the average data collected from three months that are representative of the three main scenarios. The winter scenario was represented by the average data from the month of January, The summer scenario was represented by the average data from the month of June, and the autumn months were represented with the month of either October or march. Figure (8-5) and figure (8-6) shows the same comparison for the other two models FFO and EHS respectively.

Table 8-4 Comparing the average concentration of Carbon Dioxide between the data collection and the simulation model for the three main seasons in the OSO the chemistry building

Season	(Winter) (ppm)	(spring/Autumn) (ppm)	(summer) (ppm)
Data collection	499.67	467.53	456.02
Simulation	352	386	342

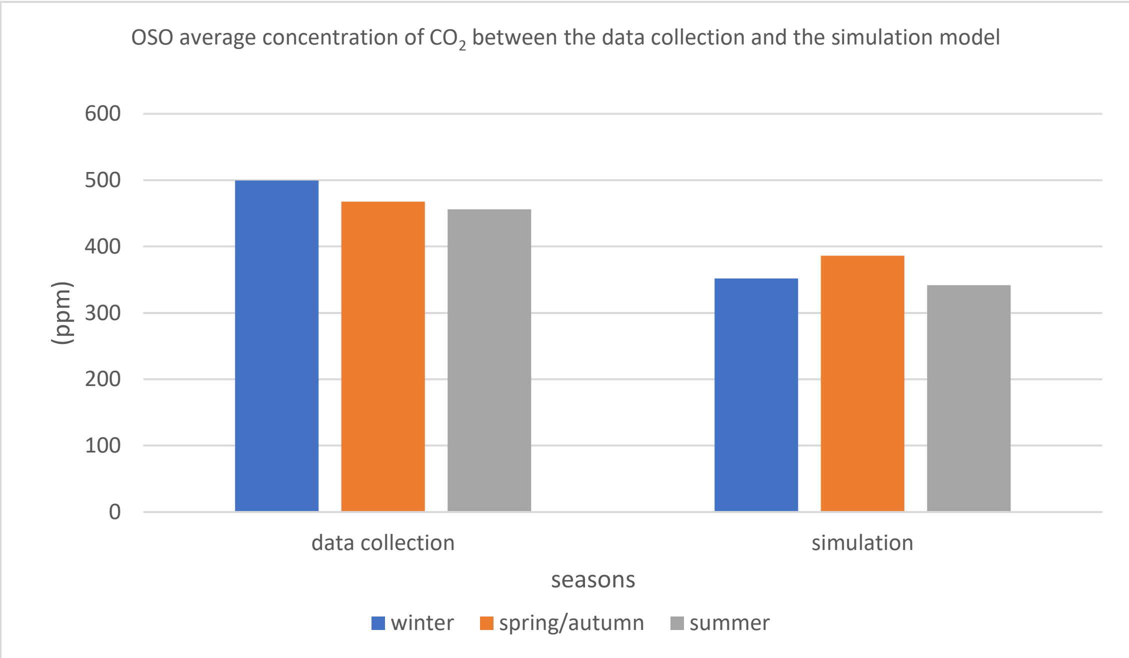

Figure 8-4 Chart Comparing the average concentration of Carbon Dioxide between the data collection and the simulation model for the three main seasons in the OSO the chemistry building

Table 8-5 Comparing the average concentration of Carbon Dioxide between the data collection and the simulation model for the three main seasons in the FFO the chemistry building

Season	(Winter) (ppm)	(spring/Autumn) (ppm)	(summer) (ppm)
Data collection	469.30	464.97	713
Simulation	462	450	541

