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Experimental Investigations of Indoor Air Particular Matter in Hot and Humid Climates

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Thesis submitted to the University of Nottingham for the degree of Doctor of Philosophy

August 2016

ABSTRACT

Throughout the era of globalization, industrial development and transportation have brought about hazardous air environment especially in developing countries. Southeast Asia with large number of labor and natural sources has expanded manufacturing area as well as the problem of local community being reluctant air pollutant. It seems to be double suffocation with emitting frequently forest fire fume covering some parts of Thailand and Indonesia. These reasons can lead to around 5-time exceeding of annual standard in the National Ambient Air Quality Standards (NAAQs). Without fresh ventilation, filtration has become more important but it may be not affordable for low income people. So this study aims to develop low cost air dust purifier being suitable for hot and humid climate based on NAAQs and BS EN.

Based on low cost and general air purifying techniques, fabric filter and solid fibre mop were selected for air cleaning efficiency evaluation in laboratory. For fabric filter, in one cubic meter wooden box, pleated fabric filter was installed in the middle of box and body spray was sourced as air particulate matter sized 2.5 micron (PM2.5). The result demonstrates air cleaning efficiency of fabric filter at 85% with high fan speed. This is equal F7 in BS EN and MERV 16 in NAAQs for fine dust filtration.

Turning to solid fibre mop evaluation, mops with several sizes of fibre diameter in particular (A) 0.08-0.58 mm, (B) 0.22 mm and (C) 0.16 mm were installed in the middle of box sized 0.41 m width, 0.51 m length and 0.45 m height. The results show the highest efficiency to clean PM2.5 and PM10 at 36% in mop C and 25% in mop B respectively. Moreover, multiple mops C and A have high rapidity of air PM2.5 removal at 0.050 mg/sec in 300 seconds; while multiple mops B and C have high rapidity of air PM10 removal at 0.005 mg/sec in 300 seconds. According to performance to clean PM2.5 and PM10, mop B with TiO_2 coating on solid fibre was selected to integrate within filter lamp.

Environmental factors are found to affect PM2.5 concentration in different trend. Temperature responded negatively; while relative humidity provided positive relationship to PM2.5 concentration. In most case of solid fibre mops tests, relative humidity dropped PM2.5 removal efficiency, but increase PM10 removal efficiency. However, high relative humidity and temperature in the filter lamp tests were set high as same as in tropical climate.

After laboratory tests, fabric filter was combined within floor lamp as lamp shade and solid fibre mop was set in the middle core of lamp with coated TiO_2 2.0% concentration and UV light bulb. Fan unit was set in the bottom of lamp in order to control system flow speed in application system. The application was placed in 2.5x2.5x2.5 m^3 bedroom for cleaning indoor PM2.5 in six different algorithms comparing to existing PM2.5 concentration. The best efficiency of PM2.5 removal is 99.07% of regime F with fabric filter, TiO_2 coating mop and fan speed at 3 m/s. This is also ranked into F9 in BS EN and MERV16 in NAAQs for fine dust cleaning filtration. Without photocatalytic process in regime B, C and D, the application could be used in lower efficiency. Higher fan speed was substantial effect on PM2.5 removal efficiency and rapidity for filter lamp.

This filter lamp was found high efficiency to clean indoor PM2.5 in hot and humid condition. Based on low cost development, this application can be applied with natural ventilation system in buildings in Southeast Asia hot and humid climate. Also other conditional climate buildings may integrate this application with lower air cleaning efficiency.

ACKNOWLEDGEMENTS

Firstly, I would like to express my sincere gratitude to my supervisors Prof. Saffa B. Riffat and Dr. Guohui Gan for the continuous support of my PhD study and related research, for their patience, motivation, and immense knowledge. Their guidance helped me in all the time of research and writing of this thesis.

Besides my sincere thanks also goes to Dr. Xiaoli Ma who provided me experimental instrument and suggest me laboratory process and research facilities. I would like to thank research administrator: Zeny Amante-Roberts who cooperated all of helpfulness in research process, laboratory instrument and meeting appointment. Without they precious support it would not be possible to conduct this research.

I thank my friend in institute fellow Sumavalee Chindapol for the stimulating discussions and proofreading. Also I thank my housemates Natenapa Promtape and Aranya Rakhab who support accommodation and food and always beside me.

Last but not the least, I would like to thank my family for supporting me spiritually throughout writing this thesis and my life in general. I am also grateful to Krajokrungpetch, Ltd. who supported PhD finance of academic grant to me for 3-year venture.

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LIST OF ABBREVIATIONS

7SEAS	The Seven Southeast Asian Studies
ABPA	Allergic bronchopulmonary aspergillosis
AC	Air conditioning
ACH	Air changes per hour
AD	Atopic dermatitis
AQGs	Air Quality Guidelines
AQHI	Air quality health index
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
AURN	The Automatic Urban and Rural Network
AVA	Air Ventilation Assessment
BC	Black carbon
BCA	The Building and Construction Authority
BRE	Building Research Establishment
BREAM	Building Research Establishment Environmental Assessment Methodology
BS EN	British Standard European Norm
BTEX	The stands for Benzeen Tolueen Ethylbenzeen Xyleen
BVOCs	Biogenic volatile organic compounds
CAA	The Clean Air Acts
CAI	Clean Air Initiative
CAPs	Climate-altering pollutants
CF	Cystic fibrosis
CFD	Computational fluid dynamic

CFR	Code of Federal Regulations
CH_4	Methane
CHD	Congenital heart disease
CO	Carbon monoxide
CO_2	Carbon dioxide
COPD	Chronic Obstructive Pulmonary Disease
CTMs	Chemical transport models
DEDE	The Department of Alternative Energy Development and Efficiency
DOP	Dioctyl phthalate
DPV	Diver Propulsion Vehicle
ECMs	Emission control measurements
EDC	Elutriation Dust Column
EEA	The European Environment Agency
EGAT	The Electricity Generating Authority of Thailand
EPA	Environmental Protection Agency
EPPO	The Energy Policy and Planning Office
ERF	The effective radiation force
ESE	European Society of Endocrinology
ESPs	Electrostatic precipitators
ETS	Environment Tobacco Smoke
EWO	The Early Warning Organic
FEV1	Forced expiratory volume at 1 second
FVC	Forced vital capacity
GCM	General circulation model
GPT	Gas permeation test

H_2O	Water
HAP	Household Air Pollution
HC	Hydrocarbon
HCHO	Formaldehydes
HEPA	High-efficiency particulate arrestance
HO_x	Hydroxides
HVAC	Heating, ventilation and air conditioning
KSP	Karolinska Scales of Personality
IAQ	Indoor Air Quality
IPCC	Intergovernmental Panel on Climate Change
LEED	Leadership in Energy and Environmental Design
MERV	Minimum efficiency reporting value
MLR	Multiple linear regression
MON	Museu Oscar Niemeyer
MV	Motor Vehicle
MVOCs	Micro Volatile Organic Compounds
NAAQS	The US National Ambient Air Quality Standards
N_2	Nitrogen gas
N_2O	Nitrous oxide
NaCl	Sodium chloride
NIOSH	The National Institute for Occupational Safety and Health
NO_x	Nitrogen Oxides
O_2	Oxygen
O_3	Ozone
OA	Organic aerosol

OSHA	Occupational Safety and Health Administration
PAHs	Polycyclic Aromatic Hydrocarbons
PAN	Peroxyacetylnitrate
Pb	Lead
PCA	Plate count agar
PEFR	Peak expiratory flow rate
PM	Particulate Matter
PM1	Particulate Matter diameter sized 1 micron
PM2.5	Particulate Matter diameter sized 2.5 microns
PM10	Particulate Matter diameter sized 10 microns
QA/QC	Quality assurance/quality control
RCCs	Respiratory care centers
RM-PQC	Resin Mastic coated Piezo electric Quartz Crystls
Rh	Relative humidity
ROGs	Reactive organic gases
RT-AQF	Real-Time Air Quality Forecast
SARS	Severe acute respiratory syndrome
SBS	Sick Building Syndromes
SEM	Scanning electron microscope
SES	The Small Edison Screw
SO2	Sulphur dioxide
SOA	Secondary organic aerosol
SPM	Suspended Particle Matter
STEL	Short-term exposure limit
TEOM	Tapered element oscillating microbalance

TGBI	Thai Green Building Institute
TiO_2	Titanium Dioxide
TNP	TiO_2 nanoparticles
TSP	Total suspended particulates
TWA	Total Weighted Average
UNEP	United Nations Environment Programme
UV	Ultraviolet
VNEEP	The Vietnam National Energy Efficiency Program
VOCs	Volatile Organic Compounds
WHO	World Health Organization
XRD	X-ray diffraction

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Chapter 1: Introduction

1.1 Background and issues

In the era of climate change, irreversible environmental variation has brought more extreme and various natural disasters such as powerful storms in USA, heat wave in Europe, Tsunamis in Asia and forest fires in Australia. As a result, the butterfly effects of global change have been considered in natural resources, human settlements and human health. According to such influence, in terms of air quality, it was assured that a number of fire hotspots in the north of Thailand correlated positively to the levels of Carbon monoxide (CO) and PM10 concentration (Sukitpaneenit & Oanh 2014). Also it is evident that 24-hr concentrations of Particle Matter sized 2.5 micron (PM2.5) and sized 10 micron (PM10) were increased their level and exceeded WHO Air Quality Guidelines (AQGs) in 2014 as same as increasing levels of Volatile Organic Compounds (VOCs) such as formaldehyde, ethyl benzene, benzene, toluene, and styrene (IPCC 2014). Then it can be seen that air pollutant was severely supported by global warming conditions.

Not only climate change issues that could increase indirectly amount of air pollutant, but human activities for example industrial developments and traffic situation are found to be top causes of dramatic high air pollution. The solutions of air pollutant problems were found in local governmental policies of traffic planning and zoning industrial areas. As evident situation, after industrial production moving to China from late of the 19th centuries, pollutant had become a major problem in Beijing, Shanghai and Guangzhou. Then, in 2013, China State Council took "Atmospheric Pollutant Prevention Action Plan" to drop particle matter level in Beijing, Tianjian and Hebei as well as to control traffic vehicle in Beijing, Shanghai and Guangzhou (Ryan 2013). However, this action plan could not be guaranteed yet how long to standardize industrial and traffic pollutions in China and that was not sufficient for protecting and treating respiratory health of WHO standards. So not only authorized plans could be released but self-protections from air pollutants should be promoted to local people in risk areas.

Before specifying air purifications, it is important to categorize basically air contaminations in five types according to their sizes from large to small in particular PM10, PM2.5, bio aerosol, gaseous compounds and VOCs. These different sizes can indicate how deep that people can breathe them in respiratory system and bring more hazardous to occupy. In a brief review, PM2.5 was identified to respiratory dust that could irritate human issues but bio aerosol and VOCs could bring about suffering symptoms from disease and environment (Wongwatcharapaiboon, Gan & Riffat 2013).

To recommend anti-pollutant devices, indoor and outdoor conditions are important indicators to choose appropriate air purified techniques. For open-air environment, street walkers have not various choices to protect themselves, but long covering suites and portable devices such as masks should be basic recommendation in high air pollutant areas. For more complicated protection in indoor area, the level of dust concentration can be limited firstly by buildings' envelope, and then several techniques installed in building elements can effectively purify indoor air quality depending on hygiene requirement.

Table 1-1 The examples of general air filtration

Name	Techniques	Media
Cartridge filters	compressed air system	filter
Pad filters	fabric filter with frame	filter
Panel filters	fibre filter	polyurethane media (washable)
Viscous panel filters	adhesive gel coating	wetted oily media
Roll filters	automated filter roll	filter
Rotating viscous panel filters	continuous curtain loop	oil bath
Bag or pocket filters	layer of framed filter	filter
Particulate air filters	High-efficiency particulate arrestance (HEPA)	filter
Electrostatic precipitator(ESPs)	agglomerator	filter, or plate with water washing
Louvres	aerodynamic separator	liquid mist particle collector
Separators	aerodynamic separator/cyclones	dust collector
Scrubbers	wet dust separators	liquid particle trap

In general, air filter can be classified by their efficiency following 2 standards in BS EN 799:2012 with 9 levels of filter efficiency and ASHRAE Standard52.2-2012 with 20 levels of filter efficient. To achieve those efficiency standards, several techniques are adapted to purify air pollutants for examples compressed systems in cartridge filters, adhesive surface traps, washable curtain loops, electronic separators and aerodynamic cyclones. Then, to focus on purifier media, there are two types such as filter which consists of fabric or fibre and liquid dust trap in terms of water flowing or oil coating following **Table 1-1** (Sparks & Chase 2016). However, the high potential of air purification ability could lead to high cost of product, so the combinations of several low cost techniques have been integrated for improving air cleaning performance.

To be noted, there was another new special technique in late 20th century called photo-catalytic degradation by the effect of Titanium Dioxide (TiO_2) coating and it became a popular technique in commercial air purifier products in short period (Augugliaro, Loddo & Pagliaro 2010). This result from air cleaning action of TiO_2 can be easily catalyzed in natural sources in particular light and humidity. However, the efficiency of photo-catalytic depends on TiO_2 coating and integrated part of TiO_2 filter. Normally, air temperature, humidity and Ultraviolet (UV) radiation were predicted confidentially to rise up in near-term future (IPCC 2014). So technique of photo-catalytic from TiO_2 has been focused to harvest effectively these natural resources.

1.2 Research questions

According to above literatures of current air pollution, real-time situation of both indoor and outdoor air pollutions were firstly monitored to double check air contaminated situation and increase reliability of testing equipment. Then, the relationship between meteorological factors and concentration of air pollutants would be analysed in order to develop a device for air cleaning. More questions that need to be asked are that general purifiers can efficiently clean indoor air, if not, how to improve the efficiency of budget purifier?

To clarify purifier efficiency, there were two types of air pollutants used in this research especially PM2.5 and PM10. So the methodology to prove those air pollutants would vary based on each type of air pollutant. Under the low cost condition, the integration of air purifier would be ultimately developed to clean indoor air in 2.5x2.5x2.5 m^3 bedroom.

1.3 Aims and objectives

This study aims to develop low cost air purified integration for cleaning PM10 and PM2.5 in hot and humid climate by two types of experiments such in laboratory and real-time monitoring. Based on hot and humid climate in Southeast Asia, environmental factors affected indoor pollutant concentrations were firstly investigated in terms of air temperature and air humidity.

In case of air filter purifiers, efficiency of pleated fabric filter was preliminary tested for eliminating PM2.5. Then fabric filter would be designed as being floor lamp shade to clean indoor respiratory dust. Turning to case of mop purifiers, fibre bunch mop would be evaluated for the performance of PM10 cleaning. Diameter sizes of fibre would be proved to affect mop structure and efficiency of PM10 purification.

In terms of photocatalytic process, the effect of TiO_2 coating surface on air purification would be examined and adapted to floor lamp installation. According to the aims of this research, seven main objectives of this research are addressed as following:

- To understand and observe current situation of indoor and outdoor PM2.5 concentration in office and accommodation buildings in Shanghai, China and to preliminarily test air particulate matter monitoring instruments.
- To investigate the relationship between level of air pollutant and relative humidity and air temperature.
- To evaluate PM2.5 cleaning efficiency of fabric filters and PM10 cleaning efficiency of mop in UK laboratory.
- To design light lamp application by using fabric filter and solid fibre mop coated by TiO_2 and then to evaluate PM2.5 cleaning performances of all regimes in existing bedroom.

1.4 Research area

Since the extension of industrial areas to Asian as seen in ASEAN Economics community, the air pollution risk has increased dramatically by human-being and disaster effects. Moreover, climate change has affected to air pollutant concentration as increasing of air temperature and humidity around the world (IPCC 2014). So this research would be scoped in hot and humid climate in South East Asia. As specific filtration techniques and devices, literature review would be indicated to current situations and problems of indoor and outdoor air pollution in hot and humid climates.

According to research objectives, the variables of this research are varied including types of filter, types of air pollutant, air pollutant concentration before and after filters, ambient environments etc. However specific position of variables would be identified in detail later depended on the objectives of each experiment. For the main essential samples, this research focuses on the concentration of several air pollutants in terms of PM2.5 and PM10, but bio contaminant in the air is a kind of limitation for this research as insufficient laboratory equipment.

Moreover, the experiments in this research included field and laboratory base. For real-time monitoring tests, there were two locations: one was in Sonjiang, Shanghai, China for testing indoor and outdoor PM2.5 concentrations and another place was in Dunkirk, Nottingham, United Kingdom to prove indoor PM2.5 concentration. Laboratory tests were in Architecture and Built Environment department in University of Nottingham, United Kingdom.

1.5 Methodology

The first stage of this research methodology is literature. In this research, indoor air quality problems in hot and humid climate have been analysed. Then, five main types of indoor pollutant are identified including fine particulate matter, respiratory dust, bio aerosols, gaseous pollutants and VOCs. The review is conducted according to types of pollutant, size range of each pollutant, concentration of pollutants, initial sources of pollutants, health and environmental effects from each type of pollutant, relationship between pollutant concentration and different existing environments, experimental process to evaluate pollutant concentration, equipment or instrumentation to monitor pollutants, latest international standards of indoor pollutant concentration, criteria of international air quality standards and also the application of indoor air quality filter performance. The findings of this systematic review would be presented along with the limitation of existing methods and recommendations for further research into indoor air quality in hot and humid climate.

Following literature reviews on experimental fields, two kinds of experiment were carried out testing filter performance in laboratory and real time dust monitoring. In laboratory tests, efficiency of air purifier elements, for examples pleated fabric filter and fibre mop, would be investigated comparing to ASHRAE standards. Also the statistical analysis would be one of methodology to rearrange reliably collected data from laboratory. For real time monitoring, 24-hr meteorological data and air pollutants concentration in Shanghai would be shown comparing to the National Ambient Air Quality Standards (NAAQS). Then indoor monitoring test of air purifier lamp would be at the end of this research. The equipment installed in UK monitoring and laboratory for dust collection would be the "DPM-4000^{TM}" Real-time Personal Diesel Particulate Monitor that was compared to the "TSI" dust meter in Shanghai.

Above methodology in this research will be clarified in details in chapter 3 and will be referred to in some part of thesis outlines and frameworks.

1.6 Research contributions

The methodology of indoor air purifying in hot and humid climate was clarified as indoor PM2.5 and PM10 infiltration reviews. The quality of each air purifying techniques would be proved in existing bedroom and the comparable results would be presented and concluded for use in hot and humid climate. This methodology and experimental techniques can be guidelines for researchers who are interested in air purification techniques.

Not only the process of research, but the knowhow of integrating air purifiers to existing gadget would also be simply examined and indicated how to use properly and economically in hot and humid climate. So this general low cost air purifier can be self-adaption in developing countries to at least first-protect themselves from severe polluted environments.

1.7 Thesis outlines and frameworks

According to aims and objectives of this research, to investigate how to integrate holistic low cost air purifier, full process of thesis is outlined in **Figure 1-1**. Based on research activities, literature review is the first step for all incident of air pollutant situation in Southeast Asia when physical data of air pollutant can be reviewed together with health effects from each air pollutants. Then reviews of experimental field are shown in terms of methodology and equipment preparations. Also international standards, compared to experimental results later, can be clarified in air PM2.5 and PM10 concentrations. In the second activity, preliminary tests are separated to laboratory test in UK and real-time monitoring in China. After pre-study of all equipment, design stage is applied in the third activity and all designed purifiers are evaluated for their performances and air cleaning efficiency. For the last activity, outcome of research can be shown in terms of indoor air purification techniques and application.

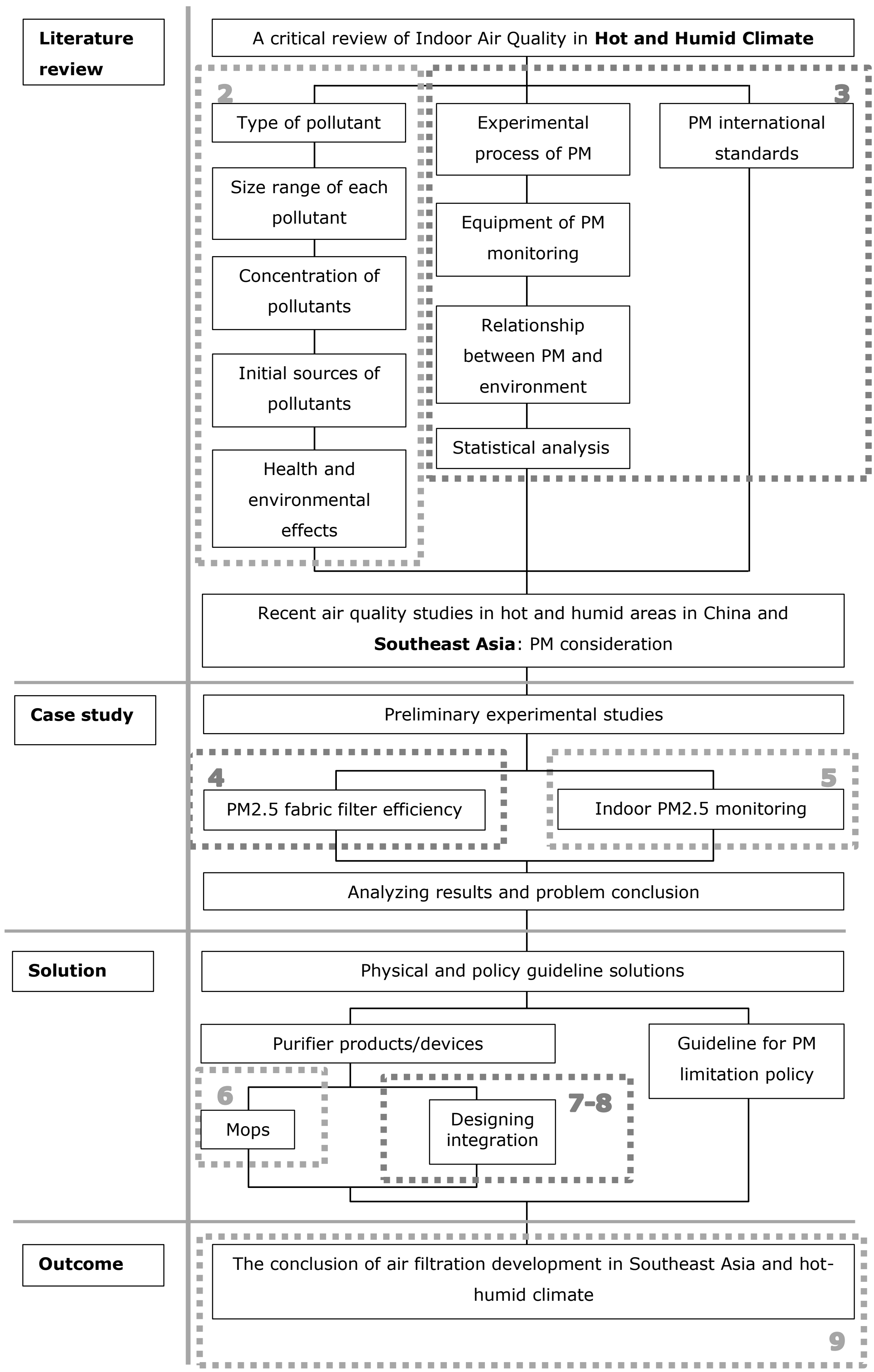

Figure 1-1 Diagram of research process and structure for the thesis

By chapter, research process in **Figure 1-1** can be separated into 9 chapters as the number shown in diagram and a brief explanation is given below:

Chapter 1: This chapter demonstrates the main important concept of this research by introducing situation of world air pollutant situations and problems. Then all research activities are briefly informed.

Chapter 2: Literature review in this thesis can be divided into air pollution situation in developing countries in hot and humid climate, characters of different air pollutants and their effects on human health, methodology and statistical analysis in experimental fields, and international standards or agenda.

Chapter 3: The methodological process is explained in details in this chapter including experiments both in and out of laboratory, testing and validating equipment, statistical sampling method and the efficiency calculation in international standards.

Chapter 4: Preliminary test in pleated fabric PM2.5 filter efficiency is illustrated all results in UK laboratory. The chapter includes analysis data, efficiency results compared to indoor air pollution standards, other relationships of meteorological data and PM2.5 concentration and the influence of pre-testing equipment in later chapter.

Chapter 5: Preliminary test in real-time monitoring results in Shanghai, China are shown in meteorological data, PM2.5 concentration both indoor and outdoor conditions. The monitoring was set in both accommodation and academic office buildings in Donghua University, Shanghai, China. The real-time record of weather data is used to another indicator to analyze research application in next step.

Chapter 6: According to the incident of air pollutants in China, research area is extended to be air PM10 purification as relating directly to PM2.5. In this chapter, solid fibre mops are estimated whether diameter of solid fibre is the best performance for cleaning air PM10. Recommended mop can be integrated to TiO_2 coating and filter lamp later.

Chapter 7: An adaptive fabric filter lamp is designed for cleaning PM2.5 in bedroom. International air quality standards are matched to indicate air purification performance of lamp application.

Chapter 8: TiO_2 coating fibre mop and UV light bulb are installed to the lamp to eliminate air PM2.5 by photo-catalytic process. The hot and humid meteorological data is set as same as hot and humid condition.

Chapter 9: The conclusions of this research can be demonstrated as the conclusion of air filtration development and recommendations for further research.

Chapter 2: Critical review of indoor air quality in hot and humid climate

To achieve study objectives, this chapter will orderly clarify (2.1) initial sources and types of air pollutants, (2.2) the effects of air pollutants on human health, (2.3) the effects of meteorological factors on selective air pollutants, (2.4) air pollution situation in Asian tropical climate, (2.5) indoor air filtration, (2.6) the experiments of air quality monitors and (2.7) conclusion as illustrated in **Figure 2-1**. Each part of review will be explained relating to main study, then methodology and all standards will be examined in the next chapter.

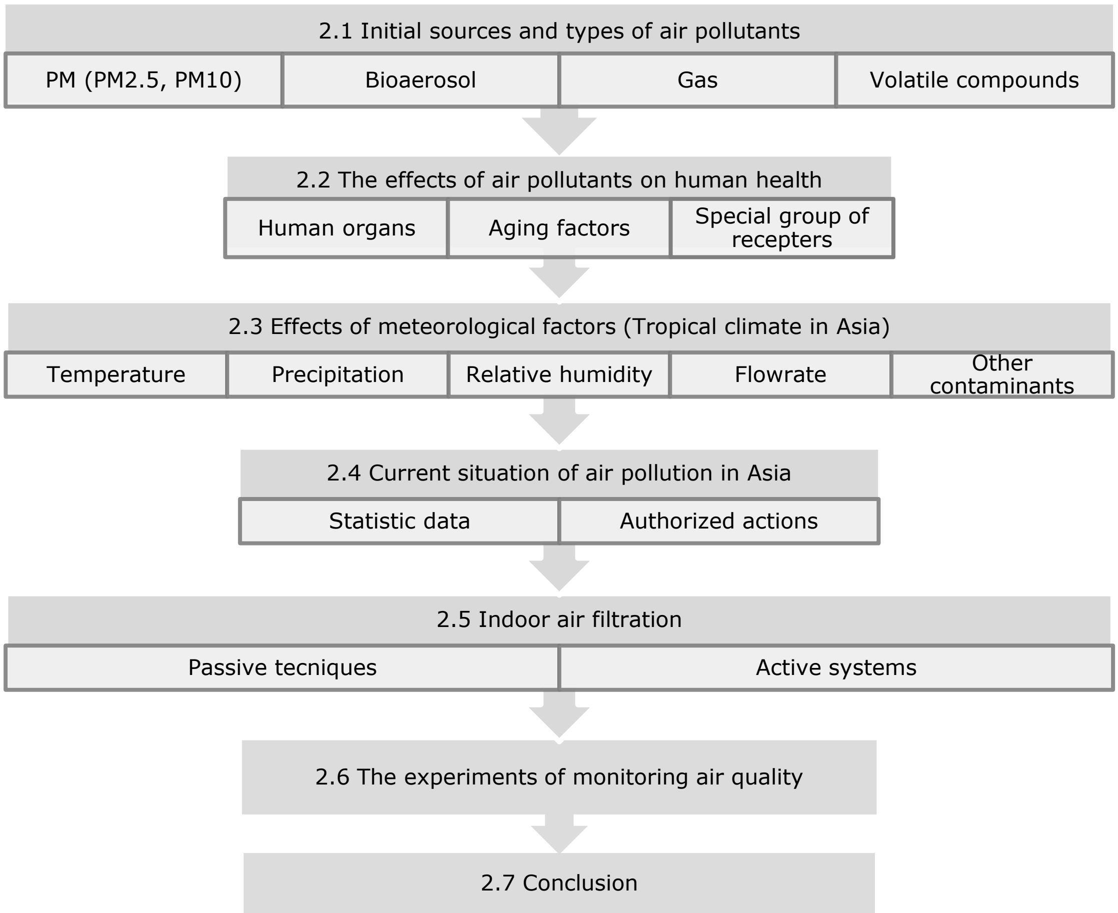

Figure 2-1 Literature review diagram

From **Figure 2-1**, the literature review begins with sources and types of pollutants including the characters of air pollutants and the mobility in human respiratory. Then pollutant types will be selected for being experimental variables in next chapter.