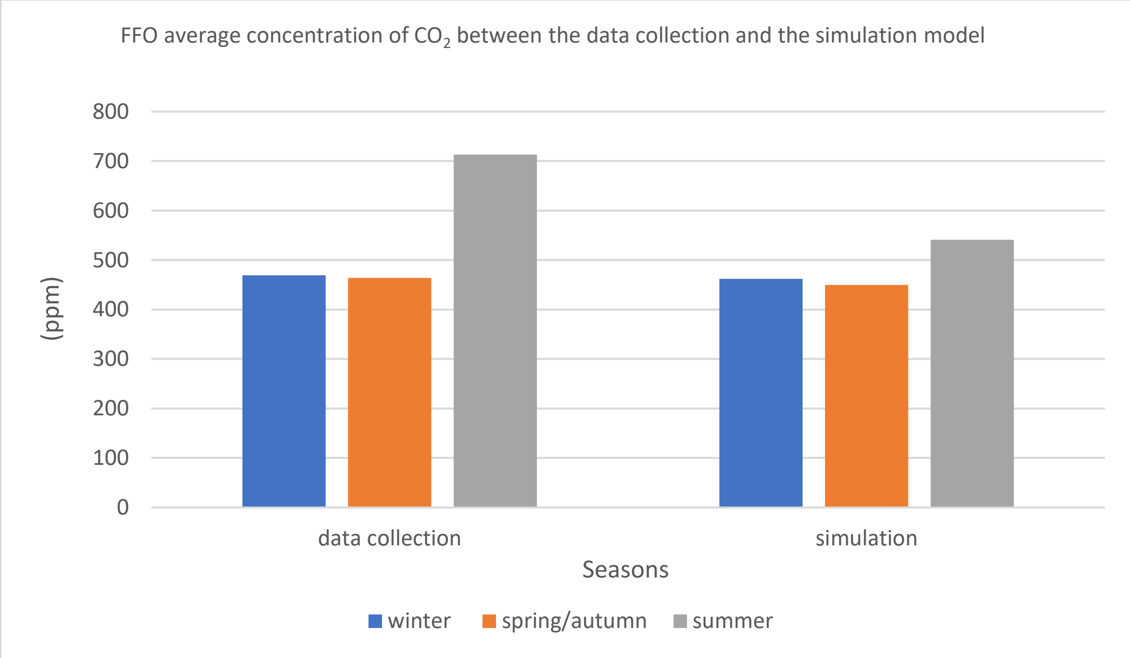

Figure 8-5 chart Comparing the average concentration of Carbon Dioxide between the data collection and the simulation model for the three main seasons in the FFO the chemistry building

Table 8-6 Comparing the average concentration of Carbon Dioxide between the data collection and the simulation model for the three main seasons in the EHS Eco-House

Season	(Winter) (ppm)	(spring/Autumn) (ppm)	(summer) (ppm)
Data collection	583.16	580.18	487.44
Simulation	422	412	406

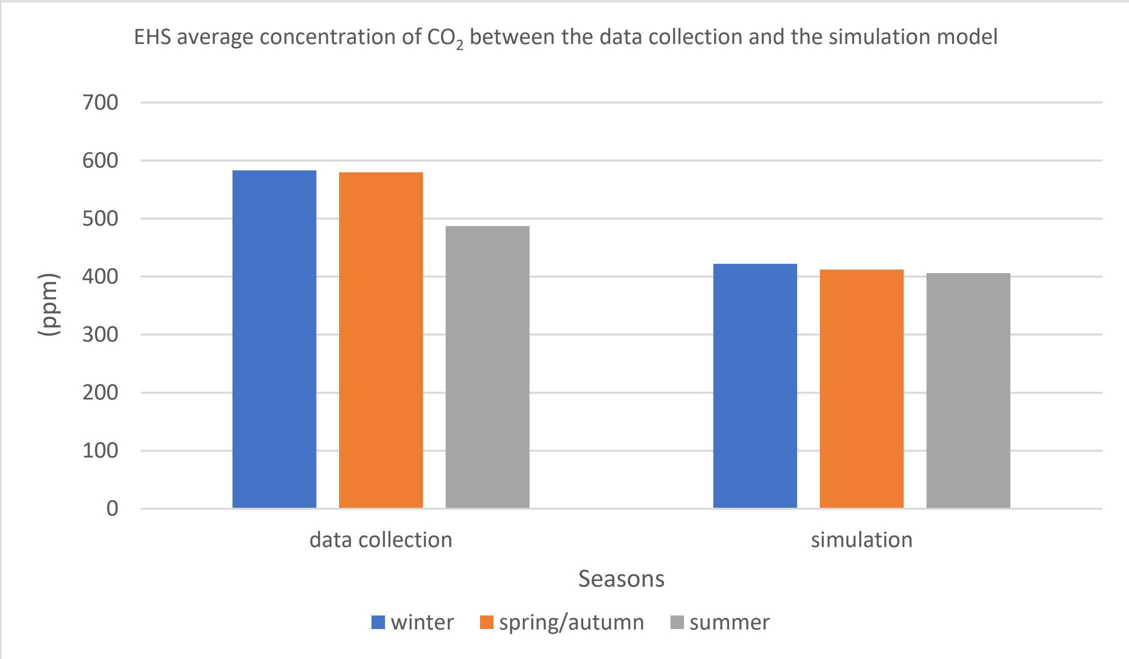

Figure 8-6 chart Comparing the average concentration of Carbon Dioxide between the data collection and the simulation model for the three main seasons in the EHS

8.2.4 Ambient temperature and relative humidity

When analysing the temperature and relative humidity in the chemistry building. It showed that the ambient temperature has been kept stable for most of the time with very few exceptions. The same could not be said about the ambient temperature inside the EHS where the ambient temperature fluctuates much more frequently. However, when looking at the data collected from all three indoor spaces, one phenomenon stands out very prominently. This phenomenon is the occurrence of overheating. The reason for overheating in all three indoor space is that during the summer period, all three spaces would have the windows and doors open all the time. By opening the windows and doors, the exterior hot air will enter the building and it will raise the temperature inside the space even if the MVHR is operating. Figure (8-7) shows a comparison between the average ambient temperature from the simulation results with the average concentration from the data collection for the OSO model. The average from the simulation was representative of the result from the three main scenarios (summer , spring/autumn, and winter. These simulation results were compared to the result from the data collection. The data collection average was calculated using the average data collected from three months that are representative of the three main scenarios. The winter scenario was represented by the average data from the month of January, The summer scenario was represented by the average data from the month of June, and the autumn months were represented with the month of either October or march. Figure (8-8) and figure (8-9) shows the same comparison for the other two models FFO and EHS respectively.

Table 8-7 Comparing the average ambient temperature between the data collection and the simulation model for the three main seasons in the OSO the chemistry building

Season	(Winter) (C°)	(spring/Autumn) (C°)	(summer) (C°)
Data collection	24.49	24.83	25.83
Simulation	21.85	22.85	28.85