2.1 Initial sources and types of air pollutants

Normally, outdoor activities can let people face directly air pollutants in terms of industrial emission, traffic combustion and wild fire, while indoor pollutant can be produced from household activities and outdoor sources as micro particle self-formable (Zhang, Jiang & Chen 2012). The main particles of road dust were mixed from tyre rubber and road surface materials with metal components for instance Lithium (Li), Sodium (Na), Calcium (Ca), Iron (Fe) and Titanium (Ti) (Dall'Osto et al. 2014). Then, from the sources to receptors body, their effective transportations are dependent on air stream parameters such as surface roughness (z_0, m), the Coriolis parameter (f, s^{-1}), radiation fluxes or even buoyancy effect of source height (Harrison & Perry 1986). Not only air stream flow rate, but the level of air pollutants can be also affected by meteorological factors, size, electrode action and types of air pollutants (Chen & Shen 2010, Samek 2009). Also, as global warming effects being concerned, the greenhouse gases (GHGs) from fossil fuel and energy consumption have responded positively to carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) levels (Ciais et al. 2013).

In case of indoor air pollution, there are more sources and other factors that can increase indoor pollutant concentration to 5 times higher than outdoor context. For example, building envelops and furniture material can be air pollutant sources and obstructions to air purification in the same time, so it is more problematic to clean indoor air. To clarify air purification techniques, it is essential to group types of air pollutant for understanding their characteristics and applying more proper air filtration.

Indoor air pollutants vary widely ranging from invisible gas to visible particles (Jones 1995). However, the types of air pollutants can be separated in various modes such as by sources of pollutants, diameter size, chemical state or health effects. For example, based on the World Health Organization's (WHO), four simple types of air pollutants taking into account high monitoring concentrations and critical impacts on human health are particulate matter, ozone, nitrogen dioxide and sulphur dioxide. This is a kind of outcome effect of air pollutant types study, but initial sources of pollutant type's research can clarify clearer in their characters.

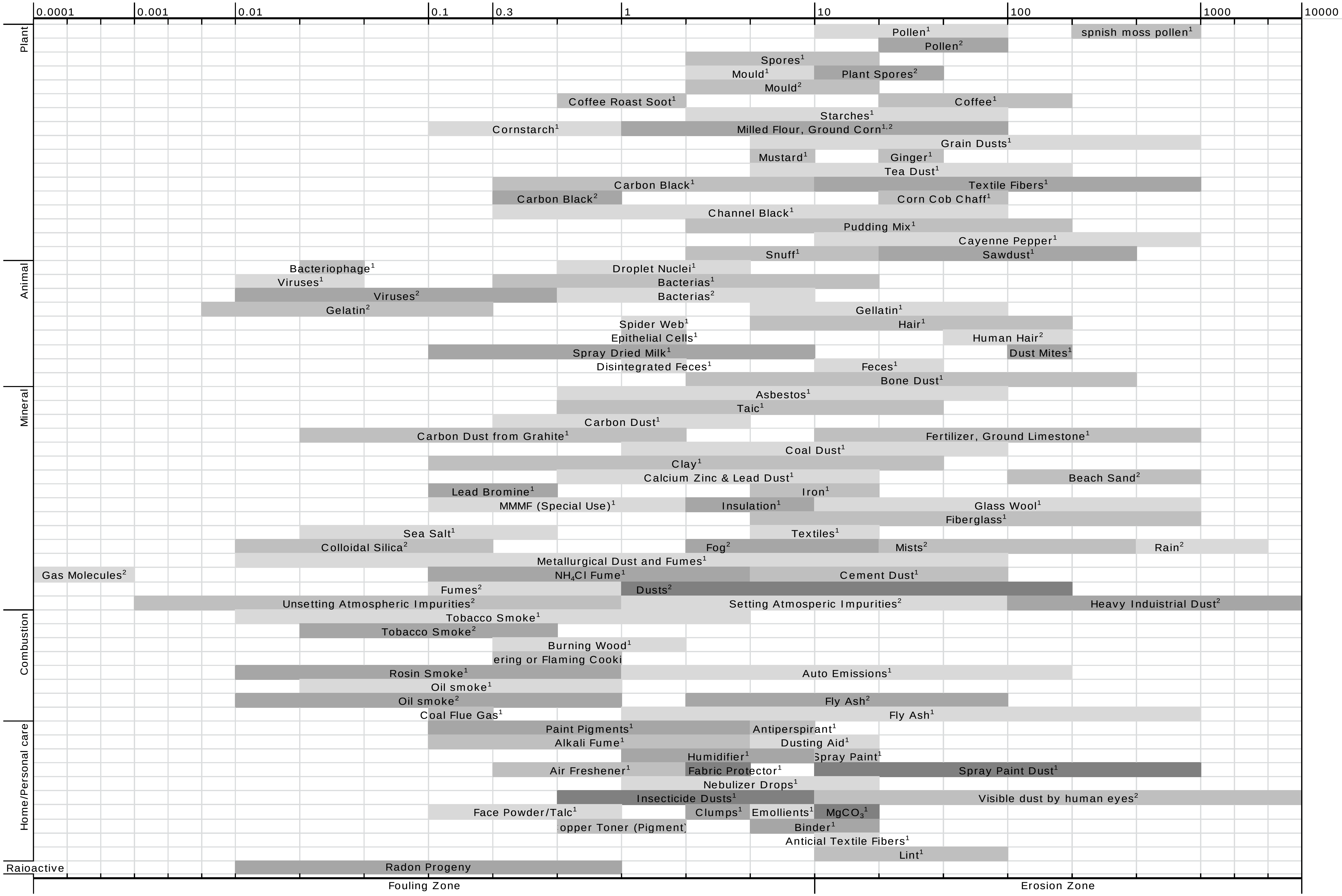

Figure 2-2 Common air contaminants diameter ([1]Owen, Ensor & Sparks 1992, [2]Sparks & Chase 2016)

From the range of particle diameter in **Figure 2-2**, there are six types of air pollutants based on sources of contaminants for examples plant, animal, mineral, combustion, personal care and radioactive (Owen, Ensor & Sparks 1992, Sparks & Chase 2016). It can be seen that mineral air contaminants cover the widest range of diameter size from 0.0001 microns to 10000 microns with gaseous, colloidal until solid states. For plant air pollutant, the range of contaminants diameter is 0.1- 1000 microns that is clearly larger than animal pollutants from 0.006 to 600 microns. In combustion group, the range of pollutants is between 0.01 and 1000 microns, but most of their sizes are smaller than 1 micron. While home air contaminants are mostly greater than 0.1 micron, radioactive compound is ranged 0.01-1 micron in terms of radon progeny only.

Another noted point in this table is the most popular size of general air contaminants found mostly in range between 0.01 and 1000 microns. So facing air pollutants in that range is the highest risk among local people in developing countries. Moreover, in that air contaminants range, there are five types of air matter state especially solid dusts, bio-aerosol nuclei, fume or colloidal state, gas and invisible radioactive compounds. In case of solid dust and bio-aerosol, it is possible that laws of settling related to particle size can be adapted to their movement study when gas molecules can apply Brownian laws to calculate movement (Schifftner 2014). Turning to hydrate colloidal state, the density gradient is applied for codifying this type of air contaminants and its purification can be focused on dilution technique. To concentrate chemical action, invisible radioactive compounds and gas are easily to form chemically themselves to solid state such happening in SO_2 photo-oxidation and sulphate particle (eds Harrison & Perry 1986).

The parameters of particle scale that can be used to identify air particle dimensions are considered in terms of several methods for example simple Martin method and graticules pattern. For Martin method, it is possible to measure approximately normal width and length of particle outlines. While, based on eyepiece graticules scale in **Figure 2-3**, particle sizing and distribution graticules patterns can be separated into Patterson Globes and circles, Porton, British Standard reticle, fairs and Walton & Beckett raticle (for asbestos fibre). Also this scale can be applied for other special purposes such as spray droplet measurement, pharmaceutical purpose etc.

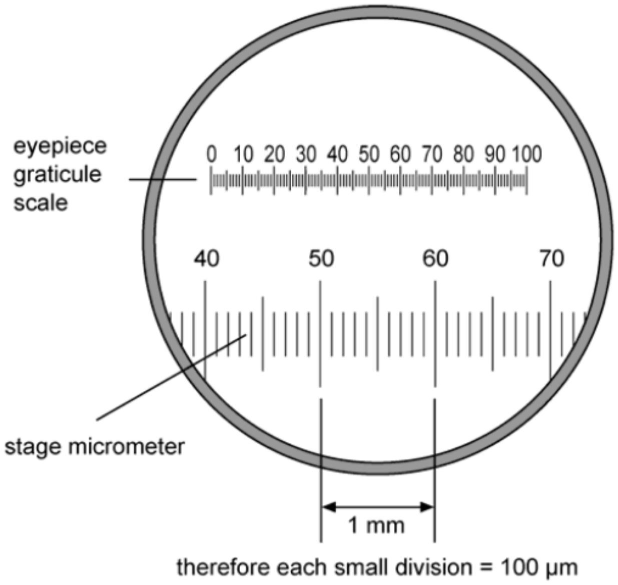

Figure 2-3 Graticule scale (Cambridge University 2008)

According to air pollutant journey, it is originally assumed that the sources, size and concentration were normally used to identify the category of indoor air pollutant because those factors can indicate how far particle flowing deeply through the respiratory system (Owen, Ensor & Sparks 1992). Generally, very tiny air pollutant as gaseous compound and bio-aerosol that can be breathed into alveolar part can be eliminated by hi-technology devices, while larger particulate matter can be filtered easier by low energy devices.

Table 2-1 The summary of initial air pollution separated by various sources and types of pollutants

Study topics			Area		
			Rural	Semi urban	Urban
Sources	Main reason		-Agricultural waste burning -Forest fire (winter)	-Industrial waste (construction factories)	-Traffic -Household cooking -Cigarettes
Sources	Probably reason		-Disaster (volcano explosion) -Power plant accident	-Traffic -Household cooking	-Disaster-in some case (sand storm in Beijing, China) -Traffic (fume from low pressure air in Changmai, Thailand)
Types of pollutants	Particulate Matter	PM2.5	-Respiratory dust produced from burning process	-Fuel burning and factories' emission -Traffic particles	-Cooking burning -Cigarettes burning -Diesel emission
Types of pollutants	Particulate Matter	PM10	-Thoracic particle emission and agricultural dust	-Transported air pollution	-Diesel emission
Types of pollutants	Gas and fume		-The production of agricultural burning	-Fuel production -Construction factories (mortar, cement)	-High productivity of engine burning
Types of pollutants	VOCs		-Possible emission from building materials		
Types of pollutants	Bio aerosols		-Specific control areas especially hospitals or accidentally infective respiratory disease		

Owning to sources and sizing study of air pollutant, this research would clarify the pollutants into 4 groups especially particle matter, bio aerosol, gaseous pollutants and radioactive pollutants as shown in **Table 2-1**. Based on developing countries and tropical climate conditions, the main sources of air pollution can be divided into three groups depended on various activities and the scattering of pollution sources (Wongwatcharapaiboon, Gan & Riffat 2013). For example, burning activities from agricultural waste elimination and forest fire can produce fume particles sized 2.5-10 micron, while the productions of crowded traffic burning in metropolitan are diesel particles (Gunawardena et al. 2012, Imran et al. 2013, Kelly & Fussell 2012, Li & Crawford-brown 2011, Pant & Harrison 2013, Wiriya, Prapamontol & Chantara 2013). Those all of outdoor burning production can be indoor air source in local buildings, while kitchen activities and anti-mosquito products can be direct source of black carbon in indoor area (Stabile, Fuoco & Buonanno 2012). In details, the characteristics of air pollutant will be demonstrated in the next step as (2.1.1) particulate matter, (2.1.2) bio-aerosol, (2.1.3) gas and (2.1.4) volatile organic compounds.

2.1.1 Particle matter (PM)

As early understanding, particulate size has been one of factor to identify types of pollutants, so this part would indicate the particulate matter by particulate diameter and sizes. Owen, Ensor & Sparks (1992) conceded that internal pollutants could be divided into 3 groups via pharyngeal system accessibility. It was found that the particle being larger than 30 μm (heavy industrial dust and fly ash), sized 5-10 μm (fine dust and spray paint dust) and ranged 1-5 μm (respiratory dust and smoke) accessed possibly the nasal passage, the pharyngeal region and the tracheal bronchiolar region respectively. In case of air PM proportion study, it was found that the concentration of particle sized smaller than 2.6 μm, 10.5 μm and 30 μm were proved around 10%, 30% and 70% respectively in the Xi'an air (Cao, Yang & Zhang 2011). However, the methodology of dust collection has some effects on concentration collection and proportion calculation as the different state of pollution and chemical action after collection.

In this study, it is correlatively to cluster particulate matter diameter into sized 10 micron (PM10) and 2.5 micron (PM2.5). For the first category of particulate matter, PM10 called possibly fine dust or thoracic dust is customarily high concentration in outdoor air especially industrial areas. Actually, only increase PM10 level is not excessively dangerous to asthmatic school children, but the level of SO_2 can increase dramatically short-term effects on pulmonary function. These can be proved by daily pulmonary system monitoring in terms of the highest forced vital capacity (FVC), forced expiratory volume at 1 second (FEV1), peak expiratory flow rate (PEFR) and forced expiratory flow 25 to 75% (FEF(25-75%)) (Aekplakorn et al. 2003, Aekplakorn et al. 2004). To focus on indoor PM10 level in Thai hospital academic campus, indoor PM10 level in medical zone is possibly controlled to lower than ambient, while indoor dust in convenient shop is monitored higher than outdoor condition (Tsai et al. 2000).

Turning to microscopic study in the early state of PM2.5, the electrical dynamics formed colloidal particle and particulates that relied on the cell thickness, electric signal amplitude, flow character of anisotropic aggregate and the concentration of particles (Pishnyak, Shiyanovskii & Lavrentovich 2011). Not only these factors can indicate the level of self-forming air respiratory dust, also burning activities can stimulate carbon black and fume productions. So local people in traffic crowded area and wild fire zone is possibly facing respiratory problems higher than industrial area. The influent of air PM2.5 effects are more dangerous than PM10 because of their characters as tinier size and straightforwardly travelling to bronchial respiratory part.

To standardize air dust levels, depended on WHO parameters, PM10 concentration should do not exceed annual mean and 24-hr mean at 10 $\mu g/m^3$ and 25 $\mu g/m^3$ respectively, while PM2.5 levels should be not more than annual mean at 20 $\mu g/m^3$ and 24-hr mean at 50 $\mu g/m^3$ (Sparks & Chase 2016). Additionally, several specific local particulate standards have referred to international standards by pointing out the concentration level of PM1, PM2.5 and PM10 (Wang et al. 2009, Cuccia et al. 2010). As the above review of particle, this study focuses mainly on monitoring the concentration of PM2.5 and PM10, whereas other pollutants are going to be still assessed in order to meet the international standard.

2.1.2 Bioaerosol

Bio aerosol is somehow dangerous for human health than tinier air pollutants as disrupting directly organ working particular in measle and mumps and zoonotic infection diseases (Harrison, Sakaguchi & Schmitt 2010). In respiratory systems, the severe levels of disease from indoor air pollutant are separated by types of bio micrometer and a significant infective ability. Owing to the tiniest scale of cell and quantitative polymerase chain, it is possible that virus is the most effective destroyers in terms of swine or influenza (Verreault et al. 2010). Even now scientists can cultivate more vaccine, but it is yet adequately known how fast genetic viruses develop.

Turning to bacteria and mold in indoor air, legionellae was outstandingly found to grow up probably in cooling tower water and to show 8-50% of bathroom air pollutants. It was also proved that this kind of bacteria affected occupant health in terms of Pontiac fever until the most severe effect in mortality (Chang & Pei-yuhung 2012). Another indoor bio-contaminant is mold that grows up rapidly in humid absorbable cellulose and breeds by air flowing spores. According to Norbäck & Cai study in 2011, sampling dusts on door frame in different 69 hotels within 20 European and Asian countries were collected and found A. versicolor, S. chartarum and Streptomyces being the main fungal species. Also in 17-house indoor air monitoring, 36 mold species were additionally found especially Aspergillus Penicillioides, Cladosporium Cladosporioides types 1-2, Cladosporium herbarum etc (Meklin et al. 2007). Besides, the precariousness of this contaminant is toxic productions from those molds found in terms of Micro Volatile Organic Compounds (MVOCs), Aflatoxin, Fumigatoxin, Sterigmatocystin, Versicolorin, Citrinin, Penicillic Acid, PR-toxin, Citrinin, Gliotoxin, T-2 toxin, Trichodermin, Viridiol, Satratoxin H, Sporidesmin G, Macrocytic Trichothecene etc. These toxins can lead to various symptoms of buildings occupants such as Sick Building Syndromes (SBS) and hypersensitivity pneumonitis.

As bio aerosols are ideal controlled by chemistry and ventilation pattern, the integration of self-antivirus materials on building surface may become optional solutions in particular TiO_2 coated techniques (Rong et al. 2011). According to bio minute particle study, not only bio reaction can affect directly infective respiratory symptom, but size of particle also bring about more severity by deeper breath into respiratory system. Therefore, smaller compound, gaseous pollutants will be examined in the next section.

2.1.3 Gas

The main gaseous elements of atmospheric environment are identified to include Ozone (O_3), Non-methane Hydrocarbons, Nitrogen Oxides (NO_x), Halogen, Hydroxides (HO_x) and biomass burning (Monks et al. 2009). The above atmospheric element study shows several elements are toxic for human respiratory. Not only affecting to human health, but gaseous elements also responded evidently to buildings and art work. For example, the atmospheric environment of Museu Oscar Niemeyer (MON) in Brazil was found NO_2, SO_2, O_3, Acetic Acid, Formic Acids and BTEX which were the main chemicals to damage irreversibly art work (Godoi et al. 2013). To generate these gaseous pollutions, it can be doubted that household activities are the main source of gas emission in general, while crowed traffics in city centre are evaluated to be another noted sources in developing countries. Therefore, in Bagalore, the relationship between air environment and street tree cover was investigated in terms of average temperature, humidity and pollutants. Consequently, sulphur dioxide (SO_2) and the temperatures of both ambient air and road surface were lower, while Suspended Particle Matter (SPM) levels showed double decrease (Vailshery, Jaganmohan & Nagendra 2013). Another optional solution in 2008 Olympic Game was shown in Beijing that the traffic policy of chemical pollutants emission control was effective launched to limit the concentration of NO_2, O_3, formaldehydes (HCHO). This strict emission control measurement (ECMs) was assumed to be the most effective policy in the short-term period (Witte et al. 2011).

Turning to pollutants from indoor material, there are 3 steps of chemical reaction especially inside material, on solid surface and in the gas phase. VOCs emissions are formed by inter-material reactions called primary emission and shown as a product of reaction in the air called secondary emission. For example, primary emission compounds with terpenes, styrene and 4 phenylclohexene can react with O_3, NO_x, OH and other reactive gas (Uhde & Salthammer 2007). Even though there was no significant effect on relationship between each type of pollutants, but ambient humidity was proved to affect both O_3 and PM2.5 (Liu et al. 2010). Of the study of smaller pollutant element, Volatile Organic Compounds (VOCs) are the next topic of this pollutant investigation.

2.1.4 Volatile compounds

According to VOCs sampling and analysing, 26 species of VOCs were recognised to be carcinogenic to humans. Also it is possible that VOCs evaporating brings about the risk of chronic suffering in humans (Juang et al. 2010). As the study of ultra-fine particles process, it was possible those aerosols could be formed from semi-VOCs by evaporating and 150-200 $^{\circ}C$ thermo denuders. However, supersaturated vapor in the air and oxygen contribution were not related to particle emission because that emission reacts within a nitrogen atmosphere (Schripp, Kirsch & Salthammer 2011).

In response to type of pollutants, all types of indoor pollutants result from indoor and outdoor activities (Foster & Kumar 2011) especially household and traffic combustion, finishing materials, building erosion and infective bio micrometer exposure. Not only those sources affect their concentrations, but ambient factors and buildings envelope can also support or limit these exposures. These findings have well represented a significant step forward in indoor air quality that health effects of pollutant are the most important to specify the harmful levels of air pollutants. Based on categorized studies and equipped limitations, this study would carry on PM10 and PM2.5 laboratories and air eliminating techniques would be matched to those selective indoor pollutants later.

2.2 The effects of air pollutants on human health

During the developing period of economy in South East Asia, the risk of pollutant suffering from air hazardous has been increasing. Consequently, the effects of air impurities can be verified in human health effects and possibly more severely in specific age group and patients.

2.2.1 Human health

As air pollutants move into human body, their various types and sizes could be adhered in different levels from body skin, respiratory systems, indirect infectable organ or even sensitive sensation. To consider physical movements of air pollutants, size can be the main indicator that examines their harmfulness to human health. Nevertheless, cell chemistry and bio invading reaction could be effective factors for cumulating destructiveness of air contaminants.

More than physical allergy effects of air dust, respiratory system has been mainly disturbed by indoor air pollutants in terms of chronic respiratory symptoms and allergic rhinitis and asthma (Owen 1992). In Thailand, it was exemplified that the increase of indoor PM10 resulted in rising respiratory symptoms in adults (Vichit-vadakan et al. 2001). Also indoor SO_2 level could support positively PM10 effects on respiratory systems such as declining pulmonary function (Aekplakorn et al. 2003). Therefore, the possibility which in multiplex types of indoor air pollutants bring about more harmfulness to buildings' occupants is higher than those in single air pollutant. Then this consequent supporting will be clarified in the effects from other contaminants.

Turning to PM2.5 study, it was found that several chemical elements could disturb lung function within 3 days especially chloride, zinc, copper, vanadium, lead and stannum, while calcium and magnesium could take 2 weeks showing lung effects (Wu et al. 2013). So the timing period of facing air pollutant is another indicator showing destructiveness on pulmonary systems. Not only the time that chemicals take action on organ, but suffering time can also annoy offices' workers as asthma and atopic allergy.

Other upsetting for occupants' perceptions is Sick Building Syndrome (SBS) including both short- and long-term effects on human health. For example, carbonic compound affects brain and visual system in terms of headaches, impairment of visual acuity and brain functioning. More specially, based on the Karolinska Scales of Personality (KSP) tests in low air quality work places, it was confirmed that sick building symptoms associated with various occupants' emotional conflict personalities. For instance, asthma affected an increase in the score of impulsiveness, whereas non-asthmatic atopic related to grow up a social desirability score and decrease in the scores of irritability, guilt and impulsiveness (Runeson, Wahlstedt & Norbäck 2011).

Regarding more hazardous, long-term effects from indoor radon and asbestos are examined as cancer. Similarly, there is another finding that Polycyclic Aromatic Hydrocarbons (PAHs) sources can lead to 30-50% higher breast cancer frequency. The PAHs sources in this study were identified from single or multiple tobacco burnings and smoking environment (White et al. 2016). Hence, sources and environment are related directly indoor air pollutants concentration and harmfulness.

As occasional effects, it is difficult to prove that mortality can be resulted from indoor air contaminants. However, by statistic associated analysis study, several studies found relationship between air pollutant and non-accident mortality (Wong et al. 2010). To specify in China, the concentration of SO_2 was analyzed to correspond to cardiopulmonary mortality, while PM10 level was indicated to increase SO_2 effects (Kan et al. 2010). The implications of mortality studies have been similarly as significant resulting from air particles exceeding indoor air quality standard.

2.2.2 Aging factors

After clarifying effects of physical adult bodies, it is doubted how those effects of indoor air harmfulness occur to children and elderly groups; who have different immune levels and reaction of perceptions.

In group of senior people, the effects of air pollutants were evidenced to escalate their perniciousness. For instance, it was found that an increase in PM10 concentration associated significantly respiratory disease and intensified their effects in elder people (Vajanapoom et al. 2002). As in similar older group, the outstanding relationship between Chronic Obstructive Pulmonary Disease (COPD) and Environment Tobacco Smoke (ETS) was found resulting from indoor air pollutants. Besides, air pollutants were found to affect elder in terms of gasping, wheezing, phlegm, cough, asthma, pulmonary function failure and pulmonary cancer (Bentayeb et al. 2013). A cardiovascular risk study shows that PM10 could lead to 95% rise of mortality in people aged more than 65 (Vichit-vadakan, Vajanapoom & Ostro 2008).

Regarding the effects of indoor air pollutants on children, the majority focused on their respiratory systems within their classroom environments. As a case in this point, Simoni et al. (2011) monitored total viable molds (VM, colony-forming units, cfu/m^3) and total fungal DNA (cell equivalents, CE/g dust) in 21 European schools. The results illustrated that mold was inversely corresponded to flow rate and its exceeding standard at 300 cfu/m^3 brought about higher risk in cough and rhinitis in children. Also an increase of fungal DNA could raise wheeze, rhinitis and cough; however, it could negatively affect spirometry as reducing forced vitality capacity (FVC) and Force Expiratory Volume 1% (FEV1). In 2490 kindergarten Chinese children, SO_2 and NO_2 concentrations were found to relate significantly together and to affect positively the asthmatic risk (Deng et al. 2015). In the same year, Filippini et al. found the evidence that babyhood leukemia resulted directly from transported pollution especially benzene or volatile organic compounds (VOCs) as same as Gao et al. study in 2014.

2.2.3 Special group of receptors

After aging concerning, conditioned group is another interesting issue as different effects of indoor air pollutants. As a sample case in Taiwan, the hospital wards and respiratory care centers (RCCs) in somehow hot and humid climate were monitored indoor air quality based on Environmental Protection Agency (EPA). The results demonstrated that VOCs level occasionally surpassed standard, and various bacterial and fungal genera increased as same as indoor respiratory dust during the period of turning on suctioning system (Chung et al. 2015). As a result, it is possible that the exceeding of air pollutants would bring about consequent effects to patients. To exemplify, pregnant female can generate incapacitate baby based on environmental chemicals included pesticide fume and cigarette smoke; while hospital patients possibly react straightaway to habited stimulations in terms of more harmfulness of symptom or occasional death.

In atopic dermatitis (AD) patients, the number of water-damaged home, which led to increase mold and fungal species, responded significantly to severity in AD children (Seo et al. 2014). In the same group of AD patients, it was evident that environmental tobacco smoke (ETS), volatile organic compounds (VOCs), nitrogen dioxide (NO_2) and particulate matter (PM) could exacerbate their symptoms by instigating oxidized skin process and then reducing natural protecting process (Ahn 2014).

In case of cystic fibrosis (CF) patients, indoor fungal impurity could result in allergic bronchopulmonary aspergillosis (ABPA) symptoms (Rocchi et al. 2015). To focus on natural body protection, immune system is well known to protect and eliminate air contaminants from inhalable air. From Miller & Peden reviews on asthma patients in 2014, it was possible that asthma would be treated directly, if immune responding, gene-environment relations, air pollutants type, allergies and other airborne disease were firstly considered.