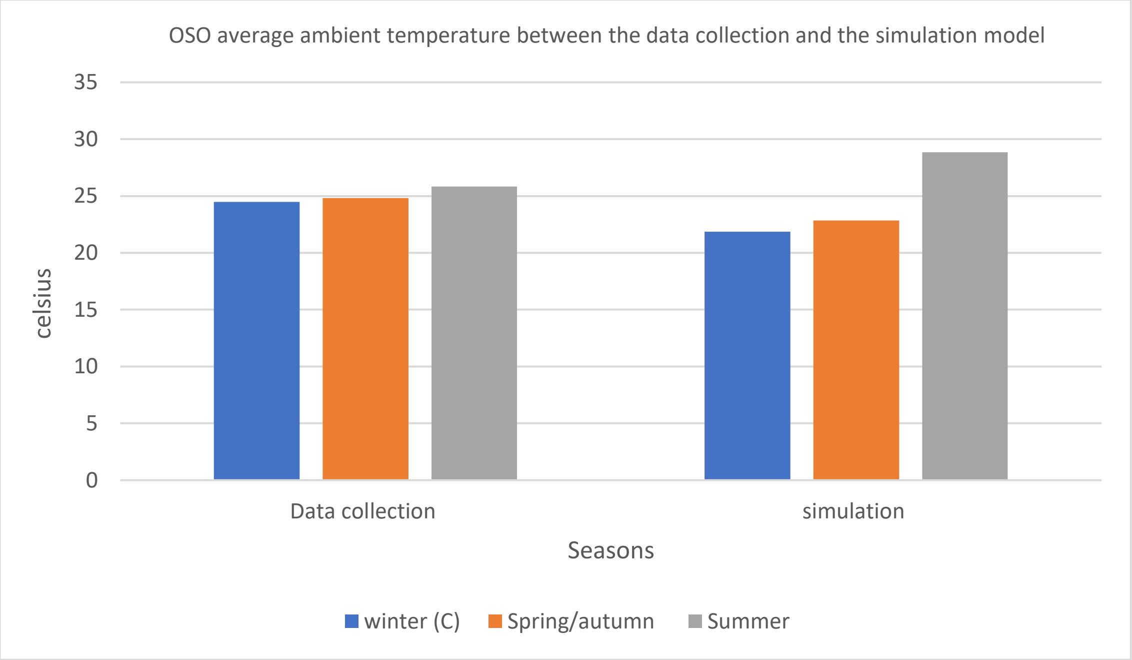

Figure 8-7 chart comparing the average ambient temperature between the data collection and the simulation model for the three main seasons in the OSO the chemistry building

Table 8-8 Comparing the average ambient temperature between the data collection and the simulation model for the three main seasons in the FFO the chemistry building

Season	(Winter) (C°)	(spring/Autumn) (C°)	(summer) (C°)
Data collection	24.42	23.96	25.98
Simulation	22.3	22.9	23.6

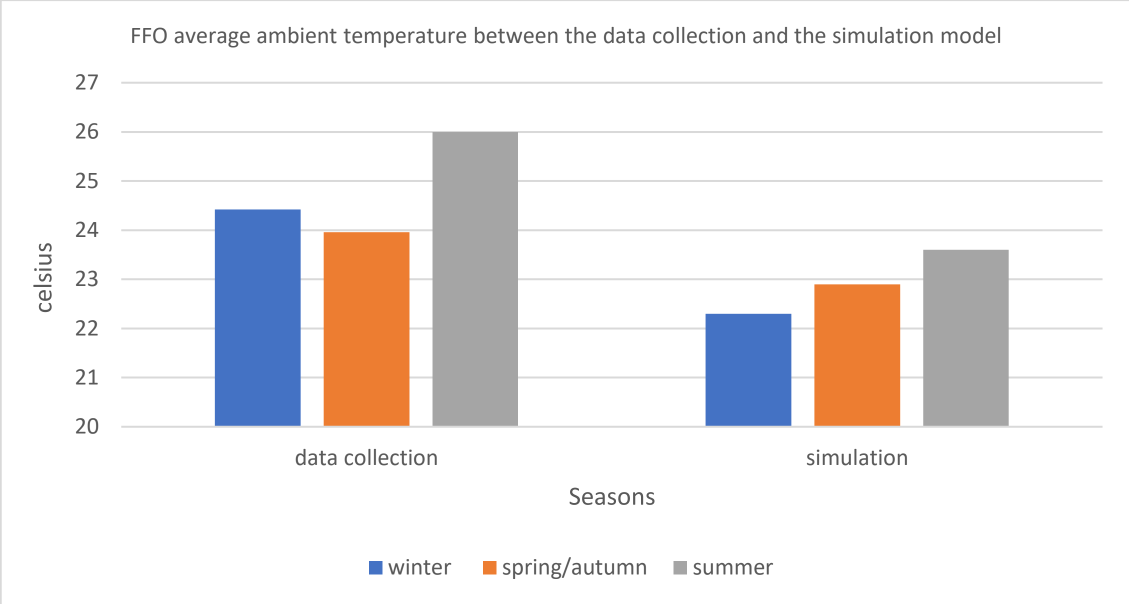

Figure 8-8 Comparing the average ambient temperature between the data collection and the simulation model for the three main seasons in the FFO the chemistry building

Table 8-9 Comparing the average ambient temperature between the data collection and the simulation model for the three main seasons in the EHS the Mark group house