The effects of smoking parents on their fetus and children have been exposed for many years as delaying fetus' organ development and asthmatic children. Moreover, Wylie et al. in 2016 found that an increase of PM2.5 from kitchen activities could cause low birth weight in pregnancy group studies. The prenatal environment was also studied to affect birth defects as congenital heart disease (CHD), if, in the first trimester period of pregnancy, environmental xenobiotic chemicals were found such as organochlorine pesticiedes, organic solvents, etc (Gorini et al. 2014).

Having discussed the diversity of health effects from different air pollutants, the next topic will clarify environmental factors responding to impurity levels and regulative environmental calculations.

2.3 The effect of meteorological factors on selective air pollutants

During the era of global warming, the consequent results have been researched in terms of sea level, meteorological detections and air pollutants effects. Also several predictive respiratory diseases have been discussed based on climate change conditions. To exemplify, air allergen and irritant would possibly increase, if CO_2 level and temperature still rise up resulted in floristic zones exposure. In addition, the exposure of crowded areas in industrials and accommodations probably lead to increase infectious respiratory patients (Barne et al. 2013).

Turning to human comfort concerning, indoor environmental data has affected human perception, occupants health and their productivities (Langkulsen, Vichit-Vadakan, & Taptagaporn 2010). Also this environmental data can affect fluctuated indoor air pollutants, so it is now necessary to explain the environmental factors based on hot and humid climate conditions. This would also reaffirm some mathematic equations used in experimental parts. As it was pointed in previous discussion that the levels of transportable air indoor impurity could be depended on building envelope, traffic condition and building distance from traffic road, wind orientation, openings design, interior layout, fresh air intake location (Tong et al. 2016). As a result, in this stage, meteorological factors would be literally inspected how these affect Indoor Air Quality (IAQ) and relative occupants' health in particular temperature, precipitation, relative humidity, flow rate and other contaminants.

2.3.1 Temperature

As the global warming conditions, even air pollutant policies could be effective method to decrease pollutant emissions in short term (Strefler et al. 2014), but the intensive effects of climate change stood still affecting holistic environment, climate-altering pollutants (CAPs) and human health. This was assured by the findings of global warming effects in 2010 that 7% of global burden disease was from inhalable air pollutants (Smith et al. 2014). Moreover, thermal heating in dynamic air flow could be used to control bacteria concentration in short exposure time. These would be an effective strategy for air purifier and sterilizer design (Jung, Lee & Kim 2009). There was also positive relationship between temperature and air pollutants particular in respiratory pollutants, fungi, pollen, and ozone (Adhikari et al. 2006). Not only air temperature that can be an effective mechanism to control aerosol concentration, but relative humidity is another factor to respond indoor air pollutant. Consequently, PM10, Rh, wind, temperature and pressure can affect undoubtedly visibility in Nanjing by extinction coefficient indicator (Deng et al. 2011). To support this relationship, a Chinese kitchen air evaluation shows the relationship between temperature and CO_2 concentration that both values varied in the same trend. However, those trends of temperature and CO_2 concentration reversed variation to relative humidity (Li et al. 2012).

In case of Tumen river, Northeast China, it was found that air polycyclic aromatic hydrocarbons (PAHs) concentration strongly associated to air particles level, temperature and CO_2 intensity (Jin et al. 2012). Hence in case of warming temperature, due to the effective radiation force (ERF) assessment in IPCC, fuel emission possibly contributes higher black carbon (BC), but lower sulphate impurities and tributary organic aerosol (Boucher et al. 2013). Another effect of temperature increase is higher ozone (O_3) as reducing peroxyacetylnitrate (PAN) lifetime and rising isoprene emission (HTAP 2010). This can affect indirectly to air humidity and other air pollutant exposures.

Based on indirect effects on system pressure, it was possible that higher temperature could drop efficiency of electronic devices or natural ventilation systems. That also affected pollutant flow direction, cumulative pollutants and air purified performance (Harrison & Perry 1986). Additionally, in general, an increase in temperature could drop air relative humidity in psychometric chart that then affected gaseous or air chemicals formations as same as bioaerosol explosion. Notwithstanding, this role could not applied in Southeast Asia in IPCC that showed positive relationship between temperature and vapour (Hijioka et al. 2014). The changing in atmospheric temperature resulted in the frequency of intensive storm happening in this tropical climate.

2.3.2 Precipitation

Throughout world warming period, the average of precipitation was predicted to increase and affect aerosol atmospheric absorptions and more extremeness in wet and dry climates. It was evidently proved that aerosol-cloud interaction respond positively to storm (Boucher et al. 2013). In Southeast Asia, it was found that precipitation will drop its frequency, but increase its intensity. That could imply to higher possibility to disaster occurring derivative from rainfall (Christensen et al. 2013). Another concerning of precipitation was shown in snowfall, which was collected and investigated higher contaminations from atmosphere. The snow ice collection could be explained and then projected higher level of air contamination in the future.

Even the precipitation was not demonstrated any direct effect on indoor air quality, but an indirect effect was strongly shown as supporting or degrading outdoor air contaminant level. In hot and humid climate, moderate rain could wash out gigantic air contaminants and ground accumulative dust. However, precipitation in terms of rain fall was projected to raise air humidity 5-10% per warming degree Celsius (Boucher et al. 2013). That was studied to possibly support gaseous productivities and organic compounds levels. Thus the relative humidity and vapour will be investigated in the next topic in case of air pollutant effects.

2.3.3 Relative humidity

Indoor air humidity normally fluctuates due to the source especially openings leakages, outdoor humidity and occupants' activities. Living activities was investigated to release temperature and vapour to indoor environment as seeing in **Table 2-2** (Clancy 2011). Indoor air humidity possibly acts as indoor air pollutants by supporting bio aerosol growth and VOCs emission.

Table 2-2 Typical moisture emission rates from users' activities (Clancy 2011)

Process	Type	Emission rate
Adult occupation	Sleeping Active	0.04 kg▪h^{-1} 0.05 kg▪h^{-1}
Cooking	Electricity Natural gas	0.2 kg/day 3.0 kg/day
Washing clothes		0.5 kg/day
Bathing/washing		0.2 kg/person/day
Dishwashing		0.4 kg/day
Unvented tumble drier		1.5 kg/person/day
Flue-less combustion	Natural gas Kerosene Liquid petroleum gas	0.16 kg▪h^{-1}▪kW^{-1} 0.10 kg▪h^{-1}▪kW^{-1} 0.13 kg▪h^{-1}▪kW^{-1}

In terms of pulmonary disease, Qiu et al. and Tseng et al. found in 2013 that lower relative humidity in season change brought about an increase emergency chronic obstructive pulmonary disease (COPD), but the results showed reverse effect in hot and dry climate. In addition, based on reviews, relative humidity affected to support mold growth, reproduction of mites, pollen dispersion, pollen allergen, hypertensive uropathy in cardiac patients and respiratory virus (Davis, McGregor & Enfield 2016). In the same review, an increase of moisture was investigated to relate to Indoor Air Quality (IAQ) as rising up above inhalable contaminants, promoting deposition of PM10, organic aerosol (OA) formation and formaldehyde emission (Liang, Lv & Yang 2016). Even the coordination of OA and PM2.5 could escalate higher harmfulness affecting to respiratory systems, but higher seasoning relative humidity could drop half PM2.5 concentration derivative via road traffics (Oanha et al. 2013) and promoted photocatalytic technique in volatile organic compounds (VOCs) degradations (Huang et al. 2016). As same as another relationship between air humidity and VOCs emission in porous materials, it was found that relative humidity at 80% affected to higher formaldehyde concentration. Also toluene varied in the same trend with moisture condition (Xu & Zhang 2011). However, in Rio de Janeiro, relative humidity responded insignificantly to PM and VOCs in natural ventilation buildings, but affect effectively mites, moulds concentrations (Rios et al. 2009).

From **Figure 2-4**, the diagram demonstrates photocatalytic oxidative process in case of TiO_2. It can be seen that there were two subordinate reactions as hydroxyl radicals and superoxide anions after UV light stimulating TiO_2 molecule. Then hydroxide and dioxide anions could be decomposed by oxidative process with organic aerosols and the ultimate products are carbon dioxide (CO_2) and water (H_2O). This chemical reactions were affirmed that pollutant removal process by TiO_2 photocatalytic reactions and purified products of process (Pichat 2010).

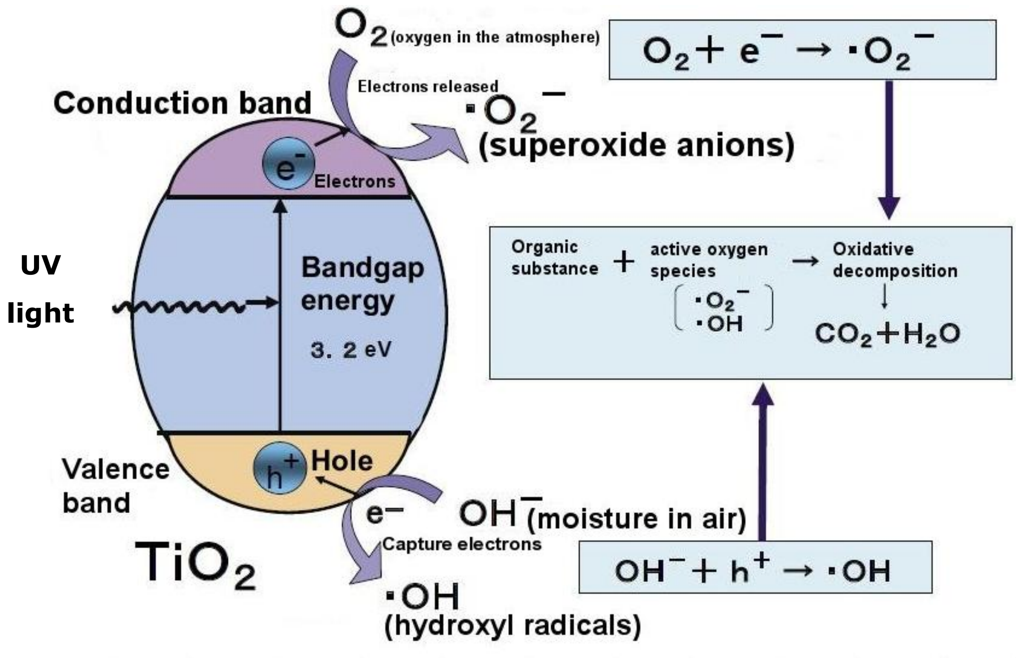

Figure 2-4 Photocatalytic oxidative process in TiO_2 (Murakami & Fujishima 2010)

Turning to electrical resistance, it was also evident that moisture related negatively to fly ash resistivity (Schifftner 2014) as seen in **Figure 2-5**. That included electrical resistance in precipitation techniques to eliminate air pollutants by electronic conducted plate.

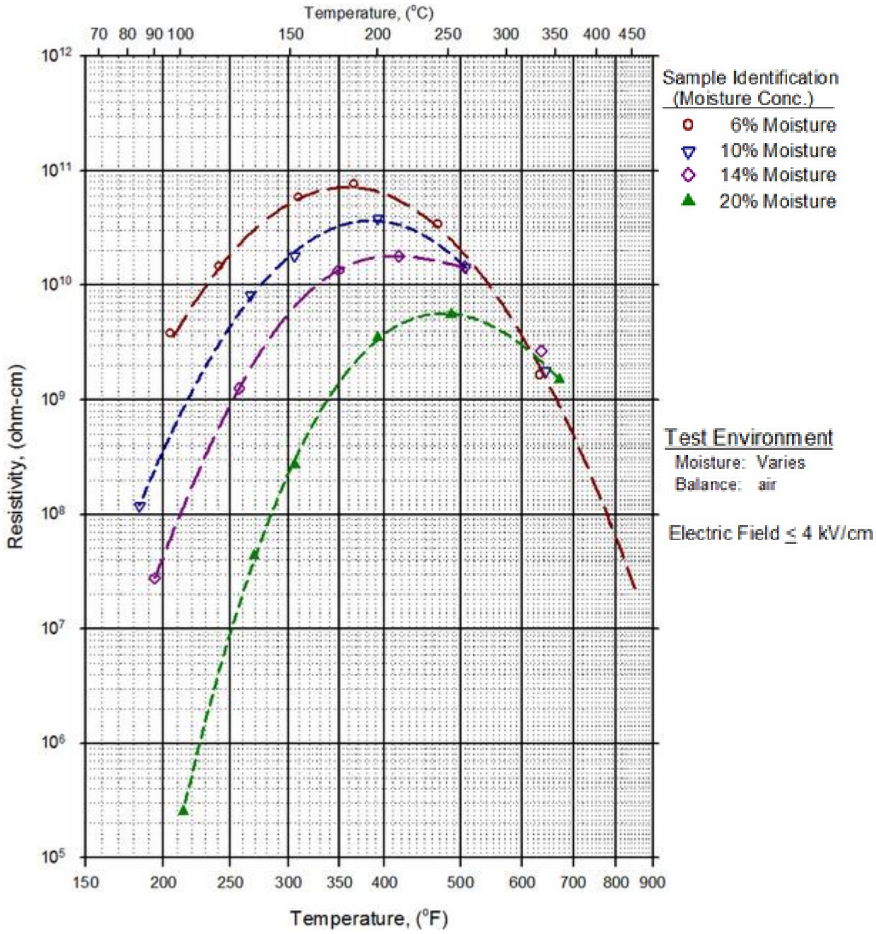

Figure 2-5 Resistivity measured as a function of temperature in varying humidity (Rhoades 2005)

To conclude, relative humidity has affected positively bioaerosol growths and organic compound formations, while it has responded negatively to roadside dust concentration by seasoning terms. In case of air purified application, relative humidity could acted as initial compound in hydroxyl reaction of photocatalytic process, so it is possible to increase air purification efficiency of TiO_2 coatings. On the contrary, in electronic plate techniques, relative humidity could rise resistance and drop system pressure to poor quality of air purification process. Relative humidity is not only factor related to indoor air quality and air purified application efficiency. Hence, the next topic will examine the effect of flow rate on indoor air pollutants.

2.3.4 Flow rate (wind speed)

Air flow rate is another important factor of indoor air pollutant as air being the media of contaminants and flow pattern relating to their accumulations. The results of indoor flow speed, gaseous concentration, temperature and relative humidity was proved evidently to disturb sick building syndromes (Norhidayah et al. 2013). In case of indoor air controlling system, the pattern of air ventilation has responded directly to occupants' inhalations. This was supported by the study of CFD simulation that showed different air flow pattern and air temperature affecting contaminant level in buildings (Jurelionis et al. 2016). Another example was showed in offices' printer room that could increase indoor aerosol concentration. According to the relationship between indoor air quality and particle emitter from office printer, simultaneous result demonstrated over 11 times of ultrafine particle concentration in the 6-hour period (Koivisto et al. 2010).

Moreover, based on air quality concerning, five components and lead (Pb) have been also monitored by the US Environment Protection Agency (EPA) under the National Ambient Air Quality Standards (NAAQs). By controlling sources location, it is important to clarify each pollutant's sources. Firstly, O_3 and SO_x result from industrial sources including coal and crude oil combustion. Other components, PM2.5, PM10, CO, NO_x and Pb, are the products of fuel combustion in vehicles and power plants engines. Also Pb emissions are mainly from the ore or metal processing from vehicle engine. In addition, NO_2 and volatile organic compounds (VOCs) emit from motor vehicle process and interior furniture finishing with sunlight stimulation (Laden & Winkelmayer 2011). Therefore, indoor ventilation was concerned in terms of calculating variables such as flow speed, flow pattern, ventilating pressure and air contaminants.

More than limiting air pollutants' concentration, indoor ventilation has obligatorily required fresh air, filtrations and regular maintenance for air mechanical systems (Clancy 2011) as in Building Regulation Part F1 and J1 (England and Wales), BS EN, WHO and ESE. The regulation of indoor air ventilation has been exemplified in **Table 2-3** as only in England and Wales.

Table 2-3 The requirements of indoor air flowrate in England and Wales (Clancy 2011)

Type of Building	Room	Min intermittent extract rate (l/s)	Continuous extract (l/s)	
			Min. high rate	Min. low rate
Dwelling unit	Kitchen	30 (adjacent to cooker) 60 (elsewhere)	13	Greater than whole building
	Utility room	30	8	Ventilation rate based on bedroom numbers
	Bathroom	15	8	
	Sanitary	6		
Non-domestic building	Printer/Photocopy machine room	20 per machine during use.		
	Office sanitary and washrooms	15 per shower/bath 6 per WC/urinal		
	Food prepare areas	15 microwave and beverage only 30 adjacent to cooker 60 elsewhere		
	Specialist space (kitchen, sport centres)	See Building Regulations Approved Document F.		

Based on indoor ventilation, different pressure is the main factor of flow driving force. This indoor ventilation can be calculated in various conditions for examples, horizontal or vertical air flows, air controlled or natural ventilations, laminar or turbulent flow patterns. To focus natural ventilation, it is possible that indoor ventilation is depended on flow rate in low outside temperature condition; while warmer outside temperature brings about constant state of ventilation. Also stack ventilation in case of multiple-story building could be forced by pressure from different inside and outside air temperature, openings' heights and sizes (Clancy 2011). In addition, the natural ventilation and human activities could be the main factor of particle level inside the building (Branisˇ, Afra'nek & Hytychova' 2009). Moreover, in Lanzhou, China, wind speed in spring time had an effect on PM concentration in different sizes (Wang et al. 2009). It is also evident that tempersture and water can control fungal spores emission and strong wind speed could disturb airborne movement and inertibility near material surface particular in off shore winds. Under the condition of strong winds and long distance of material transportation, it can be seen that bacteria concentration decrease less rapidily than spores of fungus (Jones & Harrison 2004).

For air pollutant removal, based on specific assumptions, it is possible to calculate transient or steady-state air contaminant levels. If mathematic variables could be limited in terms of (1) single source, (2) pollutant and (3) air completely mixed,

(4) constant pressure (constant flowrate and constant outdoor pollutant concentration), indoor air pollutant concentration in single room could be calculated by **Equation 2-1**. In case of no source of air contaminants, concentration would drop as the flow rate calculation in **Equation 2-2**. Moreover, **Equation 2-3** would be used when the initial pollutant concentration is zero. Then idealistic results of CO_2 concentration would be exemplified in **Figure 2-6** with (1) initial CO_2 being 0, (2) CO_2 >0 and (3) no pollutant source. As the time concerning, when t is greater than 4 times constants and the transient term is small, so **Equation 2-4** would be used. Then Equation 2.5 would show simple flow rate in **Equation 2-5** or **Equation 2-6** (if *C* being extremely less than 1).

$$C(t) = \frac{(QC_e+q)}{(Q+q)}\left[1 - e^{-\left[\frac{Q+q}{V}\right]t}\right] + C_o e^{-\left[\frac{Q+q}{V}\right]t} \qquad \textbf{(2-1)}$$

$$C_{(t)} = C_o e^{-\left[\frac{Q}{V}\right]t} \qquad \textbf{(2-2)}$$

$$C_{(t)} = \frac{(QC_e+q)}{(Q+q)}\left[1 - e^{-\left[\frac{Q+q}{V}\right]t}\right] \qquad \textbf{(2-3)}$$

$$C_{(t)} = \frac{(QC_e+q)}{(Q+q)} \qquad \textbf{(2-4)}$$

$$Q = q(1-C)/(C-C_e) \qquad \textbf{(2-5)}$$

$$Q = q/(C-C_e) \qquad \textbf{(2-6)}$$

where Q = the flowrate (M^3/s)

C_e = the pollutant concentration in outside air

q = the pollutant release rate (m^3/s)

V = the room volume (m^3)

t = the time (seconds or hours)

C_o = the initial concentration of pollutant

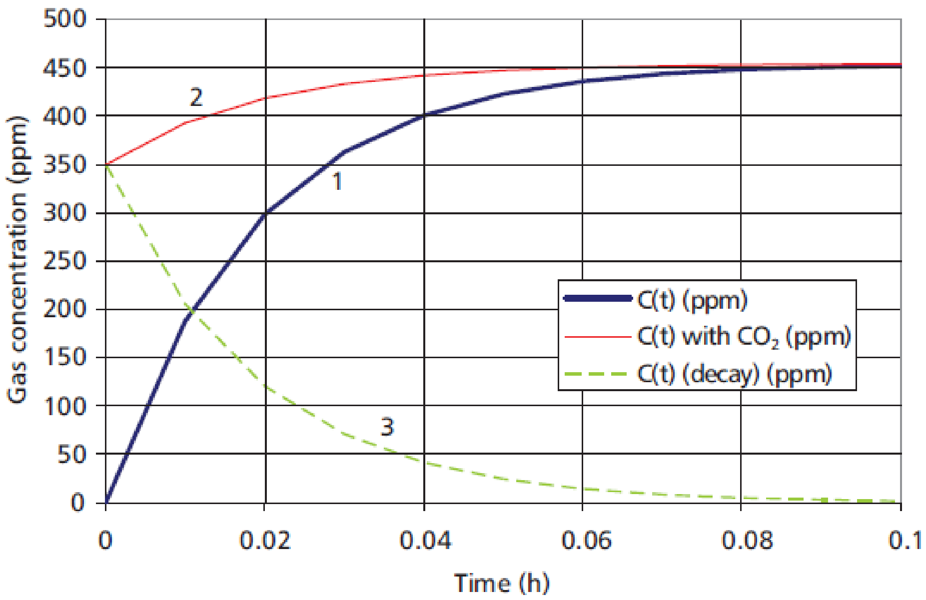

Figure 2-6 CO_2 concentration movement based on three types of sources

Table 2-4 Settling law of air pollutant based on diameter sizes (Schifftner 2014)

Type of air pollutants: Study group	Type of air pollutants: Diameter size (micron)	Rate of settling in F.P.M. for spheres specific gravity at 70 °F	Dust particles constained in 1 ft.^{3}of air: Number	Dust particles constained in 1 ft.^{3}of air: Surface area in sq.in.	Law of settling in relation to particle size (Line of Demarcation approx.)		
	6000	1750			Particles fall with increasing velocity		
	1000	790	0.075	0.000365	Particle sttle with constant velocity	$c = \sqrt{\frac{2gds_1}{3Ks_2}}$	c = Velocity, cm/sec
	600	555	0.6	0.00073		$C = 24.9\sqrt{Ds_1}$	C = Velocity, ft/min
	200						d = Diam. of particle in cm
	100	59.2	75	0.00365		*Stoke law*	D = Diam. of particle in microns
	60	14.8	600	0.0073		$c = \frac{2r^2}{g} g \frac{s_1 - s_2}{\eta}$	r = Radius of particle in cm
PM10	10	0.592	75000	0.0365		for air at 70 °F	$g = 981\ cm/sec^2$ acceleration
	5	0.148	600000	0.073		$c = 300{,}460 s_1 d^2$	s_1 = Density of particle
PM2.5	1	0.007	750000	0.365		$C = .00592 s_1 D^2$	s_2 = Density of air (very small relative to s_1)
	0.5	0.002	6E+08	0.73		*Cunningham's factor* $c = C'\left(1 + K\frac{\lambda}{r}\right)$	η = Viscosity of air in paises 1814×10^{-7} for air at 70 °F
VOCs / Bio-aerosol	0.1	0.00007	7.5E+10	3.65		C' = C of Stokes law, K = .8 to .86	$\lambda = 10^{-5} cm$ (mean fres path of gas molecules)
		0	6E+11	7.3	Particles move like gas molecules		
	0.01	0	7.5E+13	36.5		*Brownian movement*	A = Distance of motion in time, t
Gas		0	6E+14	73		$A = \sqrt{\frac{RT}{N} \cdot \frac{\tau}{3\pi\eta r}}$	R = Gas constant (8.316×10^7); T = Absolute temperature
	0.001	0	7.5E+15	365			N = Number of Gas molecules in 1 mol (6.06×10^{23})

Turning to more specific mathematic model in **Table 2-4**, calculated equations were divided into 4 types depended on diameter size of particle sizes and gaseous status. Hence the equations of particle settle would concern pollutants' diameters, pollutants' density, air density, rate of settling, when gaseous equation would focus distance of motion in time, temperature, gas constant and molecules.

In this study, it is possible to adapt above equations to calculate air pollutant concentration in laboratory and real-time monitoring in single unit.

2.3.5 Other contaminants

In this study, the research area is scoped in indoor air quality in hot and humid climate especially in South East Asia. Also tropical climate is included somewhat high temperature and humidity. Only the shore condition and some area in China is investigated the effect of natural wind from outside environment. These climate conditions affect directly outdoor sources of pollutant and somewhat natural ventilated indoor air quality. As findings in atmospheric Ozone study, it was evident that methane, nitrous oxide, carbon oxide and volatile organic compounds could increase ozone, stratospheric water vapour and global temperature (Myhre et al. 2013). Perhaps projected higher humidity can decrease ozone (O_3) concentration, while fire disaster can seriously increase PM concentration to dangerous level. As a result, the holistic approach of pollutants situation can be conducted by these optional examples; chemical transport models (CTMs) and general circulation model (GCM) simulation of future scenarios (Jacob & Winner 2009). Not only outdoor ambient effects, but these increases of environmental gas could disturb indoor air quality through being the initial source of indoor air.

To concern organic compounds, it could be seen that outdoor traffic affected the level of pollutant as being source of indoor contaminant. For example, NO_2 and volatile organic compounds (VOCs) emitted from motor vehicle process and interior furniture finishing with sunlight stimulation (Laden & Winkelmayer 2011). Not only ambient environment, but home furniture and finishing materials can produce VOCs emission especially off-gassing building materials, the room freshener, household products, mothball and painted wood products (Guo 2011). Consequently, Household Air Pollution (HAP) exposure has been considered to affect pregnancy and childhood in terms of biological tissue. As a result, cleaning cook stoves and efficient household cooking could be the solution of household pollution (Rabadán-Diehl, Alam & Baumgartner 2013). Moreover, to study indoor sources of air pollutant, burning incense and candles in Cyprus churches could bring about the peak of black carbon concentration as 10.7 times higher than outdoors (Loupa, Karageorgos & Rapsomanikis 2010). From other sources of indoor air quality, envelope should be maintained to be proper shape without infiltration crack and finishing materials should be conducted to release low emission pollution.

As a general theory, air temperature, relative humidity and air density could respond directly to air pressure and then related to air pollutant concentration such as cigarette smoke (Li et al. 2016). This was the same as higher pressure bringing about greenhouse gases in CO_2, CH_4, N_2O and N_2 in [C_2mim] (Pereira et al. 2013). For more examples, the decrease of ambient pressure could bring about smaller diameter of spray droplets, higher velocity of droplet movements (Wang et al. 2015). Moreover, even it was possible that the intensity of ozone and vapour could limit bacteria growth and spores exposure in medical test (Ratnesar-Shumate et al. 2015), but there was no evidence indicated directly ozone effect on indoor air aerosol. While SO_2 and NO_2 responded positive effect on bioaerosol in morning and evening period, and affected negatively in mid-day period (Gao et al. 2016).

Table2-5 demonstrates several relationships between ambient environment and pollutants. It can be seen that relative humidity affects every type of pollutant especially mould and bio aerosols are popularly studied their correspondent with every environment factor. In addition, the effects of velocity and flow direction relate mainly particulate matter as blow-ability of large air mass. Other contaminant is possibly used as indicator of related air pollutants as BC and burning gases levels. As well as being indicators, other types of air contaminants may support the severity of pollutant attacking on human health. This can be seen in a number of studies related to multiple level effects from particulate matter and gaseous compounds. After considering the association of environment and indoor air pollutants, the current situation in hot and humid climate in Southeast Asian and the standard of indoor air quality will be clarified in the next session.