Season	(Winter) (C°)	(spring/Autumn) (C°)	(summer) (C°)
Data collection	23.06	25.22	28.2
Simulation	20.88	26.85	35.6

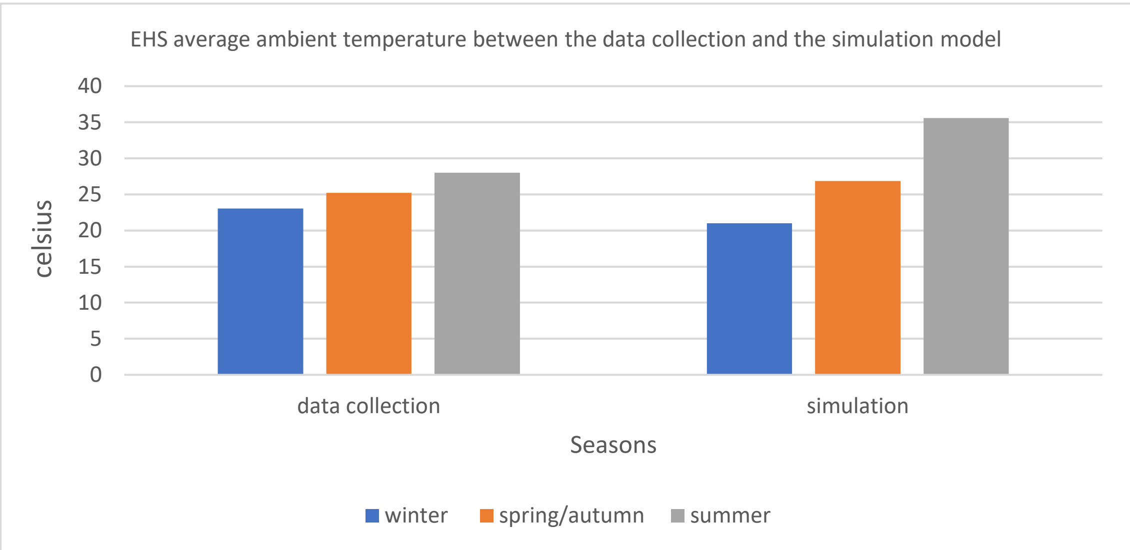

Figure 8-9 Comparing the average ambient temperature between the data collection and the simulation model for the three main seasons in the EHS the Mark group house

9. Chapter Nine: Conclusion

Buildings are essential for human lives because they spend most of their time inside of them. Over the last decades, many researchers, architects, and engineers are stressing the fact that energy consumption has become a major problem for the environment and stringent majors must be implemented to restrict the use of excessive energy. The answer to that problem was the development of Low-Carbon buildings. As they become more famous, many new buildings are constructed using low-carbon strategies. One of these strategies was the inclusion of new energy efficient technologies. Some of these technologies had shown in the literature and in this thesis that could negatively affect the indoor air quality inside the building. Either by bringing in more pollution or by simply failing to remove the existing pollutants of the inside. Therefore, this thesis was conducted to study the state of low-carbon buildings and its relation to indoor air quality. The aim of this thesis is to determine whether or not the use of low-carbon strategies or the implementation of new energy efficient technologies has any effect on indoor air quality. To achieve this several objectives were needed to be applied. The first step was to carry out a comprehensive literature review in order to establish the technological and environmental factors affecting indoor air quality in low-carbon buildings. Use data collection to assess the indoor air condition inside the building in terms of ambient temperature, relative humidity, the concentration of PM, the concentration of CO_2, and the air velocity. The third step was to carry out modelling and simulation of indoor air quality in selected low carbon buildings in the UK using the commercially available software ANSYS FLUENT 2020 R2®. The fourth step is to conduct a survey to assess occupants' satisfaction of indoor air quality in the selected low carbon buildings.