Table 2-5 The conclusive relationship between meteorological factors and air pollutants

	Temperature	Relative humidity	Wind		Pressure	Other contaminant
			Speed	Direction		
Particle	Inhalable pollutant (Smith et al. 2014, Adhikari et al. 2006), BC (Boucher et al. 2013), Pollen (Adhikari et al. 2006)	(Deng et al. 2011), PM10 (Liang, Lv & Yang 2016), PM2.5 (Oanha et al. 2013), Precipitation (Boucher et al. 2013), Fly ash (Schifftner 2014)	(Wang et al. 2009, Branisˇ, Afra'nek & Hytychova' 2009, Wang et al. 2009, Schifftner 2014)	(Jurelionis et al. 2016), Printer room (Koivisto et al. 2010)	(Clancy 2011), Spray (Wang et al. 2015)	BC (Loupa, Karageorgos & Rapsomanikis 2010)
Bio aerosol	(Jung, Lee & Kim 2009, Deng et al. 2011), Fungi (Adhikari et al. 2006)	(Deng et al. 2011, Davis, McGregor & Enfield 2016), Mould (Rios et al. 2009), Pulmonary disease (Qiu et al. 2013)	Fungi (Jones & Harrison 2004)		(Deng et al. 2011)	(Gao et al. 2016)
Gaseous pollutant	CO_2 (Li et al. 2012), PAHs (Jin et al. 2012), Ozone (HTAP 2010, Adhikari et al. 2006)	CO_2 (Li et al. 2012)	(Norhidayah et al. 2013, Schifftner 2014)	(Laden & Winkelmayer 2011)	Smoke (Li et al. 2016)	(Myhre et al. 2013, Laden & Winkelmayer 2011), Ozone (Jacob & Winner 2009), GHGs (Pereira et al. 2013)
VOCs		Formaldehyde (Xu & Zhang 2011), TiO_2 technique (Huang et al. 2016, Pichat 2010)	(Schifftner 2014)			(Myhre et al. 2013, Guo 2011)

2.4 Air pollution situation in Southeast Asia hot and humid climate

In China, Thailand and India, a co-protocol for air pollutant effects estimation has been developed in terms of the Public Health and Air Pollution in Asia (PAPA) project. From this project, it is possible that harmful situations in Asia are caused by outdoor living styles and indoor air conditioning systems (Wong et al. 2008). In terms of satellite observation, the Seven Southeast Asian Studies (7SEAS) program in Malaysia, Philippines, Singapore, Taiwan, Thailand and Vietnam found 6 activities creating aerosol particle such as natural formation, industrial production, bio mass burning, volcano eruption, woods fuel burnings and forest fire in rural (Reid et al. 2013).

During the period of winter in Hanoi, air pollution was collected and analysed the sources of particulate matter categorized into 7 groups: 40% of secondary mixed PM, 10% of diesel transportation, 16% of culinary, 16% of secondary sulphate rich, 11% of aged sea salt mixed, 6% of industry, and 1% of construction (Hai & Oanh 2013). To improve combustive engine, alcohol fumigation performance was implied to reduce importantly 57% of particulate matter (PM), 20% of nitrogen oxides (NO_x) and carbon dioxide (CO_2), but this affected to grow carbon monoxide (CO) and hydrocarbon (HC) up (Imran et al. 2013).

To concern the context of seven different cities from Asia pacific, North America and Europe, PM10 and PM2.5 mean were at 46.4 μg/m^3 and 28.6 μg/m^3 met indifferently WHO AQG standard in short term collection (Lai et al. 2013). Turning to air pollution in Thailand, more than decade, three types of particle have been monitored in terms of particulate matter diameter less than 2.5 μm (PM2.5), particulate matter diameter less than 10 μm (PM10) and total suspended particulates (TSP) of outdoor condition. Also it was found that indoor concentration of PM2.5 and PM10 higher than ambient in case of shop, while the opposite trend occurred to nursing session (Tsai et al. 2000). What's more, the monitoring of particle in south Thailand was investigated that 24-hour average PM10 and PM2.5 concentrations could meet the standard of Thai NAAQs, while both value exceeded WHO guideline as the performances between 40 and 170 μg/m^3 (Kanabkaew, Nookongbut & Soodjai 2013).

The simulation and annual meteorological dataset of PM10 in East Asia in 2007 were investigated and compared PM concentration results. It can be seen that the high level of mass concentration was found in 82 cities in China and Taiwan. For instance, in case of PM10, Shanghai and Shijiazhuang were simulated to reach the highest dust concentration at exceeding 300 $\mu g/m^3$, while real-time monitoring data in Beijing and Lanzhou showed the highest level at around 300 $\mu g/m^3$ (Chen, Tsai & Chang 2013). Even though the visibility can indicate the level of daily PM10 concentration, discontinued data is able to occur from systematic collection. To overcome this missing in Bangkok, specific regression model could adjust linear graph for visibility and PM10 concentration with humidity less than 76.5% (Vajanapoom et al. 2001). This model resulted continually in the study of PM10 and respiratory disease that associated significantly especially elderly group (Vajanapoom et al. 2002). This was the same action in cardiovascular risk study of PM10 raised 95% of mortality in people aged more than 65 (Vichit-Vadakan, Vajanapoom & Ostro 2008). Turning to the indicator of air quality in Hong Kong, air quality health index (AQHI) was developed to level the risk of PM10 concentration exceeding on health in 10 bands. Based on Canadian approach and WHO Air Quality Guidelines, the AQHI could adapt to the development of Hong Kong's existing air quality without the study of health existing (Wong et al. 2013).

The considerations of particulate matter in ambient have been studied in several cities in Asian such as Xian, Changsha, Heiloungjiang in China, Bangkok and Chiang Mai in Thailand. After categorizing 16 polycyclic aromatic hydrocarbons (PAHs), it was also found that Changsha in China reached the highest level of particulate concentration at 276.1 $\mu g/m^3$ and particulate concentration varied by the variation of season (Yang et al. 2010). By the way, in the Northeast of China study, the effect on season demonstrated the highest PAHs level in winter and the lowest value in summer (Jin et al. 2012). This was supported by particulate monitoring in Chiang Mai, Thailand that the level of particle in dry weather, low precipitation and burning activities could bring about high level of PM10 concentration in 2010 (Wiriya, Prapamontol & Chantara 2013). Also it was found that natural wind speed and direction disturb to re-suspend deposited particle (Gunawardene et al. 2012, Hai & Oanh 2013, Pateraki et al. 2010). This is similar to simulation of dust resuspension that air velocity can lead to rise PM2.5, PM10 and PM_{total} (Martuzevicius et al. 2011).

From the reviews of atmospheric particulate matter, traffic fuel combustions in both exhaust and non-exhaust conditions have affected significantly airborne concentration (Pant & Harrison 2013, Kelly & Fussell 2012, Gunawardena et al.

2012, Li & Crawford-Brown 2011). As a result, in Hanoi, Vietnam, where was ranged to be the highest air pollution in Southeast Asia metropolitans also found the PAHs concentration from town road was 6 times higher than those from country road (Tuyen et al. 2014). Transportation is also one of two main activities that resulted in high level in PM10 and PAHs in sub-urban areas in Chiang Mai, while another one was open burning of biomass (Wiriya, Prapamontol & Chantara 2013). Surprisingly, in Taiwan, there are few different main air polluted sources including construction process in home factories, cooking activities in restaurants and incense stick burnings in temples ordered respectively from high to low level of mass concentration (Lung et al. 2014).

2.4.1 Statistical data

The severity of air pollutant becomes more dramatically in high developing zone in Asia, but the solutions of this problem were not adequate to protect local human health or improve local air quality. Even indoor air quality could be effectuated by filtration and technical elimination, but outdoor supply air could be important in case of natural ventilation building. Besides, local poverties have presented controlling indoor air quality within intensive air pollution areas such as crowded traffic or industrial communities. Hence current outdoor air situation in studied area is essential for integrating air purified techniques or lunching authorized policies for air quality control. However the statistical data periods of air pollutants monitoring were dependent on local authorities and monitoring technology in that countries.

For the first example in Thailand, air pollutants have been collected data for more than 10 years for PM10 and TSP. However, PM2.5 data was only monitored at the last 3 year in some risk areas. To be noted, road side PM10 concentration both in Bangkok and periphery was very high in 2007 and 2013. This high value of air PM10 would exceed WHO AGC, NAAQs and Thai standards that resulted from an increase of personal vehicles in those years. While the situation in Northern Province was high in 2009 and 2013 because of uncontrollable forest open burning in winter time and low air pressure in that areas. In some specific provinces in Thailand acted as industrial spaces for produce construction cement and mortars, therefore, it is possible to get high level of PM10 in these areas particular especially Na Phra Lan in Saraburi, Thailand (Air Quality and Noise Management Bureau, P. C. D. 2004-2013).

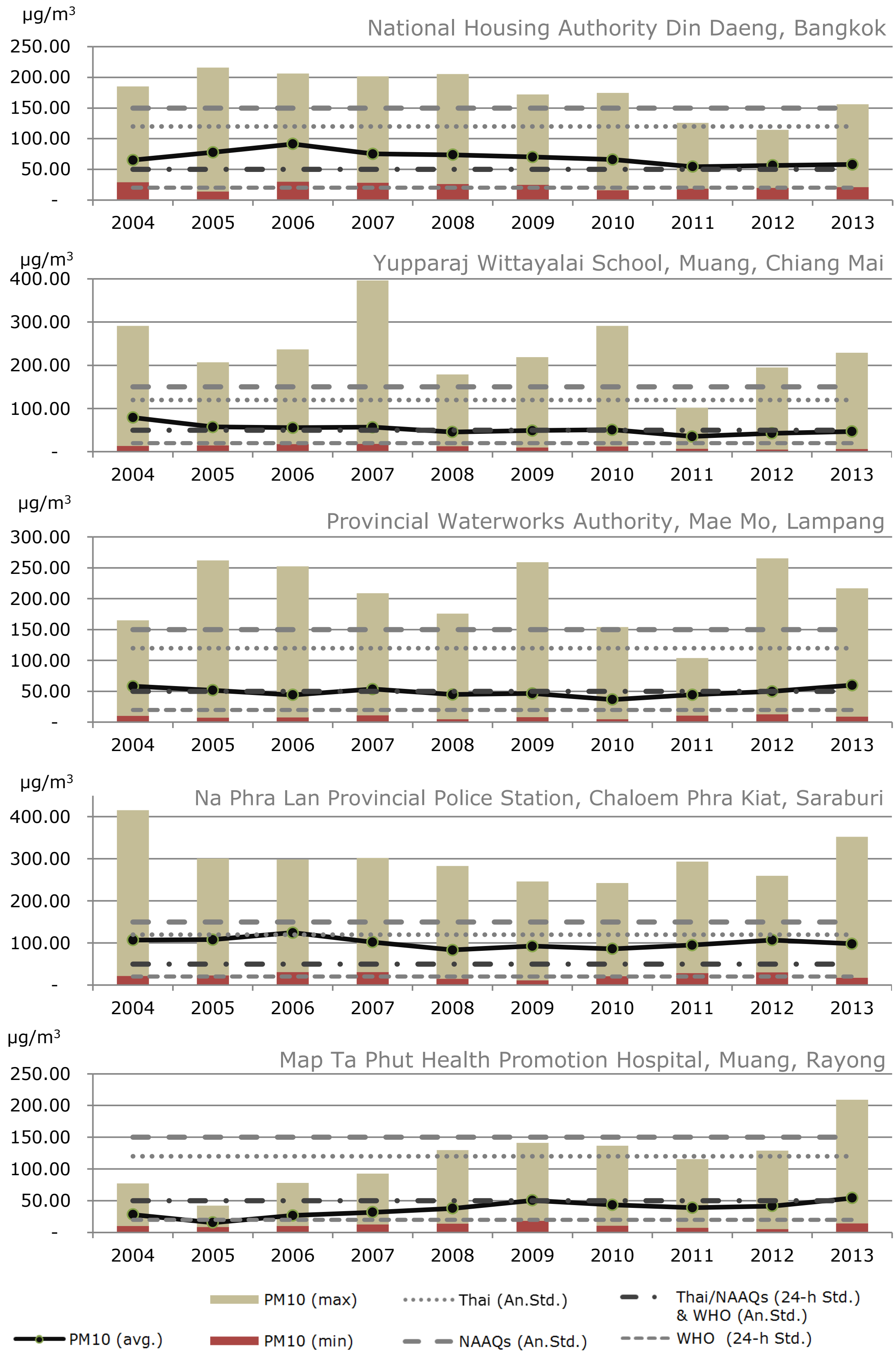

Figure 2-7 10-year PM10 concentrations in Thailand (Air Quality and Noise Management Bureau, P. C. D. 2004-2013)

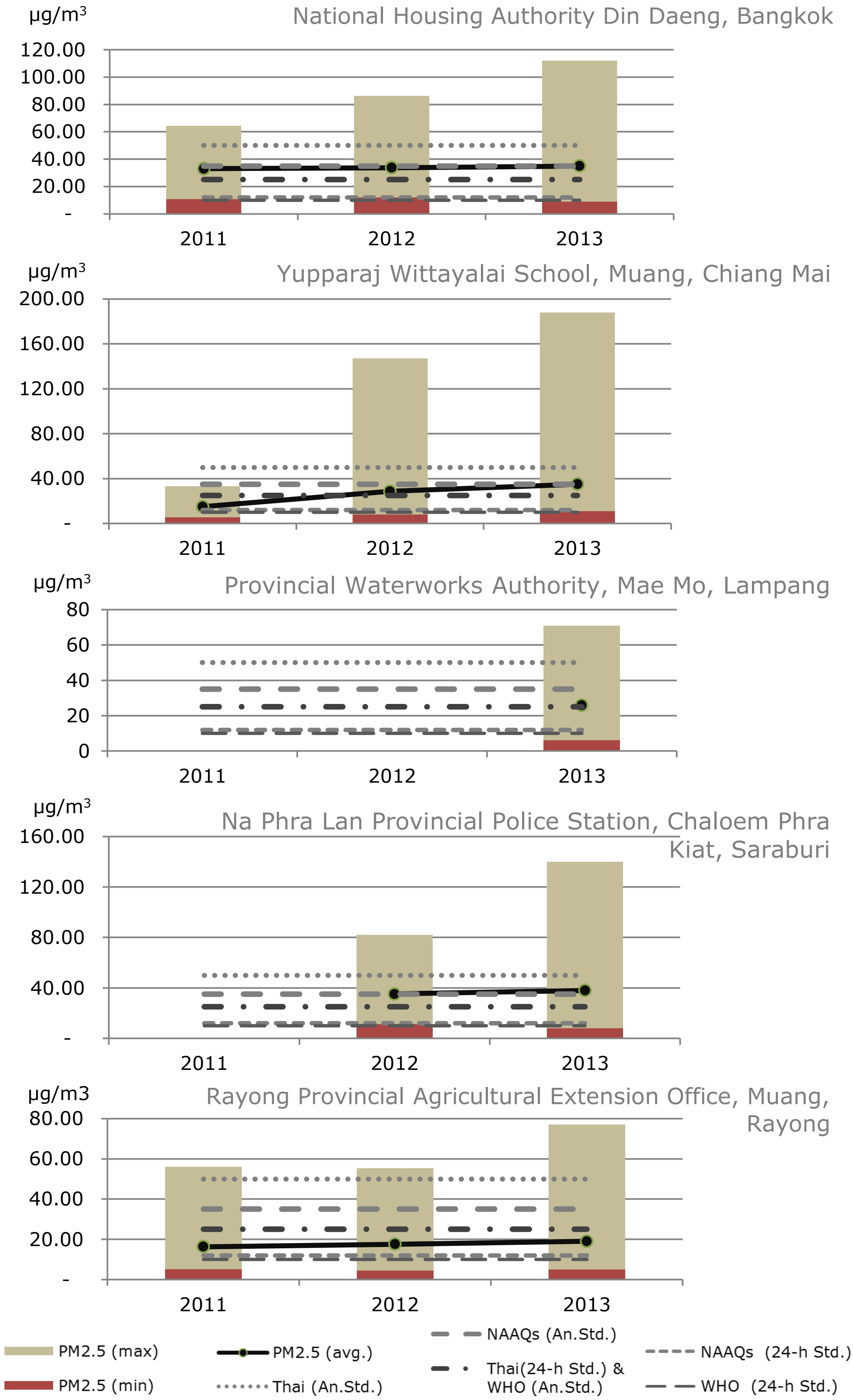

Figure 2-8 3-year PM2.5 concentrations in Thailand (Air Quality and Noise Management Bureau, P. C. D. 2004-2013)

From six road side monitoring locations, **Figure 2-7** is the example of PM10 concentration in Bangkok, Thailand. It can be seen that average PM10 concentration drop slightly from 2004 to 2013. This all values did not exceed Thai and NAAQs annual standards, but overall mean still exceeded annual standard of WHO. Moreover, minimum concentration almost topped of 24-hr standards of WHO excluded the value in 2011. Therefore, road side PM10 situation would be considered to be the first priority of environment problems in Thailand. This study can relate to indoor air particulate matter study in Thailand because outdoor pollutant can be the main sources of indoor contaminated air. If the authority could not launch the policy to clean the air, personal technological purifiers should be the first option for citizens.

According to **Figure 2-8**, the examples of annual average PM2.5 concentration in Thailand were demonstrated throughout 3-year period from 2011 to 2013. It can be seen that the concentration of PM2.5 increased dramatically in all stations. To be noted, in Na Phra Lan province and Map Ta Phut locations, the exceeding of PM2.5 and PM10 have been considered more specially because there were more than 10-year industrial zones. While it was evident in Chaing Mai that poison mist from forest burning become more seriously and resulted in higher PM2.5 concentrations over the 3-year period.

These examples of air pollutant concentration are essential for adapting air purifiers and local air quality policy. The next session will examine policy and air purified techniques for hot and humid climate in Asia.

2.4.2 Authorized actions

In England and Wales, following Building Regulation part F1 and J1, the requirement of fresh air has been essential for indoor air quality as well as filtrations and their maintenance. In addition, this regulation was based on air quality standards particular in BS EN, WHO and ESE standards (Clancy 2011). Turning to United State, due to building energy and environment concerning, the Clean Air Acts (CAA) has been developed by United States Environmental Protection Agency (EPA). National Ambient Air Quality Standards (NAAQS) was established to prevent public health and regulate pollutants emission. In labor group, air quality requirement was worker rights and Occupational Safety and Health Administration (OSHA) was the main authority to control indoor air pollutants by various standards. OSHA standards focused on occupation illnesses recording, indoor ventilation, air contaminants, formaldehyde and other indoor hazardous chemicals. Another standard for building criteria was ASHRAE that shaped indoor air quality based on air conditioning systems and it was popular in complicated industrial buildings. In European zone, the European Environment Agency (EEA) has lunched environmental policy for public regulation in 33 member countries. Also World Health Organization (WHO) in Europe released indoor air quality guidelines for public health aims and this guideline was widely applied throughout the world. However there were some region agreements in Asian countries to protect public air quality for instance Clean Air Initiative for Asian Cities (CAI-Asia 2010) cooperated with United Nations Environment Programme (UNEP) and Clean Air Asia based on China leadership. Both organizations aim to reduce fuel combustion resulted from traffic vehicles in metropolitans in Asian countries and have agreement to limit future emission levels.

From international standards and policies, Asian countries have taken local air pollutant problems into account and lunching some campaigns for limiting air pollutant. For example, it was found that authorized action could reduce air pollution problems in short term strategies as zoning traffic and timing local transportations in Shanghai, China. Also National Ambient Air Quality Standards (NAAQS) was adapted more properly to be Chinese version used in Chinese climate and economic development. As being designers in Singapore, indoor air quality was regulated by the Building Control Regulations and Singapore Standard Code for Mechanical Ventilations and Air-conditioning in Building (SS CP 13:1980) (Chan 1999). Then, being more up to date in 2005, the National Environment Agency released the Building and Construction Authority (BCA) Green Mark Rating System to promote sustainable design and green buildings (Calster, Vandenberghe & Reins 2015).

To promote energy efficiency, the Vietnam National Energy Efficiency Program (VNEEP) announced to support energy saving campaign that implied to reduce indirectly carbon emission in industrial process too (Nguyen 2015). Nevertheless, there was no evidence that Vietnam government would seriously point out air pollutant problem in buildings. Turning to Thailand's building codes, the energy-efficiency policy has been responded by 4 organizations especially the Department of Alternative Energy Development and Efficiency (DEDE), the Department of Public Works and Town & Country Planning, the Energy Policy and Planning Office (EPPO) and the Electricity Generating Authority of Thailand (EGAT). These responsibilities covered lunching indoor air quality building codes and

Environmental Impact Assessment (EIA) in terms of air change rate requirement (Calster, Vandenberghe & Reins 2015).

More than emission agreement and building codes in Asia, there were green building benchmarks for rating green building such as Leadership in Energy and Environmental Design (LEED) by U.S Green Building Council, Building Research Establishment Environmental Assessment Methodology (BREAM) by Building Research Establishment (BRE) in UK and Thai's Rating of Energy and Environmental Sustainability by Thai Green Building Institute (TGBI). To pursue these green building awards, it was essential to control building emission and energy consumption, while indoor environmental quality was acceptable included air quality. However the context of buildings in different locations such as climate and the type of building ventilation should be concerned before applying these benchmarks.

After considering current situations of air pollution and authorized policy in Asia, it was possible that quality of indoor air in Southeast Asia depended on outdoor sources, building ventilations designs and types of building. The location of buildings can identify outdoor pollutant types and concentration that can imply to the level of hazardousness on human health. Also types of building ventilation can affect the controlling of fresh air supply that is showed definitely different between air conditioning system and natural ventilation. To keep clean indoor air, perhaps filtrations can be another optional solution supporting air conditioning buildings, while might be used limitedly in natural ventilation buildings.

2.5 Indoor air filtration

Among several problems of world environment, both indoor and outdoor air quality have become more important for occupants' respiratory who spend more than 20 hours a day in the buildings. To overcome this problem, personal purifier has been used in various ways for instance hanging portable purifier, desktop filter, mask and other technologies. There are around 50-60 different types of purifier from portable purifier to high-efficiency particulate arrestance (HEPA). The portable purifier technology can be grouped into filter, ionic technology and emulsified botanical solution. The most popular purifier technology is filter that helps to decrease a range of particle sizes. Also filter can be integrated simply to other type of filter, while small purifier is portable. The small purifier type can be used in several ways for example neck hanger, USB thumb drive and light bulb.

Commonly, air filtrations can be separated simply into two types i.e. passive techniques and active systems. For the first application, passive methodology is defined to be the application possibly used without electrical consuming or used in natural ventilation. Active process of air filtration means any electrical air filtration that is more complicated than passive techniques.

Brown (1993) considered air purified techniques as filter structure, flow pattern, filter mechanical process, electric forces and particle bonds. Even filter was a kind of passive technique, the filter structure was important for purifier effectiveness. For particle bonds discussion, it was possible that each chemical adhesive character of air pollutants would be destroyed by chemical actions. The flow pattern related mathematically to filter mechanical process and electric forces in ventilation systems. Then more influent details will be demonstrated in the next step as passive technique and active air filtration.

2.5.1 Passive techniques

Air filtration without energy input can be seen especially filter and chemical action process. One passive filter can be used for purifying large air particles sized 5-10 microns. Accordingly, it is possible to apply for the first stage of HEPA air cleaning process in high flow rate system (Sparks & Chase 2016). However this method is not passive as high flow ventilation system is effective only with electrical driven fan. For the real simple passive use, it is possibly reformed as general portable mask which performance can be depend on structure and type of filters.

Based on Brown category in 1993, filters could be divided into paper filter, carded filter, porous filter and special characteristic filter. The first two filters were both from fibre materials, however, in different structures. In case of paper or fibre filters, the intersection of weaving fibre was important as relating directly to air pollutants size and purification. As same as sieving method, the calculation of filtration probability would be concerned in particle distribution and filter pore distribution. Another type of filter was shown as carded filter that could be repeated by comp metal plates. Then a cumulative distribution and probability would be randomly calculated after assuming particle number and size by Poisson distribution. As a result, the distance to nearest pores and pore radius affected directly to air pollutant performance of carded filter.

Furthermore, porous foam was another filter type, but it was not structured by fibre. For surface porosity concerning, it was possible that filter would be verified by gas permeation test (GPT) and image processing package (IPP) (Abbasgholipourghadim et al. 2015). Porous filters could be used acceptably as second-stage of HEPA filtrations in small particle diameter sized 0.5-5.0 microns in low velocity pressure at 0.12 m/s systems (Sparks & Chase 2016). In terms of special character filter or model filter, it was possible to array two-dimension carded filters until eliminating specific air contaminants. The specific contaminants could be identified in special functions particularly in pharmaceutical storages, food products and medical places.

More recently, literature has emerged that offers another type of passive technique in particular TiO_2 coating technique. TiO_2 chemical actions could eliminate VOCs, gaseous compounds and respiratory dust. However, there was a limitation of natural factor on TiO_2 catalytic process as requirement of humidity and ultra violet light. Hence, in night time or out of light season in polar climate countries it might be not possible to use this technique. Within three phases of TiO_2 crystal, only one stable phase was rutile, while anatase and brookite phases could be changed to rutile in warmer environment. The structure phase of TiO_2 could be examined in XRD pattern. It was found that coating actual thin TiO_2 anatase was the best solution to degrade methylene blue (Danish et al. 2015). After understanding all natural purified techniques, the next topic will examine electrical systems purifying air contaminants.

2.5.2 Active systems

As increasing efficiency of air purifiers, it is possible that system pressure could be electrically increased by driving force of system velocity. This can bring about faster air purification and higher air quality. Five techniques of air electrical purification were demonstrated in **Table 2-6** how suitable for each size of air particle.

For the first techniques in **Table 2-6**, air particles sized larger than 50 microns could be eliminated by gravity settling force in chamber (Kennis & Veiga 2013). With more energy consumption in higher system velocity, centrifugal force could effectively separate fine dust diameter larger than 10 microns, but still in low cost condition. In case of PM2.5, the system required higher pressure to drive system velocity pass through fibre filters. So the cost of this technique would be higher not only from energy use, but also from fabric filter cost.

Table 2-6 Operating air purified techniques fitting in particle matter (Kennis & Veiga 2013)

	Gravity settling chamber	Cyclone	Filter bags	Scrubbers	Electrostatic precipitators
Removal principle	Settling as a result of gravitational forces	Centrifugal force	Physical barrier (fabric filter) and letting gas pass through	Gas – liquid mass transfer, droplet particle	Electrical force-trapping particle from gas
Particles size (>90%)*	>50-100 µm	>10 µm	>0.5-2 µm	>1 µm	>0.1 µm
Velocities	Low	Average	Average-high	Average-high	High
Cost	Low	Low	High (filter bags)	Medium	High

*only in operating waste gas

Turning to scrubbers or porous materials, it was probable to purify ultrafine particle diameter size around 1 micron; however, this was proved only in droplet particle. The tiniest particle sized 0.1 microns could be eradicated by electrical trapping techniques and high velocity in system. Due to high performance of purifying particle, the price was more expensive for specific mechanic elements of purifier. To be noted, in case of average to high velocity, pressure drop in system related possibly to efficiency of purifier by calculation.

As physical information of filter element, fabric filter and solid fibre mop can be identified types of materials, weight and elements' dimensions. For monitoring weight of paper filter, a β-particle emitter and detector are the most popular method for manufacturing case (Brown 1993). However, fibre fabric filter is heavy enough to be weighted by normal scale as well as its dimension can be measured by regular ruler.

$$Minimum\ Likely\ Error = \frac{1+P^{1/2}}{(N_t t_o P)^{1/2}} \quad \textbf{(2-7)}$$

where N_t = the average count, unit time,

t = the time of measurement (constant), minute,

P = the penetration

According to another concern of quantification, "Poisson distribution" has been popular used to random events per unit time (Rees 2000). Also Poisson distribution can be used for quantifying the minimum error of filter tests. In case of constant air flow and constant aerosol generating, the equation of the minimum error sampling test can be examined in **Equation (2-7)**. Idealistically, this equation can be used in manufacturing HEPA filter tests during the six time downstream sampling. Also the variation of minimum error is supported to validate beneficially the filter for dust diameter 0.1 μm; while larger particle can drop the frequency of correlation (Brown 1993).

Turning to penetration concerning, the penetrating particle size rises up caused from increase of fibre diameter or velocity; while the reversal trend occurs in case of increasing filter density or thickness (Huang et al. 2013). It is also found that measuring penetrations of liquid and solid particle are the same, so viscosity and aerosol liquid constituting does not affect the penetration (Payet et al. 1992). Consequently, this study could use sodium chloride (NaCl) for testing air cleaning performance of solid mop and used body spray for testing fabric filter performance.

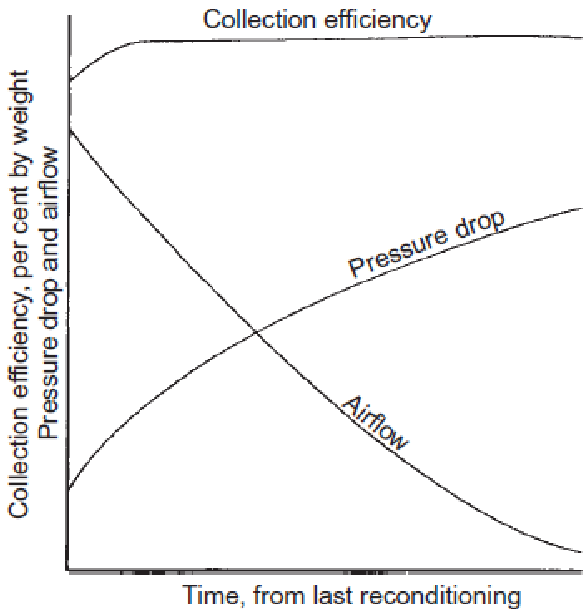

Figure 2-9 Dust collection filter performance over one cycle (Sparks & Chase 2013)

The penetration of dust is resulted from pressure drop calculation in filtration system. To concern pressure system, fabric filter normally used as house vacuum can be identified the pressure and flow rate character as shown in **Figure 2-9** for each cycle. As the mechanic flow of vacuum, air dust is quickly accumulated on fabric filter surface. Then this affects directly dust collection efficiency as an increase of filter thickness and also results in pressure drop. In case of fabric filter, type of fibre can affect dust collection efficiency as smaller opening areas from non-woven fibre can bring about higher efficiency. Nevertheless, an increase of dust collection efficiency can reduce permeability and cleanability. Realistically, fabric filter can be selected from compromising efficiency, cleanability and permeability, so there is no 100% efficiency of fabric filter in market. To maintain the air cleaning performance, fabric filter must be eventually cleaned to reduce the resistance of system as convergent trend of permeability in **Figure 2-10**. To improve efficiency of fabric filter, the coating of restricting particle can be sprayed on the upstream surface called "needlefelt substrate", however, this bring about more expensive cost of filter membrane (Sparks & Chase 2013).

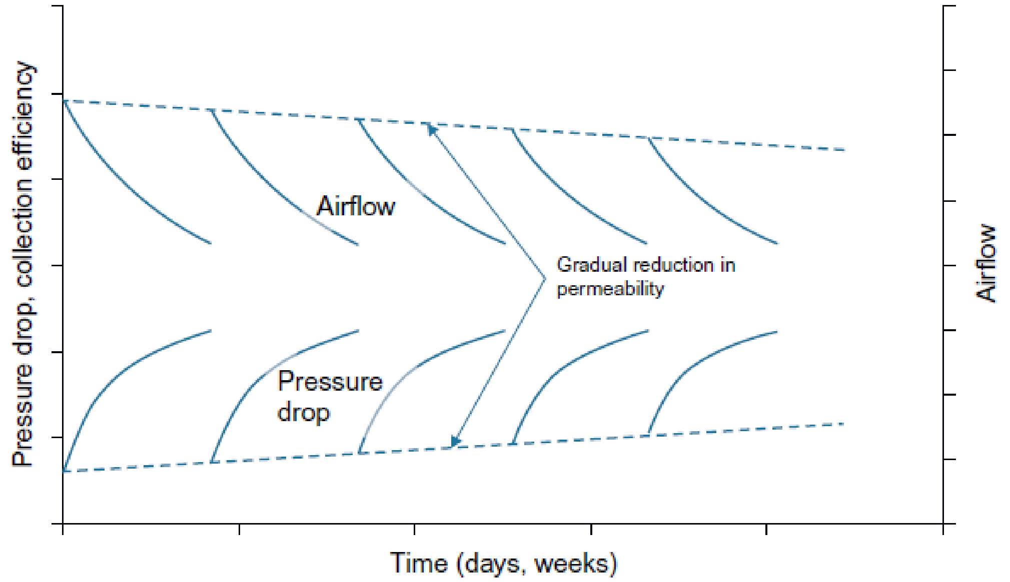

Figure 2-10 Baghouse performance over a number of cycles, showing exaggerated trends in airflow, cycle time and permeability (Sparks & Chase 2013)

To across the filter penetration, pressure drop and velocity are concerned as the main law of Darcy. However, if the filter can be introduced as an inertial component into flow system, the pressure in housing filter devices may be higher than Darcy's prediction. In case of non-standard conditions of pressure and temperature, it is moderately important to measure pressure drop for maintain the sterilization of filter as same as in case of difference in flow volume between inlet and outlet openings (Brown 1993).

To avoid flow block of filter system, it is possible which pressure drop in cartridges should be limited in range 0.3-0.7 bar for sterilizing pre-filtration application. Actually, general sterilizing filter provide an initial pressure drop at approximately 0.1 bar and the pressure loss of system flow should be included in all stage of air filtration. However, higher pressure difference can lead to higher cost of application development. Due to normally increase of pressure drop, general filtration systems should be resterilized or changed filters to maintain air cleaning efficiency, so routine filter bags are required to inform expiration (Sparks & Chase 2013).

2.6 The experiments of monitoring air quality

During the comparative study between indoor and outdoor particle concentration, dust sampling was enabled to collect air samples in 100 locations and energy-dispersive X-ray fluorescence spectrometry and ion chromatography were used to identify each small elements in air samples. These instruments can be used for sub-micrometer (PM1), fine thoracic (PM2.5) and thoracic (PM10) (Horemans & Grieken 2010). What's more, as black carbon particle (BC) study, an aethalometer could measure BC emission and a scanning mobility particle sizer classified the size of particles after those particles from the candles and incenses were counted by a condensation particle counter (Stabile, Fuoco & Buonanno 2012). The response methodology of PM10 was collected via gravimetric passive method and analysed by laser beam technology, while carbondioxide (CO_2) was characterized by infrared sensors (Heudorf, Neitzert & Spark 2009).

The optional methodology of indoor air quality study is computational fluid dynamics (CFD). As achieving more accuracy result, particle resuspension from wall surface was used to be the boundary based on dimensional analysis (Kim et al. 2010). It was possibly to simulate enzyme particle emission rate by CFD comparing with experiment based on Elutriation Dust Column (EDC) (Liu et al. 2009). However, CFD has a somewhat limitation on time-consuming and high cost of computer program, multiple linear regression (MLR) with 25% error is therefore another option to investigate the relationship between velocity and particles (Wang, Zhao & Chen 2010). To consider predicative possibility of CFD, another simulated program is a Real-Time Air Quality Forecast (RT-AQF) based on a three-dimensional air quality model. Weather model was based on the Model of Aerosol Dynamics, Reaction, Ionization and Dissolution (WRF/Chem-MADRID) and RT-AQF models was pollutants predicting models in terms of O_3, PM2.5, biogenic volatile organic compounds (BVOCs) and ammonia (Chuang, Zhang & Kang 2011).

Another consideration of indoor bio aerosols is experimental equipment that is mostly different from other indoor pollutant detective device. For bacteria monitoring, an impactor sampler with colonies on plate count agar (PCA) and Columbia colistin-nalidixic acid agar with 5% sheep blood (CAN agar) was located on pedestrian way in Tokyo underground station to collect bacteria aerosols. As a result, 11 bacteria species were identified and dominant bacteria colonies on agar plate were Staphylococcus epidermidis and Micrococcus spp (Seino et al. 2005). To monitoring fungi species, optional active methodology in cyclone sampler was settled comparing with passive method in the personal aeroallergen sampler based on component mass gravity. As a result, A. alternata, C. cladosporioides, and E. nigrum were effective with passive methodology, but P. chrysogenum was collected by only active method (Yamamoto et al. 2011).

According to VOCs study in porous materials, a dynamic dual chamber method was set by various level of humidity in 25%, 50% and 80%. It was found that formaldehyde responded dominantly to high level of air humidity at 80% (Xu & Zhang 2011). Another laboratory test of VOCs, the reaction of carbon byproducts and various toluene ozonation catalysts were identified characteristic by X-ray diffraction, Raman spectroscopy, BET and ICP-MS based on studied temperatures between 22 $^{\circ}$C and 100 $^{\circ}$C. The result was found that siliceous MCM-41 catalyst brought about lower toluene comparing with c-alumina catalyst (Rezaei & Soltan 2012). From photocatalytic VOCs degradation, TiO_2 nanoparticles (TNP) was also analyzed and identified by sol-gel process and small rutile traces were characterized by X-ray diffraction (XRD). Other effects may be affected to ethylene, propylene and toluene oxidation concentration in absorption, flow rate, catalyst weight and reaction temperature (Hussain, Russo & Saracco 2011). Lastly, to determine odor emission, chemical emission laboratory, computational simulation and mathematic model were used to determine time operational and dynamic of indoor air monitoring (Wolkoff & Nielsen 1996).

According to **Table 2-7** demonstration, the conclusion of instrument matching provide convenient for all pollutant experiments. However, equipment selection depends on the limitation of laboratory and properly testing condition. Therefore, this research will examine experimental equipment for pre-testing PM2.5 in the section of experiment’s progress.

For this research, dust monitors used in experiments are portable dust track adapted from cyclone kit. Full performances and functions of all instruments will be demonstrated in details in the next chapter. In addition, X-ray diffraction was adapted to identify TiO_2 coatings in photocatalytic experiment. For more details, the methodology and the results of photocatalytic experiment will be completely explained in chapter 7-8. The results from other research are suitably compared to noted results.

Table 2-7 Matching equipment of pollutant data collection

Types of pollutant	Objective of testing			
	Monitoring concentration	Counter/Sampler	Diffraction/Analyser	Simulation/ Mathermatic equation
Particle	- Aethalometer (Stabile, Fuoco & Buonanno 2012)	- Dust sampler (Horemans & Grieken 2010) - Gravimetric passive method (Heudorf, Neitzert & Spark 2009)	- Energy-dispersive X-ray fluorescence spectrometry and ion chromatography (Horemans & Grieken 2010) - Scanning mobility particle sizer (Stabile, Fuoco & Buonanno 2012) - Laser beam technology (Heudorf, Neitzert & Spark 2009)	- Elutriation Dust Column (EDC) (Liu et al. 2009) - Multiple linear regression (MLR) (Wang, Zhao & Chen 2010) - Real-Time Air Quality Forecast (RT-AQF) (Chuang, Zhang & Kang 2011)
Bio aerosol		- Impactor sampler with colonies on plate count agar (PCA) and Columbia colistin-nalidixic acid agar with 5% sheep blood (CAN agar) (Seino et al. 2005) - Cyclone sampler (active method) and personal aeroallergen sampler (passive method) (Yamamoto et al. 2011)		
Gas			- Infrared sensors (Heudorf, Neitzert & Spark 2009)	- Real-Time Air Quality Forecast (RT-AQF) (Chuang, Zhang & Kang 2011)
VOCs	- Dynamic dual chamber method (Xu & Zhang 2011)		- X-ray diffraction, Raman spectroscopy, BET and ICP-MS (Rezaei & Soltan 2012) (Hussain, Russo & Saracco 2011)	- Computational simulation and mathematic model (Wolkoff & Nielsen 1996) - Real-Time Air Quality Forecast (RT-AQF) (Chuang, Zhang & Kang 2011)

2.7 Conclusion

In conclusion, universal studies of air pollutants have been done in terms of air pollution types, effects on human health and factors of pollutant intensity. Based on air contaminant size, five types of air pollutant are separated into VOCs, gas, bioaerosols, PM2.5 and PM10. Those pollutant sizes affect consequently human health as irritating issues, respiratory systems, occupants' symptoms or even cancer. The intensity of pollutant and the hazardousness of health effect can be varied by sources and meteorological factors in particular temperature, humidity, flow rate and other air contaminants.

In the scope of Southeast Asia, air pollutant monitoring studies are mainly on emission gas and particulate matter sized 2.5 μm (PM2.5) and 10 μm (PM10). Also it is found that both PM2.5 and PM10 concentrations have exceeded EPA standards in risky air pollution areas especially industrial developments, transportation expansion and forest fire emission. As the problems of air quality in hot and humid climate, the solution has been shown in terms of authorized policies to mainly control traffic area and industrial expansions in particular traffic zoning policy in China. However, individual protection and purification have been another optional solution for local people.

Nevertheless, in the era of serious air pollutant problems, air purifiers and protections have become more important as undeniably facing air pollution. Modern air purifiers have been shown in several types and techniques depending on price, type of air particles, space functions, environment and local devices used in ventilation process. For existing devices, however, the price of innovative air purifiers have still been expensive as integrating to complicated technologies especially air conditioners and still consumed amount of energy to cool down and clean air in hot and humid climate.

The technologies used in air purifiers have exemplified as gravity settling chamber, cyclone, filter bags, scrubbers and electrostatic precipitation. For PM10 and PM2.5, filter bags are the main solution to purify these two air pollutants because of acceptable air cleaning performance, fitting in hot and humid climate and low cost for adaptation. Additionally, the reviews of experimental field could be a basic knowhow of all dust experiments in this study. The adaptive methodologies and instruments will be explained fully details in the next chapter.

According to literature reviews, air purifier techniques need to be developed in terms of application cost, the integrative design with existing devices and air purified efficiencies. However, the cost has related directly to integrative design of air purifier and materials. So this study focuses on integrating techniques in order to reduce the cost and meet sufficient efficiency of air purifier standards.

Because of several techniques of air purification, this research provides the suitable techniques for hot and humid climate by evaluating their efficiencies in hot and humid condition. To evaluate fabric filters performance, in case of PM2.5 and PM10, it is essential to calculate pressure drop in system and probability of particle size matching to filter pore. For photo-catalytic purification, it is important to concern type of TiO_2 crystal phase, air temperature, UV light explosion before coating TiO_2 on mop fibre. Consequently, the integration of fabric filter and TiO_2 mop coating can be integrated to floor lamp in order to clean bedroom air within hot and humid environment. Then international standards are showed in methodology chapter to rank the level of filter lamp performance.

Chapter 3: Methodology and experimental process

As the hypothesis of research, there are sub-experiments to clarify each objective and the methodologies are technically dependent on each experiment. For the first stage of each study, related experimental literature was reviewed as the base of experimental theory. Then equipment and experimental tools would be set technically for full experiments. The results were collected by data logger and manual collection. Lastly, the results were analyzed and compared to other related research and occasionally concluded to be executive summary and guidelines.

Based on the research gap to find low cost indoor air cleaning techniques, source and incident of air pollutant were the main problems of air pollution in Southeast Asia. The outdoor sources of air pollutants were identified as traffic vehicles, constructional industries and illegal burning forest. Transportation could bring about carbon emission and PM2.5, while wind along roadside could increase PM2.5 and PM10. In Thailand's industrial zone, particulate matter diameter sized 10 micron has increased since the expansion of industrial development. Not only PM10 from constructional industries, but PM2.5 could be also generated from illegal burning forest. From outside air pollutant, it is possible to purify air contaminants before supplying to indoor air. Moreover current environment as hot and humid climate would affect air pollutant concentration in terms of temperature, humidity and other contaminants. The gap in this research can be examined in terms of finding and developing air purifiers for efficiency and low cost reasons in hot and humid climate.

The solutions of indoor air pollution problems could be considered in two terms both physical purifiers and policy standards. In case of physical purifiers, there are 3 types of gadgets especially filter, mop and purifiers. The potentials of these three examples of purifier gadgets were evaluated. Also international policy would be categorized and estimated whether they are proper for South East Asia or not, if not, whether it should be improved for hot and humid climate. So general products of filter, solid mop and filter mask would be evaluated and the potential compared to international standards and local benchmarks. In terms of air purifier systems, the integration of effective potential and energy saving have been considered to be the modern trend of purifier developments. Also the potential of filters have been developed in various sizes of air pollution.

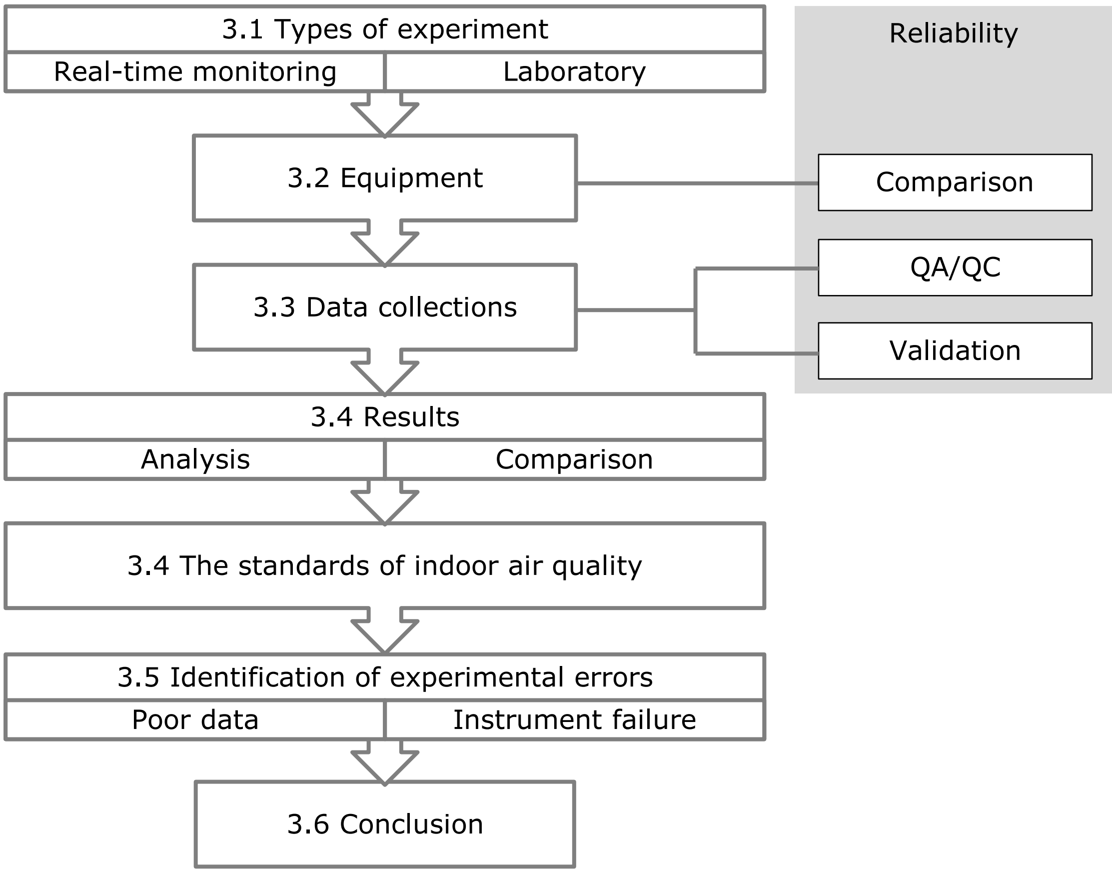

Figure 3-1 Research methodology

The outline in **Figure 3-1** shows the main methodology of this research including the assurance of data collection and equipment preparations. To begin with, two types of experiments are used in this research as a real time monitoring and filter performance tests in laboratory. Equipment can be used in both experiments. Data collections of real time and laboratory tests are different in case of time period and location. This collected data can be validated by dust monitoring equipment comparison and quality control of experiment before being analysed technically by statistical method. The results are also compared to other studies and indoor air quality standards. As another indicator concerning, the filter performance can be evaluated by air filter standards. Ultimately, the error of experiments and instrument failure are identified.

3.1 Types of experiment

To carry on research problems, there are two types of experiment used in this study. The first one is real-time monitoring used in PM2.5 monitoring in office and residential buildings in China and filter lamp evaluation. The second one is laboratory experiments in evaluating mops, fabric filter and filter lamp. The quality control of experiments complied with the European requirement and correlated to PM2.5 monitoring of the Automatic Urban and Rural Network (AURN) in the UK (Air Quality Expert Group 2012). Some equipment was used repeatedly in both real-time monitoring and laboratory tests.

3.1.1 Real time experiments

As air quality real-time monitoring in Shanghai, air pollutant was investigated according to indoor and outdoor PM2.5 concentrations, air humidity and temperature. These data were 24-hr collected in summer season in both residential and academic official buildings as the example spaces in **Figure 3-2**. To carry on this experiment, it was beneficial to pre-test equipment and edit data collection with comparison table to avoid data collection error. Also the characters of air PM2.5 were identified both in residential and office buildings.

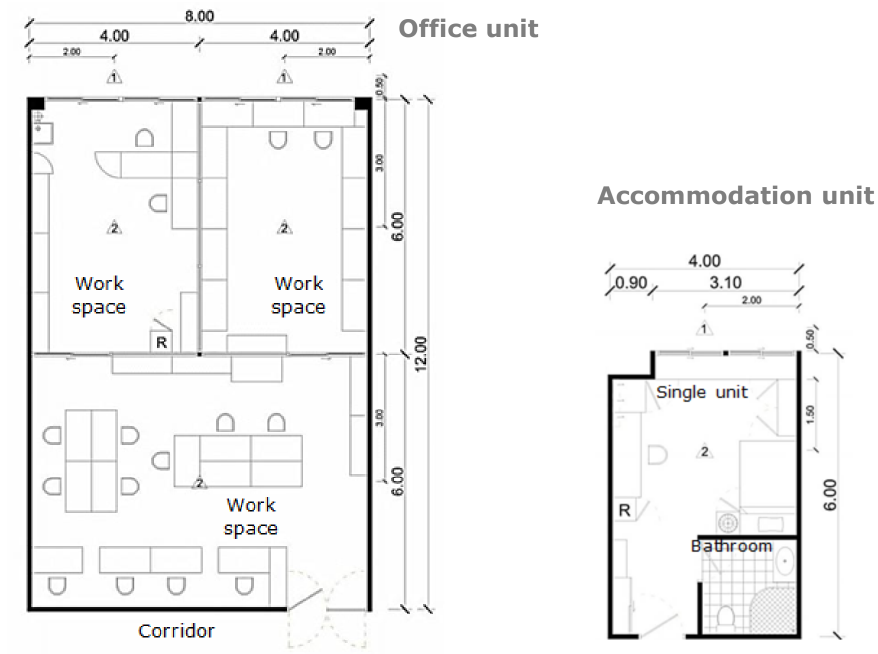

Figure 3-2 The examples of real-time monitoring in Shanghai, China

Shanghai area is identified to be economic and commercial districts in the centre, however, several academic campuses locate at the edge of city with transportation hubs and agricultural clusters. The main problem of air pollution in Shanghai is from road transportation, so the government has launched the policies to limit car and driving day. This study aims to investigate air PM2.5 value in academic area near transportation hubs and to identify the relationship between air humidity and air PM2.5 in hot rainy season. Both residential and official units will be examined in details in Chapter 5, however, equipment preparation and dust meter comparison are stated in this chapter.

Another monitoring was carried out using filter lamp testing at the end of this research. This monitoring was set in existing bedroom in Nottingham, United Kingdom to investigate the performance of integrative filter lamp to purify air PM2.5. The small bedroom as 2.5 m width, 2.4 m length and 2.5 m height dimension was located in Nottingham, United Kingdom. However, in this experiment, air humidity and temperature in bedroom were controlled as same as hot and humid climate. Because TiO_2 photocatalytic process could be occurred chemically in adequate air humidity, oxygen and ultraviolet light, this filter lamp would be applied in the bedroom set with artificial environment such as spray foggy and ultraviolet light bulb. The details of experiment and application design will be demonstrated in details in Chapter 7. Then the results of this real time monitoring can be compared to another monitoring method used dust cyclone as Filter Dynamic Measurement System (FDMS) or Partisol instruments in the Automatic Urban and Rural Network (AURN) monitoring in UK (Air Quality Expert Group 2012).

3.1.2 Experimental boxes in laboratory

According to the purpose of air filter evaluation, two experiments were set in laboratory in particular fabric filter evaluation and air cleaning mop evaluation. The difference of two air filter type is potential of air pollutant type cleaning that fabric filter can clean well air PM2.5; while fibre mop can purify only PM10. However these two types of air filters need pressure driving or electronic systems controlling flow direction.

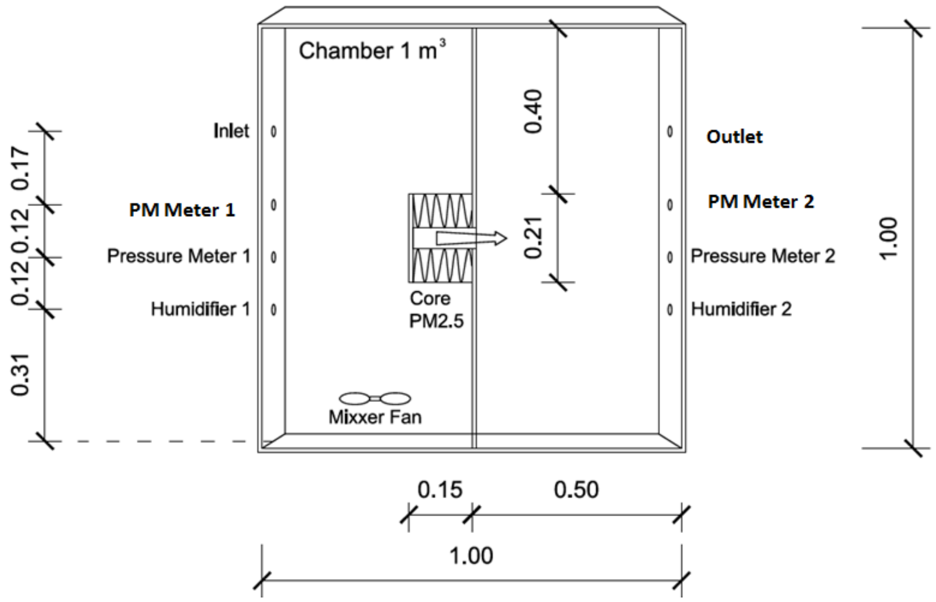

Figure 3-3 The experimental box for fabric filter test

For fabric filter test in the 1 m^3 enclosed box in **Figure 3-3**, wooden boards with waterproof painting were chosen to be the main construction material. Then pleated fabric filter core was installed in the middle of box. The main inlet flow in this experiment was sourced by body spray with controllable speed fan. After the system getting steady state, the ambient temperature, relative humidity and inlet air speed were monitored at both inlet and outlet of system.