The three methodologies have given a different aspect to look at the conditions inside the three occupied spaces. The use of the data collection for a long period of time has given a good well-rounded picture of the conditions inside the space during the entire year. The data collection last for a whole year for both OSO and the EHS, and 7 months in the FFO. Most of the data collected from the three spaces had given predictable result in terms of ambient temperature, relative humidity, PM concentration, CO_2 concentration, and air flow. However, in many cases, there were some unpredictable results. Like the increase of ambient temperature in the summer, the difference in indoor air quality between the OSO and FFO. These results were unpredicted since both spaces are located in the same building. Some of the findings in this thesis showed that PM concentration was affected by both the presence of people inside the space, indoor sources, and the method of ventilation. On the other hand, CO_2 concentration was mostly susceptible to human presence. Another findings from the data collection showed that people interaction within the space has a great impact on the condition inside the space. This could be evident from the use of the kitchen area in the EHS, and it could also be shown in the opening of windows during the spring and summer periods.

In the simulation analysis, the study of the airflow of the three spaces had shown that using a mechanical ventilation is a great way to achieve acceptable indoor air quality. However, in some cases, the mechanical ventilation system alone is not enough to guarantee good indoor air quality. The FFO for example has its own mechanical ventilation system but the indoor condition inside of it is vastly different from the indoor air quality in the OSO. Another problem encountered in the simulation analysis of the three space is the issue of overheating. It seems like the design of the two buildings have incorporated a lot of good strategies that allowed it to gain reputable certification. But these certification does not guarantee that the building has solved all the issues inside of the building. A good example of that would be the problem with the sun rays that caused some issues to many students who were working inside the chemistry building. The result from the simulation showed that the design of the air flow inside the spaces has a great impact on the airflow inside the space and subsequently the presence of pollutants inside the space. This could include the location of the inlets and outlets, the number of inlets and outlets, the type of air ventilation used, and the active usage of people inside the space.

Lastly, the survey has also contributed immensely toward the study of indoor air quality. The participant of the survey has shed light upon different areas that were included in neither the building simulation nor the data collection. Some participants have experienced stuffy air inside the chemistry building, others perceived the air to be dusty, and others have noticed the smell of wood being ubiquitous inside the building.

There are some challenges encountered in this thesis. The first was the continuation of data collection. The devices had to be present at all time inside the monitored space and they register the data every 30 minutes all day. However, sometimes the employees accidentally unplug the device or, on some occasions, there would be some maintenance work that requires the building to shut off during maintenance hours.

Despite that, there were enough data to give the overall condition of the indoor air quality inside the space. Another challenge is that the device that was chosen to collect both the PM and VOC concentration inside the room, could only register the PM levels but not the VOC levels. Even though, the smell of wood was very prominent and many employees had reported smelling the scent of wood very often inside the room. The problem was that the device could only register several types of VOC. This could mean that the type of VOC that was emitting from the wood panels inside the chemistry building was not the same type of VOC the device is calibrated to detect. In regards to the simulation analysis. The only issue encountered was the file size and the limitation of the number of cells and surfaces that the user is allowed to construct. The maximum number of cells allowed was around 500,000 cells per model which might reduce the accuracy of the result. However, the result of the simulation is very much aligned with the data collection.

The result of the study has shown that the implantation of new energy efficient technologies did not compromise the indoor air quality inside the space. In fact, the use of new technologies like MVHR has insured the air quality inside the space and allowed for the pollutant inside the space to reach an acceptable level. However, there were some issues that were discovered when analysing the data and performing the simulation for the three selected indoor space for this study. The first of these problems is that in the chemistry building, for example, not all areas inside the building have the same indoor air condition. The data from the OSO has much better indoor air quality compared to the FFO. This could show that when designing a low-carbon building all areas inside the space are important and no certain region should be neglected. The second problem was found in the EHS in which the natural ventilation did not provide an adequate indoor air quality condition. The third problem is overheating. the issue of overheating was present in all three indoor spaces which showed that in cold regions like the United Kingdom, there should a well-developed solution that will ensure that indoor air condition in low-carbon building is well kept in all seasons. Another potential problem that was discovered in this research is that some of the rooms selected for the case study have exhibited unequal spread of pollutants like PM inside the space base on the simulation result.

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