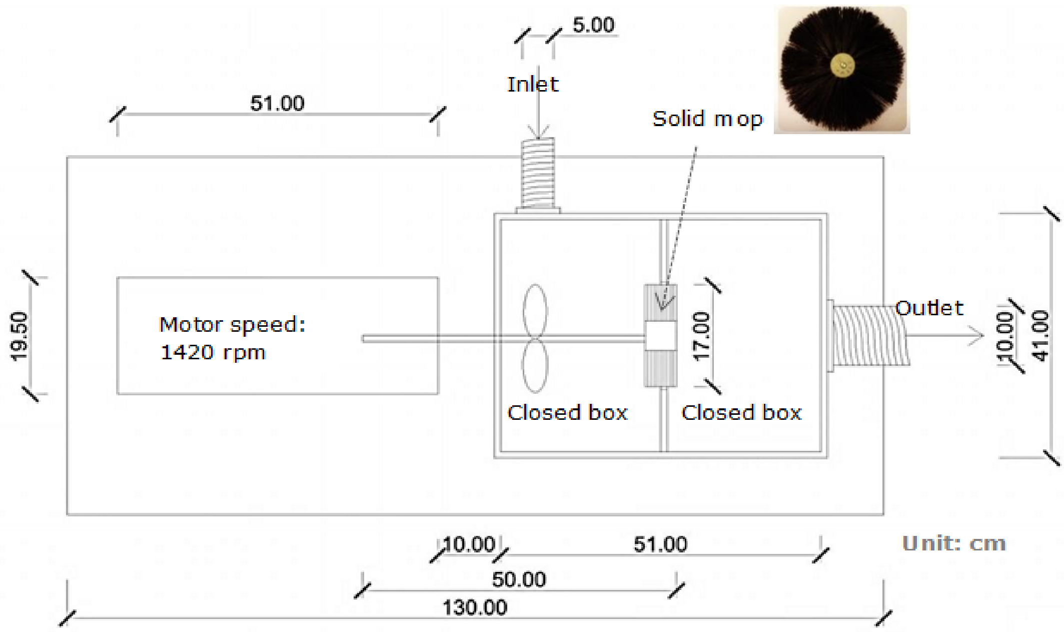

Figure 3-4 The experimental box for fibre mop tests

In the experiment of fibre mop testing, the dimensions of plastic box were width 41 cm, length 51 cm and height 45 cm as shown in **Figure 3-4** and the box location was in laboratory in Nottingham University. Then solid fibre mop would be connected directly to motor with main metal core diameter 8 mm. Even though the maximum ability of rotation in this motor was 1420 rpm (rotations per minute), this experiment was set rotation at 340 rpm that was fast enough to evaluate dust cleaning efficiency (Riffat & Ma 2012). Then three types of mop would be swop to install in the same core with fan blade and motor controlled speed and rotating direction. To increase air cleaning performance for solid mop, water spraying set was installed to increase relative humidity and helped novel mop to clean particulate matter. The equipment would be reused in every experiment. So the next session will identify all equipment was be used in this research.

3.2 Equipment

According to the same type of environmental data, it was possible to used repeatedly monitoring meters which were beneficial to comparison and expertise of equipment use. This section identifies all used equipment and calibrating method.

3.2.1 Types of equipment

To carry out all experiments, devices shows in **Table 3-1** are installed to monitor air particle, relative humidity, temperature and pressure. Firstly, the DPM-4000™ Real-time Personal Diesel Particulate Monitor and the DustTrak™ DRX Aerosol Monitor 8533 were dust meters used to collect PM2.5 and PM10 in UK and China laboratory tests. Secondly, pressure meter series Digitron 2000 Series Pressure Meters Manometers was used to measure pressure in laboratory boxes. Thirdly, Anemometer (Hot wire anemometer AVM 714) was placed in the same place with pressure meter in order to monitor air speed and calculate flow rate later. Moreover, two humidity probes were link to data logger in order to monitor relative humidity and temperature.

This Haz-Dust Real-Time Diesel Particulate Monitor Model DPM-4000 is a complete and personal portable package to measure air contaminants in breathing zone and then to report comprehensive graph. DPM-4000 can store airborne concentration in micrograms per cubic meter ($\mu g/m^3$). The display can report statistical data in terms of Total Weighted Average (TWA), short-term exposure limit (STEL), Max, and Minimum and also show adjustable alarm for data collection. The main systems of the DPM-4000 Diesel Particulate Monitoring kit comprised of GS-1 Respirable Cyclone and one 37mm sampling cassette preloaded with quartz filter. The filter cassette can be used for carbon collection based on NIOSH analyzing method 5040 and Valuable Survey Tool for MSHA& NIOSH Compliance Program. The specification of particulate matter size ranged between 1 and 10 µm with precision at +/-2 $\mu g/m^3$ in the range of flow rate 1.0 – 3.3 liters/minute. The enhanced accuracy of meter is +/- 10% to filter gravimetric SAE fine test dust with calibrating to NIOSH gravimetric reference NIST traceable.

Another real-time dust meter in this research is the DustTrak™ DRX Aerosol Monitor 8533 used for real-time dust monitoring in Shanghai experiments. This DustTrak DRX monitor is suitable for indoor workplaces monitoring such as offices, industrial workplaces and dormitory rooms. The main function of DustTrak monitor is for measuring several types of aerosol pollutants such as PM_1, $PM_{2.5}$, Respirable dust, PM_{10} and Total PM size fractions by 37-mm cassette with mesh filter. For reliable results, the meter is automatically zeroed by zero filter and compared with gravimetric analysis certificate. Collectible aerosol concentration ranged between 0.001 and 150 mg/m^3 with analog outputs and STEL alarm feature.

Turning to pressure meter, the 2000 series can measure air pressure range between 25m bar and 10 bar with waterproof standard (IP67 BSI Cert 229/000132) protection case. The operating ambient temperature ranged from 0 °C to +50 °C and instrument accuracies ranged from -10 °C to +50 °C.

For air velocity, Hot Wire Anemometer AVM-714 can monitor air velocity ranging 0.2-20.0 m/s with 0.1m/s reading resolution. The operating temperature ranged from 0 to 50 °C (32 °F to 122 °F) and the operating humidity is less than 80% RH by custom one-chip of microprocessor LSi Circuit. The basic accuracies of anemometer are +/- 3%+1 digit in air velocity and +/-0.8 °C +/-1.5 °F in temperature.

Table 3-1 Equipment for PM2.5 experiments

Meter model	Picture
1.Dust meter DPM-4000^{TM} Real-time Personal Diesel Particulate Monitor	
DustTrak™ DRX Aerosol Monitor 8533	
2.Pressure meter Digitron 2000 Series Pressure Meters Manometers	
3.Anemometer Hot wire anemometer AVM 714	
4.Humidity probes HMP45A Humidity and temperature probes	
5.Data logger Data Taker DT85 Data Logger	

To monitor air humidity and air temperature in laboratory, the dataTaker DT85 is used with 32 isolated channels and 48 common analog inputs for all combination of several probes. The accuracy of DC Resistance output is 0.1% in temperature ranged 5°C to 40 °C and 0.25% in temperature ranged -45°C to 70 °C. According to analog sensors of temperature and humidity, the dataTaker DT85 can be connected to the RTDs with Pt, Ni and Cu materials with resistance ranged 10Ω to 10KΩ. HMP45A humidity probe consisted of humidity sensor (HUMICAP©180) and temperature sensor (Pt 100 IEC 751, 1/3 Class B). HMP45A probe can measure relative humidity ranging from 0.8 to 100% RH with accuracy ±1% RH at 20 °C and stability <1% RH/year. In the same probe, temperature can be measured in range -39.2 °C to 60 °C with accuracy ±0.2 °C at 20 °C. All main instruments are demonstrated in **Table 3-1** to inform pictures and meter models in this study.

3.2.2 Instrument data comparisons

The data comparison of equipment could avoid the error data of monitoring results. In this study, the comparisons have done in laboratory in Nottingham and Shanghai. To compare 2 pressure meters, one used in experiment and another same model pressure meter from instrument laboratory storage was selected to compare data. Air pressure at around 500 pascals was prepared by high speed fan and then would be decreased gradually until closing the fan. The different values of pressure would edit the accuracy of this test by adding or minus extra values.

Another TSI dust meter was compared to using Hazdous meter and consequent results were adjusted to realistic results. Dust meters were compared in the high value of particle concentration at around 10.00 mg/m^3 before concentration value decreases to 0.10 mg/m^3. The multi-function of humidity probe, air temperature and relative humidity were separated to 2 times of comparison. For temperature testing, 2 probes were put near a heater with temperature's around 50 ℃ before moving them together out to room temperature place and occasionally to the iced box by the temperature at around 2-5 ℃. To accurate humidity, water spray could generate the high relative humidity at approximately 85-90% in an enclosed box, and then blow dryer would use to decrease the humidity to nearly 15-20%. So 2 probes of humidity meter were accurately proved in varied condition and the different values improved the accuracy of result. Last but not least, anemometers were compared by high speed fan at the speed around 7.00-8.00 m/s before decreasing slowly to 3.00 m/s and finally to 0.00 m/s. Then the different value of air flow would be average and adapt the real values from this experiment.

Table 3-2 Adjusted value of all experimental probes after comparisons

Meters		Adjusted value	Unit
Dust	1-DPM	0.10	μg/m^3
	2-DRX	-0.10	μg/m^3
Pressure	1	15	Pa
	2-other	-15	Pa
Anemometer	1	0.10	m/s
	2-other	-0.10	m/s
Relative humidity	1	-0.22	%
	2	0.22	%
Temperature	1	0.09	°C
	2	-0.09	°C

Two humidity proves were used to collect relative humidity and temperature in many experiments in this study. To avoid error from data collection, data collections were edited as in **Table 3-2**. In testing box, spraying water was used to increase air humidity then dry the air by fan. As a result, relative humidity data from humidity probe 1 and 2 could be adjusted by -0.22 and +0.22 respectively. As same as temperature, the temperature degree from probe 1 and 2 would be adapted orderly by +0.09 and -0.09.

In brief, this section referred the instruments and the comparison of each instrument in order to achieve more accuracy of the result. The next section, experimental process will be clarified step by step in order to collect dependent result.

3.3 Data collection

3.3.1 Quality assurance/quality control procedures

For quality assurance, the method of data collections should meet quality standard for air filter test, whereas quality control was focused on the accuracy and reproducibility of result as well as consistency of involving techniques. In case of the Automatic Urban and Rural Network (AURN), all PM2.5 measurements follow procedure of validation and ratification. QA/QC checklists of AURN data consisted of data representative, sufficient accuracy of monitoring, comparable results, consistent time and the error lower than 10% of all year collection (Air Quality Expert Group 2012). So QA/QC procedures are based on sampling protocols, equipment preparation, sample containers and documentations. For sampling protocols, the experiments are designed for appropriate filter evaluation and particulate matter collections included environmental data. Then the equipment is concerned in terms of suitable model or meter, cleanness, comparison, up to date maintenance and consistent data collection.

The efficiency of filtration is normally assessed based on filter purpose and airborne types (Brown 1993). For airborne particle, the captured air pollutant can be measured as quantity and can be identified chemicals; however, this is dependent on equipment to monitor or collect air particle. In this study, dust meter could track the dust quantity in the air as a measured quantity per air volume without identifying chemical of air pollutants. The quantity of airborne collection can indicate filtration performance in terms of filtrated efficiency analysis.

In case of manufacturing process, filtrated materials could be considered in terms of material recovery, easy cleaning surface and depth of filter. In case of depth filter or filtrate cake, it is possibly used for cleaning very small air contaminants and gaseous pollutants. The evaluation of filtrate cake efficiency can be demonstrated in penetration analysis. The first two considerations on recovering and surface cleaning purposes are more popular for air particle filtration. So this study evaluates system performance as an efficiency of air particle filtration; while filter elements are basically informed for physical explanations.

In this study, for experimental box experiment, system flow was monitoring flowing direction, speed and pressure of inlet and outlet air. Also fabric filter and solid mop were always cleaned before testing. It is noted that the viscosity can affect pressure drop in case of different volume between in and out flowing air and different height of openings. However, it does not respond to penetration in case of filtration test (Payet et al. 1992).

3.3.2 Validation

In filter performance test, experimental validation is normally concerned in terms of the most popular element used in previous tests. For liquid aerosol size 0.1-0.3 μm, dioctyl phthalate (DOP) has been used to integrity test in filter element resistant to oil or oil proof. However, according to possible health hazards, pure corn oil is allowed to be used instead. Usually, most 70% of aerosol is less than 0.3 μm from the total aerosol sized 0.05-0.3 μm (Sparks & Chase 2013). In case of nonresistant to oil filter, Sodium Chloride (NaCl) has been used as initial aerosol based on filter test requirements (42 CFR Part 84) of National Institute for Occupational Safety and Health (NIOSH) in 1996. So, to evaluate filter in this study, body spray is used to represent air PM2.5, while Sodium Chloride (NaCl) is used to represent PM10.

For the purpose of validation in this study, the accuracy is proved by reference comparison and precision of data collection is assured by more than 2 times repeatable experiments. Then the results are represented based on linear statistical analysis. The result of validation will be elucidated in the part of discussion.

3.4 Results

3.4.1 Data analysis

In case of real-time monitoring, the results were plotted in 24-hour period and the trend line could be demonstrated with regression analysis. Then 24-hr mean data is compared to international standards in case of real time monitoring in Shanghai, China. Also geological factors are provided in terms of air temperature and air humidity. Turning to laboratory test, the time periods of tests are dependent on steady state of data collections. Temperature, air humidity and pressure are monitored for conditional identifications. Then data is collected and calculated the air cleaning efficiency to compare with the international standards of air filter.

3.4.2 Comparison

The comparisons in this study can be separated into standard and other research comparisons. Based on quality assurance (QA)/quality control (QC) method and data collection, 24-hr results are compared to international standards to identify air dust concentration problem. Also the quality of air after pass through filter is compared to international standards to calculate filter performance. Then, in terms of filter evaluation, the performances of air filters are ranked by international air filter standards. The international standards will be demonstrated in the next topic for air quality and filter rank.

For quality control, the results are compared with other studies. To assure the accuracy of data collection, digit results are confirmed with other research and identified the error problems of experiments. Also instrument failures are investigated the influent effects of experimental results.

3.5 The standards of indoor air quality

Air quality standard can inform the performance of filter how well it cleans each type of air pollutant. NIOSH categorizes air pollutants into nine classes and also categorizes air filter resistances into three efficient degradations (NIOSH 1996). This standard separates air contaminants and air filter based on manufacturing process. For other purposes, such as human health, air quality standard can depend on NAAQS and WHO standards. As the purpose of air controlling systems, ASHREA standards can be used for building occupants comfort perception. For environmental concern, EPA standard is the main air quality standard. Lastly, British Standard (BS EN), NAAQS and ASHRAE can be various indicators of filters performance depending on functional purpose.

3.5.1 Types of air quality standards

As the pollutants monitoring in naturally ventilated room, NAAQS is used to be a criteria of 24-hr PM2.5 and PM10 average concentration. If exceeding NAAQS criteria, the strategy of controlling indoor air quality in classroom building was suggested to be a current consideration (Chithra & Shiva Nagendra 2012). Another HVAC system studies in 2 different scenarios, the optimized result depended on an objective of air control. Higher ventilation at 6 ACH was the solution for reducing influenza infection, while lower ventilation at 1-3 ACH was more effective for energy efficiency. However, to reach the optimization of indoor air control, holistic integrated techniques should be considered together in terms of Automated Clearing House (ACH), human comfort, infection risk and energy consumption. In addition, the hybrid Diver Propulsion Vehicle (DPV) for reducing infection risk objective was summarily to be more optimized method than Motor Vehicle (MV) (Pantelic, Raphael & Tham 2012). Turning to passive system, according to severe acute respiratory syndrome (SARS) in 2003, Air Ventilation Assessment (AVA) has been a guideline for building ventilation system design in urban area in Hong Kong (Ng 2009). Also natural ventilation rate was proved to reduce airborne diseases in hospitals in Hong Kong. As providing 69.0 air changes per hour (ACH), natural air flow shows possibility to decrease air cross-infective disease (Qian et al. 2010). From the reason that the level of air bioaerosol and VOCs could possibly be related to level of air PM2.5 and PM10 formation process, the minimum air change rate used in this research laboratory test is limited no lower than 1 ACH in laboratory box.

To consider heating ventilation and air conditioning (HVAC) systems, American Society of Heating Refrigeration and Air Condition Engineers (ASHRAE) Standard 62.1-2004 have launched international criteria of indoor air quality. As ASTM D6245 model in ASHRAE Standard, CO_2 level in classroom were elevated to exceed 2000 ppm depended on users, but average value should be 1100 ppm. Moreover, total volatile organic compounds (TVOC) and particulate matter were too low to be clearly detected, but new finishes and furniture had low VOCs emission particular in wall, carpet, finishing material (Morse et al. 2009). Following ASHREA Standard 62.1 and 62 comparisons, CO_2 concentration must be controlled by ventilation as same rate. But it is different in terms of ventilation rate control strategies as those strategies from ASHRAE 62 achieving more effectively to save energy than those from ASHREA 62.1 version (Ng et al. 2011). However, this international standard has a somewhat limitation on natural ventilation building evaluation.

Focusing on VOCs, as the study of indoor air quality in Thailand, air samples were collected on Tenex-TA sorbent tube and analyzed by thermal desorption-gas chromatography/mass spectrometry (TDeGC/MS). It was investigated that VOCs concentration changed significantly especially in toluene and limonene with average value at 110 and 60.5 mgm^{-3} respectively. However, the principal of VOCs analysis should be included 13 VOCs emission (Ongwandee et al. 2011). Additionally, as VOCs releasing probably from building paint, the Early Warning Organic (EWO) and the Resin Mastic coated Piezo electric Quartz Crystls (RM-PQC) have been the criteria of indoor air quality by using Ventilation rates (Air change rates) and concentration of VOCs monitoring. It was found that environmental damage functions for paintings related to the level of organic acids (Grøntoft et al. 2010).

For the filter testing and certification, National Institute for Occupational Safety and Health (NIOSH 1996) has launched regulations at 30 CFR Part 11 (30 CFR 11) and then has reformed them to 42 CFR Part 84 (42 CFR 84). These rules aim to authorize and standardize respirators testing and certification. Based on nine classifications of air cleaning filters, indicators refer mainly to three level of minimum efficiency and three types of aerosols characteristics as showed in **Table 3-3**.

Table 3-3 Filter classification under 42 CFR 84 (NIOSH 1996)

Minimum Efficiency	Aerosol Test		
	NaCl Non-Oil Aerosols*	DOP Includes Oil Aerosols*	DOP Includes Oil Aerosols
95%	N95	R95	P95
99%	N99	R99	P99
99.97%	N100	R100	P100

*May have time use restriction on this filter series

According to **Table 3-3**, test requirement of N-, R- and P-series degradations are relied on sodium chloride (NaCl), full oily element and dioctylphthalate (DOP). For N series with maximum testing dust concentration at 200 mg per respirator, it is important to use sodium chloride (NaCl) rather than dioctylphthalate (DOP) because of oil resistance. Then, as a mentioning minimum efficiency, the performance of filters must be not less than their efficiency percentages in the table. Also the environmental conditions of monitoring test shall be set to 85 ± 5% relative humidity at temperature 38 ± 2.5°C in the period of 25 ± 1hours. For R- and P-series, the initial substances are changed to be dioctylphthalate (DOP) with the same control environment especially relative humidity possibly has a severe effect on filter performances. To be noted, even 30 CFR 11 required inhalation resistance test but there is no requirement of airflow resistance test in the 42 CFR 84. Because filter test is not for filter at worksite, so inhalation test requirements are deleted from the early version (NIOSH 1996).

Table 3-4 National regulations, limits and requirements on indoor air quality (Max limits)

National organization/Country	Time (in hour)	PM_{10} (in μg/m^3)	$PM_{2.5}$ (in μg/m^3)
WHO	24	50[d]	25[d]
NAAQS	24	150[c]	35[c]
England	24	50[f]	25[f]
Hong Kong	24	180[a]	75[e]
Thailand	24	120[b]	50[b]

[a](Černecký et al. 2015)
[b](PCD 2016)
[c](EPA 1990)
[d](WHO 2016)
[e](CAN 2013)
[f](Environmental Protection 2010)

Table 3-5 The standard of Particulate Matter (EPA 1990, updated on Dec 14, 2012)

Pollutant		Primary/ Secondary	Averaging Time	Level ($\mu g/m^3$)	Form
Particle Pollution (Updated on Dec 14, 2012)	$PM_{2.5}$	primary	Annual	12	annual mean, averaged over 3 years
		secondary	Annual	15	
		primary and secondary	24-hour	**35**	98th percentile, averaged over 3 years
	PM_{10}	primary and secondary	24-hour	**150**	Not to be exceeded more than once per year on average over 3 years

However, international standards somehow are very high quality for Asian air quality especially in industrial areas. Even several local Asian air standards are relied on international standards, but local bench marks are always higher than developing countries standards. In this study, 24-hr standards both for international and local areas are identified for PM2.5 and PM10 as shown in **Table 3-4**. For the reason of comparison in Southeast Asia, NAAQs based on EPA is the main standard for identifying the problem of air pollution. So, in this study, NAAQs standard in **Table 3-5** is used for comparison and discussion. This is related to air filter standards based on EPA air filter rank later.

3.5.2 Filter efficiency indicators

According to MERV ranking in chapter 3, PM2.5 and PM10 can be gathered into E2 and E3 groups respectively. So the air cleaning efficiency would be calculated differently by **Equation 3-1 and 3-2** depending on type of pollutant (Doty & Turner 2013). For PM2.5 cleaning, E2, air cleaning efficiency calculation in **Equation 3-1** would be the main process. Nevertheless, in terms of E3 or PM10 concerning, dust arrestance would be calculated as same as **Equation 3-2**.

$$\mu_e = n_t / n_u = (n_u - n_d) / n_u \qquad \textbf{Equation 3-1}$$

where μ_e = *air filter efficiency*

n_t = *particles trapped*

n_u = *particles upstream*

n_d = *particles downstream*

$$\mu_a = 1 - C_a / C_b \qquad \textbf{Equation 3-2}$$

where μ_a = *dust arrestance*

C_a = *dust concentration after filter*

C_b = *dust concentration before filter*

For the purpose of investigating air cleaning performance, equipment and experimental box were set in order to collect dust concentration both inlet and outlet part of box. Then dust data from both inlet and outlet would be compared to NAAQs depended on type of dust. However, the condition of spraying water would be considered as a main factor of air cleaning performance and concluded to be a notification of mop adaptation in general purifiers. For the estimation of air cleaning efficiency, dust results would be calculated and compared to MERV level in **Table 3-6**, while the meanings of E1, E2 and E3 can be identified in **Table 3-7**. All of results and estimated data will be demonstrated in the discussion part.

Table 3-6 Minimum Efficiency Reporting Value (MERV) indicators (Doty & Turner 2013)

MERV	Composite Average Particle Size Efficiency, % in size range, μm				Average Arrestance,%
	HEPA	Range 1	Range 2	Range 3	
	0.12-0.5	0.3-1.0	1.0-3.0	3.0-10.0	
1	n/a	n/a	n/a	E_3<20	A_{avg}<65
2	n/a	n/a	n/a	E_3<20	65≤A_{avg}<70
3	n/a	n/a	n/a	E_3<20	70≤A_{avg}<75
4	n/a	n/a	n/a	E_3<20	75≤A_{avg}
5	n/a	n/a	n/a	20≤E_3<35	n/a
6	n/a	n/a	n/a	35≤E_3<50	n/a
7	n/a	n/a	n/a	50≤E_3<70	n/a
8	n/a	n/a	n/a	70≤E_3	n/a
9	n/a	n/a	E_2<50	85≤E_3	n/a
10	n/a	n/a	50≤E_2<65	85≤E_3	n/a
11	n/a	n/a	65≤E_2<80	85≤E_3	n/a
12	n/a	n/a	80≤E_2	90≤E_3	n/a
13	n/a	E_1<75	90≤E_2	90≤E_3	n/a
14	n/a	75≤E_1<85	90≤E_2	90≤E_3	n/a
15	n/a	85≤E_1<95	90≤E_2	90≤E_3	n/a
16	n/a	95≤E_1	95≤E_2	95≤E_3	n/a
17	SULPA>99.999 (PM size 0.1-0.2 μm, ceiling panel media)				n/a
18	ULPA>99.999 (PM size 0.3 μm, ceiling panel media)				n/a
19	HEPA>99.99 (PM size 0.3 μm, ceiling panel media)				n/a
20	HEPA>99.97 (PM size 0.3 μm, box media)				n/a

Table 3-7 Application guidelines for various types of MERV (2012. ASHRAE handbook)

Rank	MERV	Contaminant examples	Types of Application
E3	1-4	blowable large particle	manufacturing air environment
	5-8	pollens, mould, spores, cement element	HVAC device filters, pre-filter of HEPA, Electrical protection
E2	9-12	flour, coal dust, some bacteria, grinding dust, *Legionella*, combustion dust	pre-filter of HEPA, schools, clean residential buildings, general clean industrial and commercial spaces, food production space
E1	13-16	bacteria, powder, paint pigment, some virus, fumes, droplet nuclei	hospital surgery area, smoking area, clean commercial buildings
HEPA	17-20	virus, carbon element, salt, combustion smoke	clean room, orthopaedic surgery, carcinogenic element, pharmaceutical manufactories

In this section, purifier's arrestance calculation in ANSI/ASHRAE standard in 2012 will be base of efficiency finding in every chapter. However, the arrestance will be following Minimum Efficiency Reporting Value (MERV) based on particle size and air hygiene level requirement. As particular matter study, the scope of research will be limited to cover PM2.5 and PM10 which are found to be main contaminants in general air. Therefore, it is possible to categorize PM2.5 in the range E2, MERV 9-12 and PM10 in the range E3, MERV 5-8 for efficiency analysis.

To compare other standards, air purifiers can be exemplified as the classification of BS EN 799:2012 in **Table 3-8**. In this British standard, it is important to monitor pressure in purifier systems to assure the flow direction and sufficient flow driving force to clean air pollutant. Then the average of arrestance (A_m) and efficiency (E_m) are mainly considered to classify filter into G, M and F groups. Then, in case of fine particle, filters performances are concerned the minimum efficiency correlating to the average efficiency (%) of particle size 0.4 μm.

Table 3-8 Air filters classification in BS EN 799:2012 (British Standards Institution 2012)

Group	Class	Pressure drop (Pa)	Avg. arrestance (A_m) of synthetic dust (%)	Avg. efficiency (E_m) of 0.4 μm particles (%)	Min. efficiency of 0.4 μm particles (%)
Coarse filter	G1	250	$50 \le A_m < 65$	-	-
	G2	250	$65 \le A_m < 80$	-	-
	G3	250	$80 \le A_m < 90$	-	-
	G4	250	$90 \le A_m$	-	-
Medium filter	M5	450	-	$40 \le E_m < 60$	-
	M6	450	-	$60 \le E_m < 80$	-
Fine filter	F7	450	-	$80 \le E_m < 90$	35
	F8	450	-	$90 \le E_m < 95$	55
	F9	450	-	$95 \le E_m$	70

*Under airflow 0.944 m^3/s

According to the air quality standard of Britain in **Table 3-4**, the air standard is very high quality for industrial area in Southeast Asia. So the evaluation of filter performance in **Table 3-8** is quite too high quality to indicate filter performance in this study. Then MERV classifications in NAAQs standard are the main indicator used in this comparison of all results.

3.6 Identification of experimental errors

The errors of experiment can occur in different reasons in particular real time monitoring in in-used room, changing activities of users and instruments failure. Therefore the error of data collection has been identified the reason and the effects on results.

3.6.1 Data quality elucidation

In case of real-time monitoring, the error problems can occur related to users' activities such as body movements, door/window openings and daily chemicals use. It is no denying that these activities affect directly to airflow and dust concentration in single unit. Therefore, the dust concentrations cannot be expected for real time monitoring at fixed conditions. However these problems of real time dust concentration change are always happened in semi-free ventilation in hot and humid climate as well as local houses in urban area.

3.6.2 Instrument accuracy

Based on the example annual data collection, the symptoms of instrument error can occur in case of unrelated data, unexpected increasing data, sudden downward change of volatile concentration and poor comparison with other co-location (Air Quality Expert Group 2012). For the long term monitoring, it can be seen that instrument error is a big effect on experimental process and data collection.

Turning to real time monitoring in shorter period, 24-hr period of monitoring in Shanghai showed some problem of data logger such as losing some data. This is because of unstable electricity support in Shanghai. So the data logger, which collected every 10 minutes in 24-hr period, can lose some data. The solution of this problem is manual data collection at the same time by another portable instrument. This can support the reliability of data by comparison data. For avoiding the possible new error of comparative instrument, the discussion of data collection errors and limitations have been done with previous users.

For laboratory test, the error from instrument is less because the short time monitoring. So the risk of data loss rarely happened in filter performance tests. Even it is possible to miss some data, it is easy to redo the experiment in the short period. However the experimental error happened in case of laboratory weather conditions. Due to outdoor supply air of testing box, it is possible that the temperature and air humidity change in the different season can affect the performance of air filter. Also this affects occasionally the comparison of results from different geological factors. From this problem the statistical analysis is used to assess and identify the relationship of dust concentration and geological factors. The effects of all error problems in real time experiment and laboratory test are examined in the discussion part to identify the reason of problems.

3.7 Summary

In conclusion, based on main research field, there are two types of experiments which one is real-time monitoring in order to identify dust situation in Shanghai, China and is laboratory tests to investigate filter performances in Nottingham, United Kingdom. The main instruments for particulate matter size 2.5 μm monitoring consisted of dust meter, anemometer, pressure meter, air temperature and humidity probes. The data logger is used to collect relative humidity and air temperature from humidity probes in laboratory in UK.

Comparisons of instruments were done in preliminary test, but only dust meter was compared to TSI model of dust meter in Shanghai, China.

To collect data, the quality assurance/quality control procedure was concerned throughout the experimental process. Several meters in this study would be assured that was suitable for air PM2.5, temperature, relative humidity and pressure collections. Then all instruments had to be compared and assured the consistence of experiment. According to the validation, sodium chloride (NaCl) is used to represent PM10 rather than DOP for safety purpose; while body spray is used to be the initial source of PM2.5. Then experimental results can be repeated and compared to other research.

For the reliability of results, statistic method is used for analyzing both laboratory data and real time data. Also multiple linear regressions are used to identify the significance of correlations between dust concentration and geological factors. Then the average of whole period data is compared to international standards. The air cleaning performances of filter systems are calculated and ranked by MERV classification from NAAQs standard. Lastly, the errors of experiment are identified the reason from collective method or from instrument. Unexpected errors are identified the reasons of problem in discussion part.

The next chapter will examine preliminary tests of fabric filter performance in laboratory. Full experimental box sets are demonstrated with fixing and movable instruments. The results are compared the efficiency of air filters and are calculated in order to rank filter performance into MERV. Then, chapter 5 will examine the details of instruments setting in real locations in Shanghai, China and the results of real-time experiment will be analyzed and discussed at the end of chapter. Most of instrument used in laboratory is used again in real-time monitoring for evaluating innovative purifiers. Also the air cleaning results of laboratory tests can identify the best solutions of fabric filter and solid fibre mop for developing innovative light lamp purifiers in real-time test. To be noted, the methodology and instruments of photocatalytic experiments will be separately clarified in chapter 7 with the process of lamp design.

Chapter 4: Preliminary studies of PM2.5 purifier filter

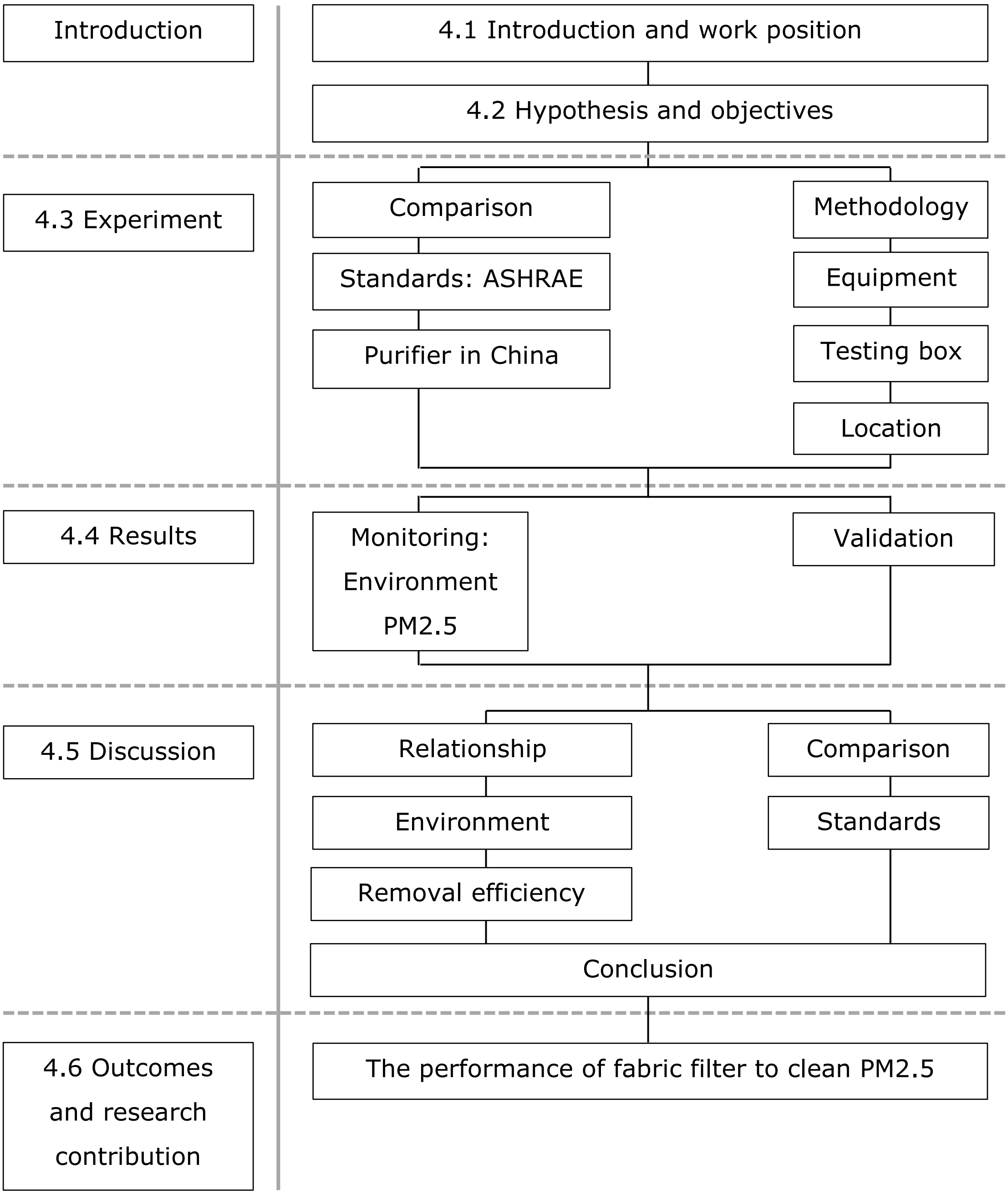

Figure 4-1 The diagram of chapter 4 issues

4.1 Introduction and work position

One of the most significant processes of this study is pre-study of experiment that could be based for all experiments. This study firstly aims to investigate the performance of fabric filter for air purification and the relationship between Indoor Air Quality (IAQ) and relative humidity (Rh) and temperature. To prepare further experiments for air pollution evaluation, experimental equipment, testing process and experimental control would be clarified from literature reviews and pre-study of experiment.

Indoor air pollutants can be analysed by various systematic methods and one of favorite algorithm is size separation. Size selection can group air contaminants into five groups depended on the depth of respiratory breath for example Particulate Matter sized 10 micron (PM10 or fine dust), 2.5 micron (PM2.5 or respiratory dust), bio aerosol, gaseous chemicals and Volatile Organic Compounds (VOCs) (Wongwatcharapaiboon, Gan & Riffat 2013). In this chapter, PM2.5 is considered to be the selective pollutant in order to evaluate fabric purifier for PM2.5. As particle absorbance, it is possible that PM10 monitoring can predict significantly PM2.5 concentration (Mues et al. 2012). So PM10 can be secondly concerned for double checking relationship of meteorological factors and PM concentration.

According to five types of pollutant, this chapter examines PM2.5 investigation correlated to meteorological factors and evaluates the performance of pleated fabric purifier. There are various meteorological factors that affect to indoor PM2.5 concentration for examples wind speed, pressure, air humidity and temperature. For the first factors, rising wind speed can increase fine dust concentration (Krasnov et al. 2015), but somehow wind speed and pressure were negatively related to PM1.0 (Jian et al. 2012). For the forecasting case of effect on PM2.5 in China, ambient gases respond mainly PM2.5 concentration, while humidity and pressure have more influent to PM2.5 than to wind speed and temperature (Qin et al. 2014). Even wind speed and pressure factors were proved as the main effects of indoor dust level; theirs would be controlled in this study.

In Beijing, the concentration of PM2.5 can be decreased in case of rising precipitation (Zhang et al. 2015b). That can be implied to the negative relationship of air humidity and PM2.5 concentration (Zhang, Ni & Ni 2015) as same as finding in Guangzhou (Zhang et al. 2015a). However, the relationship of Rh and ultrafine particle was found positive correlation in Hangzhou, china (Jian et al. 2012), but was insignificantly in Beijing and Shanghai (Zhang et al. 2015a). Thus it is possible that this relationship finding can be dependent on climate, exiting sources and monitoring equipment.

Another meteorological factor of dropping PM2.5 concentration is air temperature increase in Beijing and Hong Kong (Zhang, Ni & Ni 2015). This is similar to another research correlation that pointed the inverse trend between temperature and particle matter (Krasnov et al. 2015, Mue et al. 2012). Nevertheless, there is one argument that temperature can be positively correlated to ultrafine particle (Jian et al. 2012).

Idealistically, for the efficiency of photovoltaic household devices and occupants' comfort in hot and humid climate, it is normally better to increase wind speed in order to reduce temperature, relative humidity and PM concentration (Mekhilef, Saidur & Kamalisarvestani 2012). However, this ideal situation is dependent on day or night time, more specific climatic factors, sources of pollutants and other else. In this study, the correlation between meteorology and air purified efficiency was investigated.

As a preliminary experiment, the comparison of equipment was examined in methodology chapter and experiment was set in laboratory. Then the results would be assured reliability by statistic calculation and comparing to other research results at the end of this chapter. In the next step, hypothesis and objectives will be stated for this chapter experiment.

4.2 Hypothesis and objectives

Noted question of this experiment is whether PM2.5 core dust filter meet the standard of air filter performance or not, if not, how to improve this part of purifier device. Another causal hypothesis is whether particle concentration relates to meteorological factors or not, if so, what the direction of relationship. To carry on hypothesis, the objectives are notified as four following points.

- To monitor PM2.5 concentration, relative humidity and temperature at both inlet and outlet of experimental box.
- To evaluate PM2.5 fabric filter core in terms of cleaning efficiency compared to NAAQs and general air purifier performance in China.
- To investigate the relationship between meteorological factors and particulate matter concentration by statistical analysis.

- To examine statistical correlation between meteorological issues and the cleaning efficiency of PM2.5 fabric filter.

4.3 Experiment

Air quality has been one of the main global issues throughout this decade because their pre- and post-effects have directly influenced global environment and human health. According to previous environmental research, gaseous pollutants and large particulate matter are originated from engine combustion, wild fire and industrial processing can affect directly respiratory system. This experiment focuses on respiratory dust which can be breathed to minute tube in human lung. Following National Ambient Air Quality Standards (NAAQS), this type of particle in indoor air should not exceed 35 $\mu g/m^3$ (or 0.035 mg/m^3) over 24 hours (EPA 1990).

To purify respiratory dust in indoor condition, filter selection is based on air cleanliness requirement, size of indoor dust, dust concentration, air flow system and other location factors. So the range of purifier can vary from medium to high efficiency with typical techniques such as straining, inertial impingement, interception, diffusion and electronic effect (ASHRAE, 2012). To support those air cleaning techniques, filter medias are used to increase the potential of air cleaning. A selective media in this study is fabric filter that can be applied to various types of air purifiers.

Nevertheless, the standard of purifier device is more complicated by limiting level of PM concentration and calculating the ability of air cleaning in terms of efficiency. According to ASHRAE guideline equation, sizes of particle and types of spatial function have been specified with one of two equations for calculating efficiency. So next session will clarify two types of air cleaning ability calculations and will identify which one is suited for PM2.5 fabric filter evaluation.

For the estimation of PM refining ability, air filter efficiency and arrestance equations have been described the difference of solving mathematic models and variables. In case of air filter efficiency, the scope of particle size is stated on micro particles sized 0.30-10.00 micron (E1-E3), while arrestance calculation is suitable for large and massive particle sized greater than 3.00-10.00 micron (only E3). The equations of air filter efficiency and arrestance calculation are examined in **Equation 3-1** and **3-2** respectively (Doty & Turner 2013).

As respiratory dust concerning in this study, **Equation 3-1** solving air filter efficiency is appropriate for PM2.5 in E2 range, MERV 9-12. From this equation, the performance of PM2.5 dust filter is evaluated and compared to short-term NAAQS (24 hours). On behalf of subsequent section, methodology can verify monitoring PM2.5 concentration and relationship between meteorology and PM concentration.

As the mentioning of methodology in chapter 3, this pre-study chapter would carry on monitoring experiment and apply testing tools from that chapter. According to respiratory dust fabric filter, it is possible that filter porous can strain particulate matter which diameter's sized 1-5 µm and it may be used in pre-HEPA system. That results in higher pressure and velocity when it is used. However, the limitation of this study is difficult to control pressure in semi-natural condition box. Thus this experiment was set pressure and velocity to be dependent and controlling variables respectively. In this study, PM2.5 core with the dimension of 0.15 m height, 0.30 m width and 0.12 m depth was tested its efficiency in a semi-controlled testing box in natural ventilation room.

Table 4-1 Equipment for PM2.5 pre-testing experiment

No.	Types	Model	Position
1	Dust meter	DPM-4000^{TM} Real-time Personal Diesel Particulate Monitor	Inlet and outlet of experimental box
2	Pressure meter	Digitron 2000 Series Pressure Meters Manometers	Measuring the pressure between box inlet and outlet
3	Anemometer	Hot wire anemometer AVM 714	Inlet and outlet of experimental box
4	Data logger	Data Taker DT85 Data Logger	Connecting to Rh probes
5	Humidity and temperature probes	HMP45A Humidity and temperature probes	Connecting between Data logger and experimental box

To set the testing box, five instruments were located into chamber with different objectives. Firstly, DPM-4000^{TM} Real-time Personal Diesel Particulate Monitor was the dust meter which collected both inlet and outlet respiratory dust. Secondly, pressure meter series Digitron 2000 Series Pressure Meters Manometers was detected pressure to be dependent variable. Thirdly, Anemometer (Hot wire anemometer AVM 714) was stated in the same place with pressure meter in order to monitor controllable wind speed and calculate flow rate later. Another two equipment numbered 4-5 were link together in order to monitor relative humidity and temperature both outlet and inlet condition. These instruments are illustrated in above **Table 4-1**. In Chapter 3, the comparison of each instrument was assured in order to achieve more accuracy of results. The next section, experimental process will be clarified step by step in order to collect dependent result.

Turning to experimental box, in the 1 m^3 enclosed box, wooden boards with waterproof painting were chosen to be the main constructional materials and PM2.5 core filter was installed in the middle of box followed **Figure 3-3**. According to the main purpose of PM2.5 filter test, the main inlet flow in this experiment was sourced by particle diameter sized 1-5 μm or respiratory dust. In this case, body spray was used to be the source of inlet dust with controllable speed fan and the outlet vent was also prepared for testing the system pressure. By the way, before getting steady state, the ambient temperature, relative humidity and inlet air speed were monitored at both inlet and outlet of system in order to find out PM2.5 concentration.

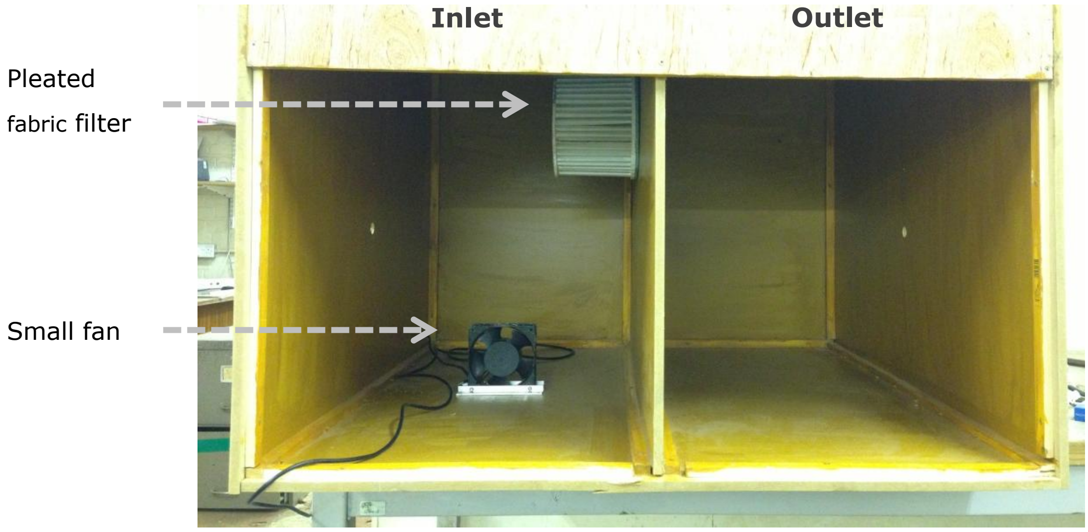

Figure 4-2 The half lower of experimental box before enclosed all surface by wood

From **Figures 4-2**, experimental box illustrates how to install testing equipment in the box. It can be seen that pleated fabric filter was located in the middle of box to cover the round cut of wooden broad and it was sealed by water proof silicone. At the bottom of box, small fan was putted into inlet part to increase flow pressure in the box system. To stimulate system air flow, it was important to assure that inlet part had adequate pressure. However, too high speed fan could bring about turbulent air flow in system. Thus, in this study, the specification of fan was SUNAN model DP200A (2123XSL.GN) with VAC 220-240, speed 2700/3100 RPM and air flow 95/115 CFM as showing in **Figure 4-3**.

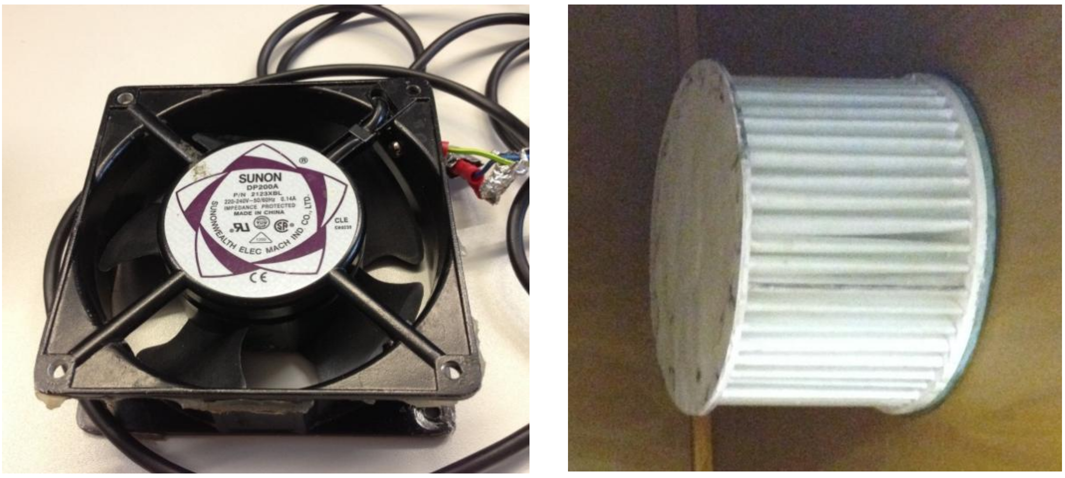

Figure 4-3 Mini fan and fabric filter in experimental box

For the purpose of validation, another air purified technique was assessed in Shanghai environment. To compare pleated fabric filter performance with general purifier in China, one low energy and sustainable product would be selectively recommended in this section in order to study its air purified performance. In hot and humid climate condition, the ability of reducing air temperature and humidity could be integrated in this purifier.

To develop air controlled system, dehumidifier is the main technology to increase systems efficiency in tropical climate. Therefore various types of dehumidifiers could be integrated to air cooling system for example low temperature regeneration desiccant wheel, desiccant fibre pipe and liquid desiccant module with membrane. As the first recommended system in this report, the liquid desiccant system is mainly explained to dehumidify and cool down indoor air. To begin with the system of air fluid, it is possible that treated air was from outdoor air or returned indoor air. Then treated air was forced to pass fibre membrane for dehumidifying and reducing temperature. Lastly, treated air was purified by adding fabric filter before it was drove to the room again by low energy fan.

After the explanation of all monitoring equipment, the next step will examine ambient environment inside the box and consequent results such as PM2.5

concentration, relative humidity and temperature. What's more, primary results will be calculated for air cleaning efficiency and analyzed their relationships at the end of this chapter.

4.4 Results

4.4.1 Geological conditions

As the controlled variables, velocity and pressure were set to be different condition of experiment. In high air flow condition, the test system was controlled air flow rate at 0.034 m^3/s (approximately 1.08 m/s at inlet) and different pressure at 502 pascals, while air flow and pressure in low pressure box were 0.012 m^3/s (approximately 0.38 m/s) and 205 pascals respectively. The pressure loss in the system may occur from the reason of interior materials and fabric filter friction. These 2 variables did not much fluctuate, so it was possible to read average value throughout an experimental period. Along with humidity probes, it is divided to be inlet and outlet part and each probe could monitor both ambient temperature and relative humidity. As monitoring environmental conditions of experimental box, **Figure 4-4** shows the range of temperature and humidity in the experiment throughout the 1.40-hour period. At the part of inlet, the temperature swung between 23.00 °C and 25.00 °C, while the relative humidity possibly fluctuated from 27% to 30%. Turning to exit area, the temperature decreased into the range of 22.00-24.00 °C, whereas relative humidity increased slightly to 29-32%. The lower outlet temperature occurs because heat loss for interior materials of box and fabric filter. To be noted, the trends of temperature both in and out part increase slightly and affect consequently in negative trend of relative humidity throughout experimental period.

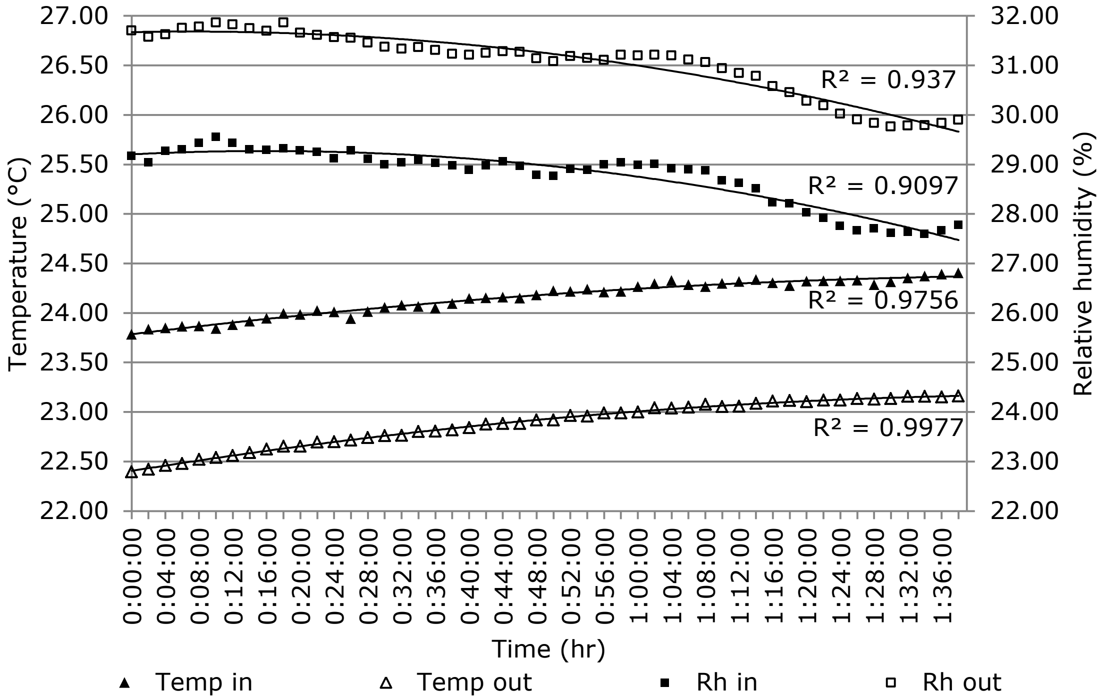

Figure 4-4 Ambient temperature and relative humidity inside experimental box

As focusing on the test condition, it is important to monitor temperature and relative humidity and also control flow rate and pressure in the testing box. This efficiency test was separated into 2 conditions those one which was low flow rate at approximately 0.012 m^3/s and another one got high flow rate at around 0.034 m^3/s. After testing system remained steady state in the first 1.30 minute, PM2.5 had been sprayed into the box inlet for 10 seconds. Then dust concentrations both inlet and outlet had been monitored until the system become steady state again. This process was also repeated the same way in the second condition but inlet air velocity differed from the first condition as higher air flow and different pressure. Then the results of dust concentration would be calculated the efficiency followed **Equation 3-1**.

4.4.2 Particle matter

The results of in and out dust concentrations are showed in **Figures 4-5** and **4-6** compared to NAAQS. In case of high flow rate as **Figure 4-5**, there is a significant difference between in and out dust concentration that inlet dust level is higher than those in outlet by nearly 0.04 mg/m^3. To compare with NAAQS at 0.035 mg/m^3, the dust level in existing room was exactly found higher than standard; while filtered dust concentration appeared lower than standard if no increasing in dusts spray. The results obtained from the preliminary analysis of in and out dust concentrations were calculated for cleaning efficiency concerning. It can be seen that the efficiency is approximately 60% in case of no extra dusts spray. In terms of high concentration of dust, PM2.5 dust was evenly distributed into inlet air during the 20-second period. Then filtered dust concentration rises instantly up to reach 0.62 mg/m^3 in 50 seconds after spraying before taking moderately off to normal level in 3 minutes later. Relative filter efficiency increases by approximately 40% before making a trough to 5% later, then it goes back to normal state.

Turning to another dust concerning point as shown in **Figure 4-6**, in case of low flow rate, line graph demonstrates the concentration of PM2.5 in the air before and after passed PM2.5 core. It can be seen that inlet dust concentration almost higher than outlet concentration throughout the period of 9 minutes and dust efficiency demonstrates the highest point of performance at the same with inlet dust concentration peak. But, to determine all of particle concentration, it can be seen that both inlet and outlet dust levels exceed EPA 24-hr standard at 0.035 mg/m^3.

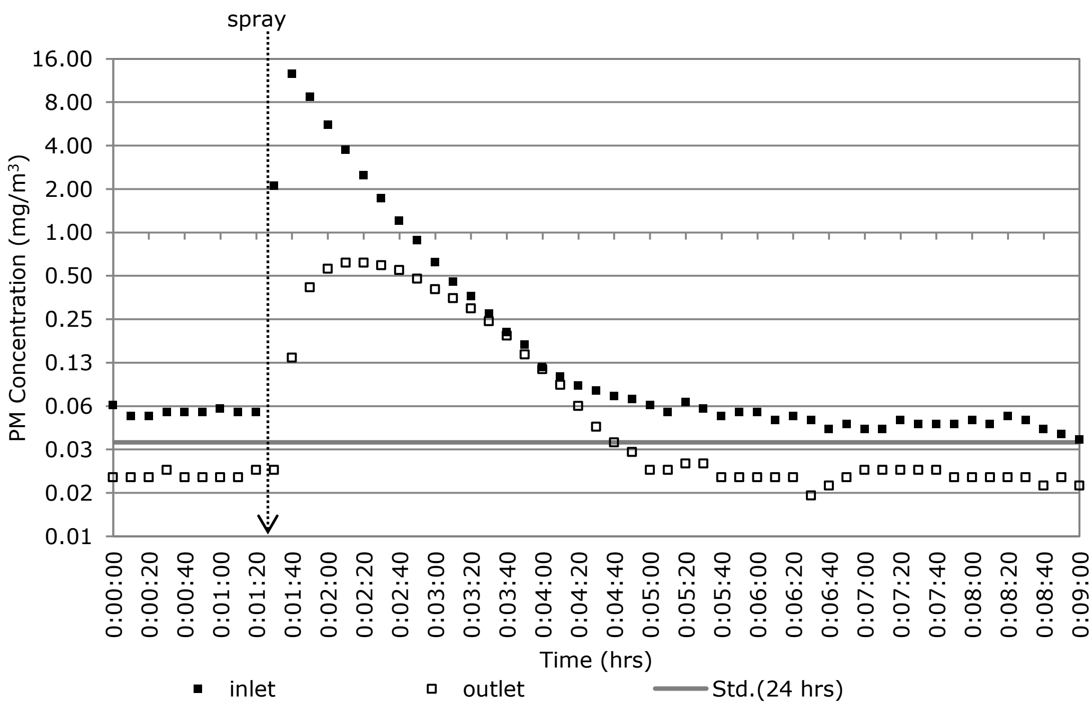

Figure 4-5 PM2.5 concentration from the experimental box in high flow rate condition (ρ= 0.034 m^3/s)

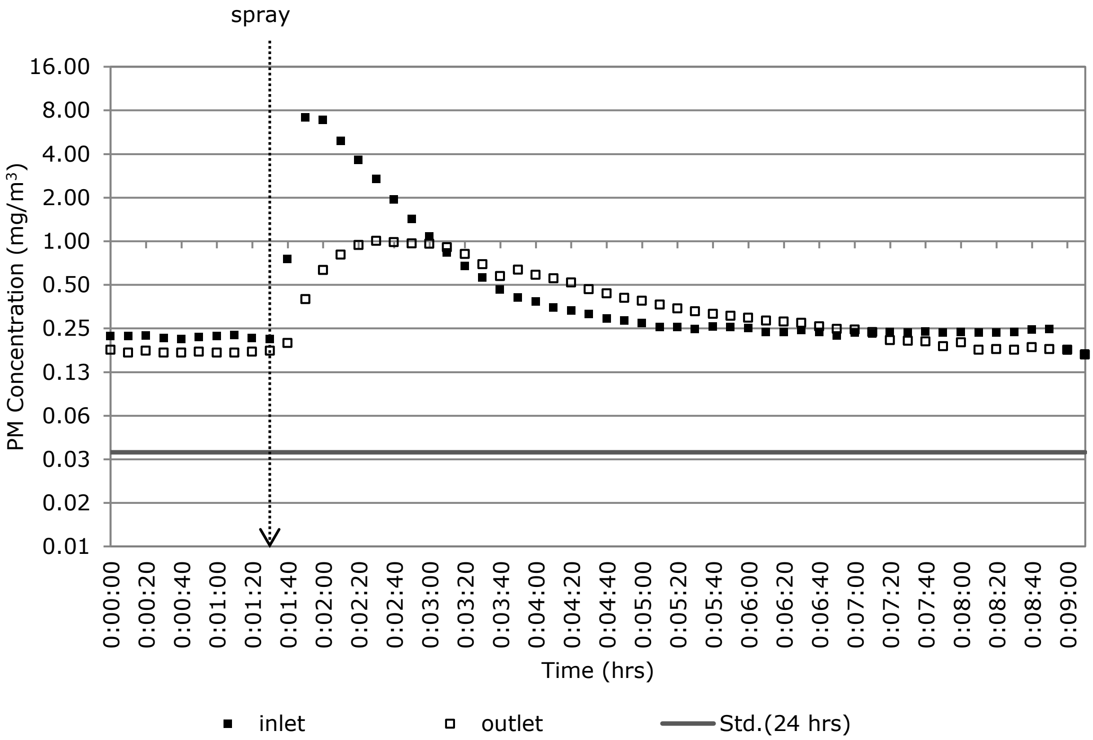

Figure 4-6 PM2.5 concentration from the experimental box in low flow rate condition (ρ= 0.012 m^3/s)

After spraying PM2.5 at 1.30 minutes, PM2.5 concentrations of inlet and outlet rocket from base by 7.00 mg/m^3 and 0.80 mg/m^3 respectively. Also the outlet dust concentration gets 40-second time lag to touch the peak after inlet dust reaching the peak at 1.50 minutes at 0.80 mg/m^3.

In the short period, dust level from inlet exceeds outlet dust level from 3.30 to 7.00 minutes that is possibly caused from the different density of inlet and outlet air mixtures. This is proved by the character of various pollutants removal in **Figure 4-7** that affects slope of curve and interval time of pollutant reduction (Popescu & Ionel 2010). Another possible reason of lower graph of inlet is air pressure factor affecting higher than material friction factor in inlet part in the 3-minute period. While outlet air pressure factor drops to lower than materials friction factor in the same period. So it is possible to imply that the lower density of outlet air mixture results in the slight slope of dust concentration reduction.

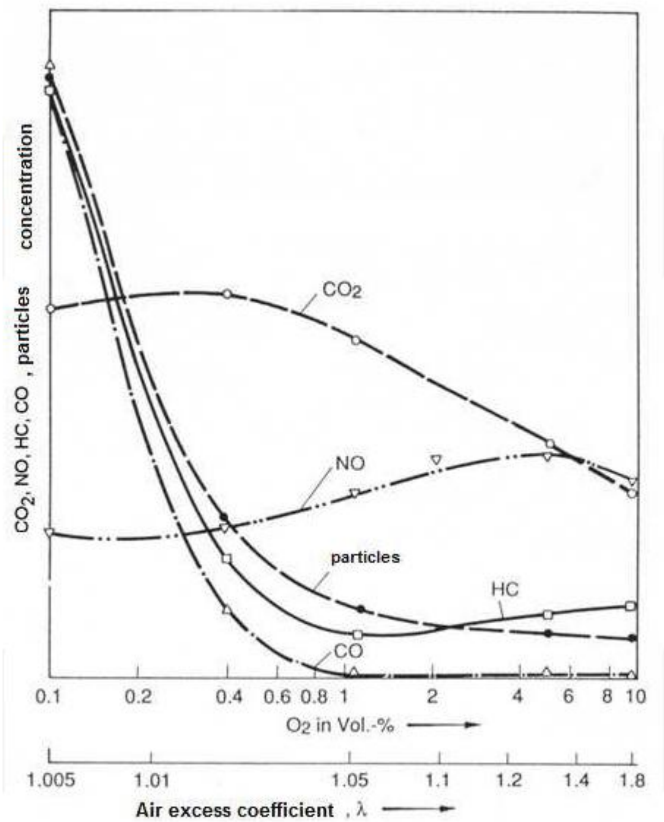

Figure 4-7 Dependency of some pollutants to air-fuel ration value inside the combustion chamber (Popescu & Ionel 2010)

According to above results, the most striking point to emerge from the data is that the level of dust efficiency in both high and low air flow can be ranked by MERV (ASHRAE 2012). This is important because these results after ranked by MERV can identify air cleaning performance of fabric filter for developing innovative light lamp purifier at the end of this research. However, there is one limitation of particle removal efficiency test about velocity that ASHRAE standard 52.2 notifies into 0.60-3.80 m/s. So, for low pressure condition, PM removal efficiency will be only comparative data and will not be used in further research.

4.4.3 The validation of fabric filter test

For the purpose of validation, inlet dust reduction was considered and compared to the system of liquid desiccant module for air purifier. The trend of dust removal is drop from very high level of dust concentration at above 6 mg/m^3 to lower than 1 mg/m^3 in the first 1.30 minutes period as showing in **Figure 4-8**. The data were collected from inlet channel in fabric filter test in case of low velocity at 0.38 m/s and high velocity at 1.08 m/s. The inlet air contaminant in fabric test was body spray that density of air mixture is normally higher than smoke and respiratory fume.

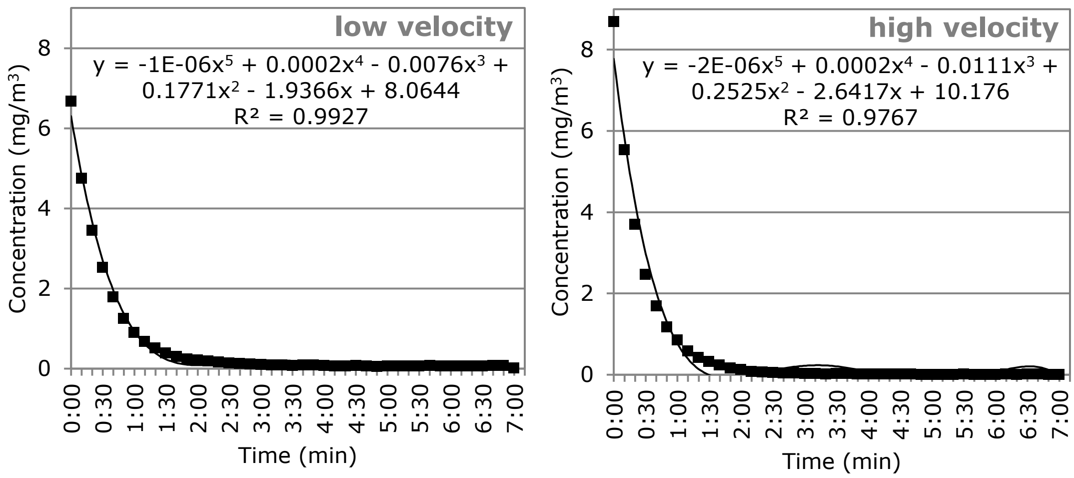

Figure 4-8 The reductions of inlet particle concentration in laboratory

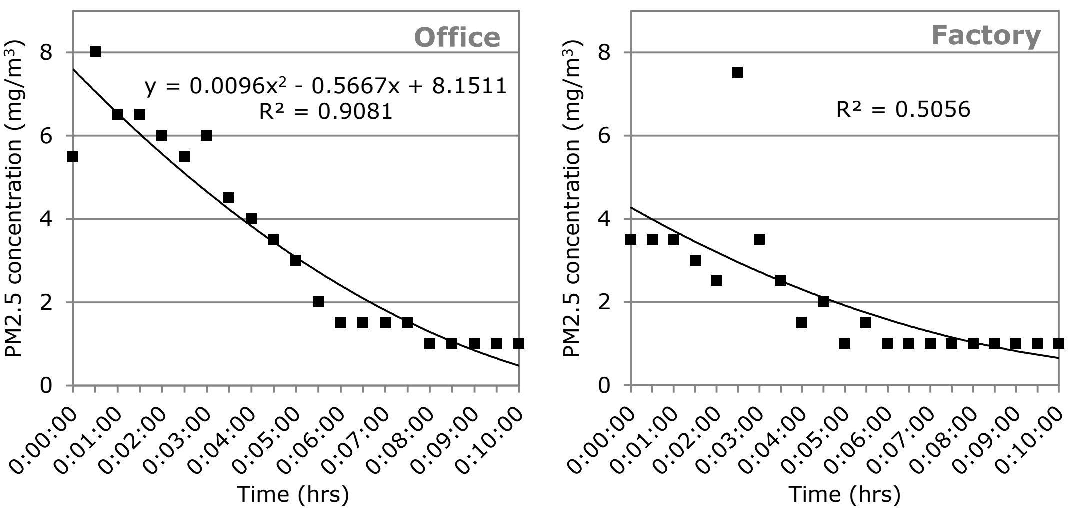

Figure 4-9 PM2.5 concentration from an unofficial purifier assessment in Shanghai

The trend of particle reduction in fabric filter test is compared to the liquid desiccant air purifier tests which their results in **Figure 4-9** illustrate PM2.5 concentration in different types of buildings in Shanghai, China. These minor tests of general air purifier were unofficially done for purpose of dust meter tests and pre-monitoring air pollutants situations within 325 m^2 factory and 50 m^2 office areas. The heights of floor to ceiling are 5 m in office and 2.5 m in office room. The dust meter was located in the middle of functional areas with the height at 1 m from floor. It can be seen that the trend of particle concentration drop to less than 1 mg/m^3 as same as fabric filter test.

The rapidity of reduction can be explained by the difference of collective method and the density of air mixture. For the different method reason, the fabric filter tests were done in laboratory box and the reductive data was collected in inlet part. Consequently, all of air mixture mass would be forced to pass through the filter by driving fan. While, in Shanghai, the test of desiccant purifier was evaluated in single unit room which dust monitor was set 1-m distance from air purifier. Therefore, monitored data was the mixture between inlet and outlet air of purifier and the rapidity of air cleaning would drop slightly.

Turning to another reason of high rapidity in dust reduction, the density of air mixture in the test depended on different types of air pollutant. In fabric filter test in laboratory, body spray was used as inlet source; while cigarette smoke was used in desiccant purifier test. That could bring about the different slope of dust reduction graph.

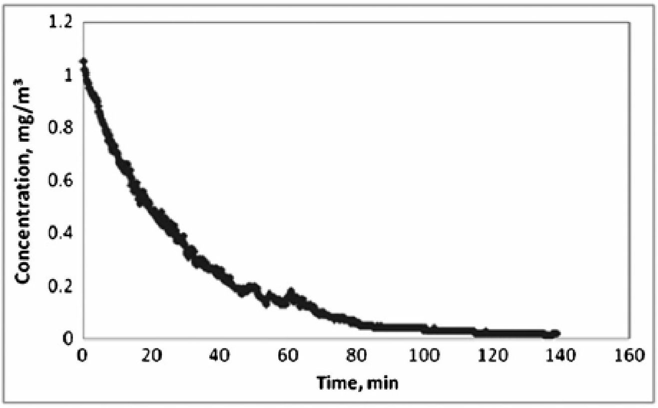

Figure 4-10 PM2.5 concentration from photocatalytic mop evaluation (Riffat & Ma 2012)

Even the results of both above experiments examined the same trend of dust reduction, however, these result were collected by only one observer. To avoid the bias of experiment, another experiment result in **Figure 4-10** was used for comparing the trend of dust reduction. Air pollutant in the experiment was diesel fume which character of fume was nearly cigarette smoke. The graph shows a slight slope of reduction in the period of 140 minutes as same as reduction trend of cigarette smoke in desiccant purifier test.

4.5 Discussions

4.5.1 Efficiency

The efficiency of air filter was calculated from the average dust concentrations in inlet and outlet parts. Then the efficiencies are compared between the values of air desiccant purifier in China and those of pleated fabric filter in Nottingham. Consequently, the efficiencies would be ranked into MERV level based on ASHRAE.

Table 4-2 Dust cleaning performance of pleated fabric filter in different air flow testing

Location	System airflow	Air cleaning performance of fabric filter		
		Arrestance (%)	MERV level	BS EN 799:2012
Nottingham	High	85	E2, MERV 15	F7
	Low	50	E2, MERV 10	M5
Shanghai	Office	99	E2, MERV 16	F9
	Factory	97	E2, MERV 16	F9

In **Table 4-2** PM removal performance is indicated in terms of cleaning efficiency and MERV level. To rank air cleaning performance, the average air purifying efficiency in high pressure system was 85% which could be ranked to MERV 15 in ASHRAE standard; while another one in low pressure condition got 50% cleaning efficiency could be in MERV 10. Comparative results of air purifier efficiencies in China are found to be higher than those of pleated fabric filter in Nottingham. The efficiencies of purifier in office and factory spaces are 99% and 97% respectively which can be grouped into MERV 16 for E2 pollutant.

To compare with BS EN standard, it can be seen that the arrestance of fabric filter in high and low velocity systems are ranked into F7 (Fine filter) and M5 (Medium filter) respectively; while the arrestance of desiccant purifier in both office and factory are higher with F9 rank. With these air cleaning efficiency comparisons, even fabric filter's efficiency can be ranked in nearly high level of MERV and BS EN standards but it can be developed for higher efficiency by combining with other systems such as air cleaning mop and photocatalytic process.

The next step of this research will investigate the relationship between dust concentration and meteorological factors such as relative humidity and temperature by regression analysis methodology. Then conclusion and discussion will be stated at the end of relationship analysis.

4.5.2 The relationship between geological factors and dust concentration

According to research objectives, geological factors are considered to affect dust concentration in air cleaning system or not, if so, what the trend of relationship. To analyze the relationship, inlet dust concentration, temperature and relative humidity were collected every 10 seconds within the previous laboratory of dust monitoring test. When the dust monitor process was collecting, 2 separating humidity probes have been monitoring both temperature and relative humidity from inlet and out part of laboratory box. Then the same collected data would be rearranged for purpose of relationships analysis by multiple regressions.

$$Dust\ concentration = 2.287711 - 0.02344(Rh) - 0.05788(Temp) \quad \textbf{(Equation 4-1)}$$

Based on multiple regression analysis, the equation for predicting the relationship between dust concentration and geological facts is in **Equation 4-1** with P<0.05 and more detail in **Appendix C.1** and **C.2**. Then the results of all relationships are demonstrated in **Figure 4-11**.

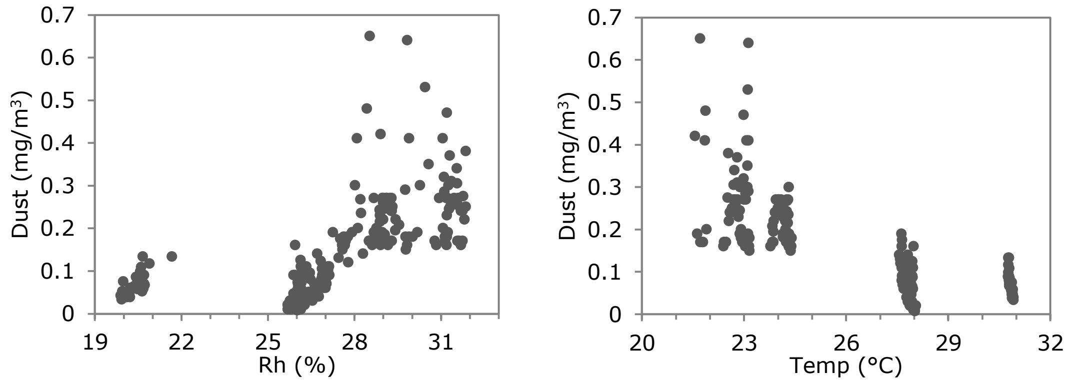

Figure 4-11 The statistic plot of multi-regression test in dust concentration related to relative humidity and air temperature (more details in Appendix C.1 and C.2)

In **Figure 4-11**, it is evident that PM2.5 concentration responds positively to relative humidity level, while reacts negatively to temperature level (P<0.05). The correlation between dust and temperature is practically assured the result by **Figure 4-12** which demonstrates negative relationship too (Mues et al. 2012). However, based on significant 0.05, relative humidity is found no relating to particular mater sized 2.5 micron as showing in the table of statistical analysis in Appendix C.1 and C.2. However, relative humidity and temperature related not only dust concentration; it was also found relating to dust formative process, types of dust and chemicals process. So the results of relationship may differ in case of different types of air pollutants.

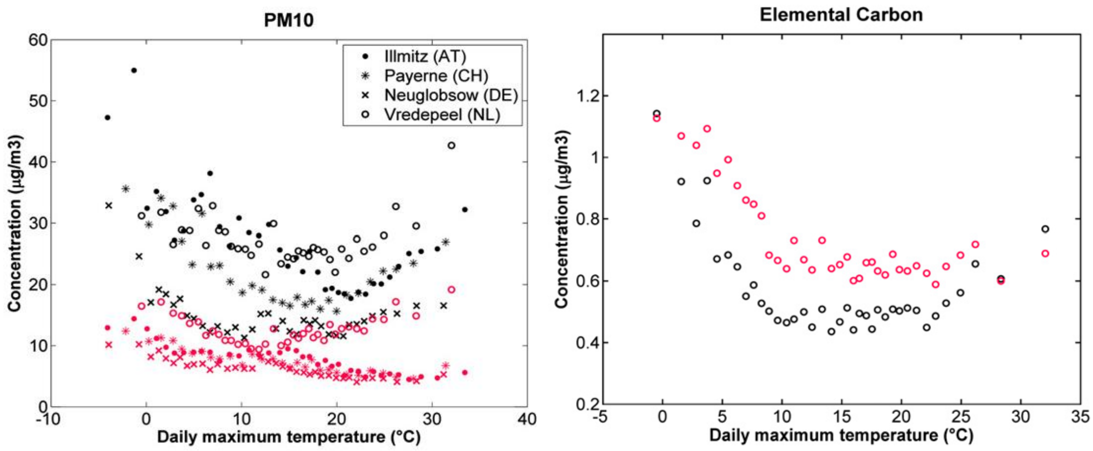

Figure 4-12 A case study of statistic relationship between various elements and temperature (Mues et al. 2012)

To conclude, this chapter has mainly evaluated PM2.5 filter performance compared to ASHRAE standard. To monitor dust concentration, the results show different reductions between inlet and outlet PM2.5. The rapidity of inlet reduction is more obviously than outlet dust reduction resulted from different density of air mixture. The cause of rapid inlet reduction is from the factor of air pressure in inlet part being higher than materials friction factor before switching their effects in the part of outlet. This could bring about outlet concentration exceeding inlet concentration in low velocity case. Then the relationship between testing variables has been secondly taken into account. The result of PM2.5 filter testing in high and low velocity was shown an average value at 85% (MERV15) and 50% (MERV10) efficiencies respectively for E2 particle types. Based on BS EN 799:2012, the arrestances of fabric filter are F7 (fine particle) for high velocity and M5 (medium particle) for low velocity. As comparing to air purifier in Shanghai, that integrating gadget was hold high efficiency at more than 97% (MERV16 and F9) in both indoor official and factory cases.

Then multiple regression analysis revealed that PM2.5 concentration relates significantly to temperature in negative trend; while responds positively to relative humidity ($P<0.05$). Further research might explore the efficiency of more various air filters and more meteorological factors affected respiratory dust. Moreover, further work needs to be done to establish whether filter materials relate to performance of filter or not, if so, in what way.

4.6 Outcomes and research contribution

There is no denying that the sources of pollutant in developing countries is expanding, so filter efficiency of dust reduction and other factors relating to dust concentration should be now considered to avoid poor indoor environment. In air quality product's observation, PM2.5 cleaning performance of fabric filter was clarified for general uses in both industrial producers and consumers. As this fabric filter could be commercially used in high efficient dust purifiers, it is possible that this outcome can be knowhow for systematic designers, filter producers and even in customers.

As preliminary test, this laboratory test was done in UK weather without environmental controls such as an increase in relative humidity and temperature. So the next chapter shows weather condition in summer in Shanghai, China. Then relative humidity and temperature in next experiment would be set as same as in hot and humid climate. Also laboratory instruments in this experiment would be used in all experiments in this research. Instrument setting and experimental design would be relied on this preliminary test

This work contributes to existing knowledge of air filter testing by providing more understanding in testing equipment for further chapter, filter performance evaluation and variables' relationship analysis. It is possible to use this work results for comparing and double check for more reliability of further work.

Moreover, the findings of this study have a number of important implications for future practice. Firstly, this application was tested in indoor environment in Nottingham, United Kingdom, but there is no guaranteed the performance of air cleaning in hot and humid climate yet. So this might be another suggestion for further research as long as relative humidity and temperature affected on PM2.5 purifier and concentration respectively. Secondly, other meteorological factors such as atmosphere gas and local wind could be related to PM2.5 concentration and purifier, so this can be another concerning for further research.

In developing countries, air purifier development is becoming more important as local people cannot avoid higher industrial pollutants, transport combustion and kitchen activity from crowded houses. So this work is expectedly continued in various terms study as above recommendation for further research to improve indoor air quality and human health protection.

Chapter 5: PM2.5 monitoring experiments in Shanghai, China

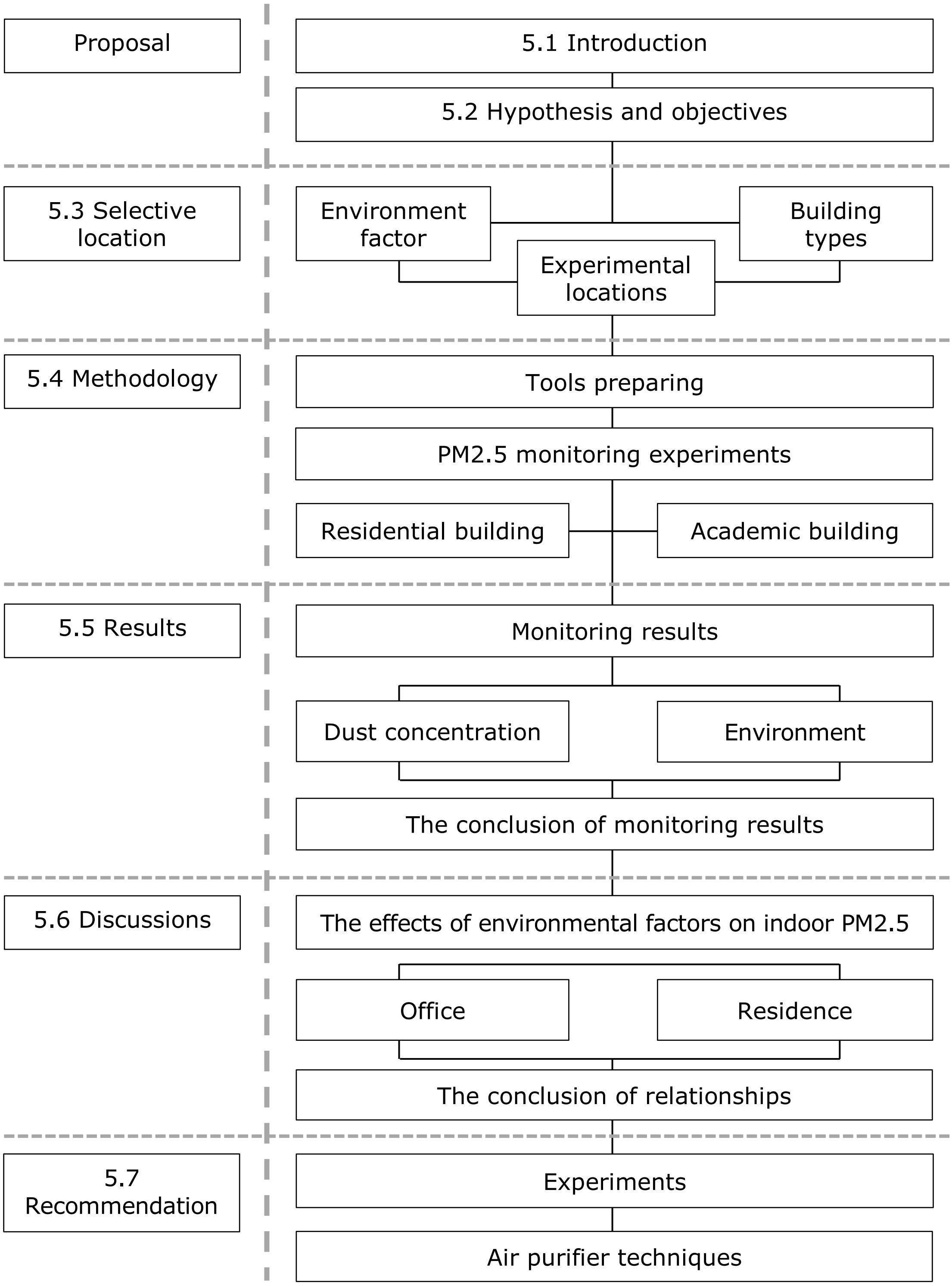

Figure 5-1 The diagram of chapter 5 issues

After understanding more PM2.5 filter characters in Chapter 4, real-time monitoring of indoor and outdoor PM2.5 concentration was now carried on for observing current situation of respiratory dust in Songjiang, Shanghai. In this study, the sources of pollutant were almost identified from traffic activities and transportation. Also the relative humidity effect on PM2.5 concentration was taken into account and predicted future trend by environmental scenario.

5.1 Introduction

The simulation and annual meteorological dataset of PM10 in East Asia in 2007 were investigated and compared PM concentration result (Chen, Tsai & Chang 2013). The high levels of mass concentration were found in 82 cities in China and Taiwan. For instance, in case of PM10, Shanghai and Shijiazhuang were simulated to reach the highest dust concentration exceeding 300 μg/m^3, while real-time monitoring data in Beijing and Lanzhou showed the highest level at around 300 μg/m^3. As a result, the assumption of this study is whether PM2.5 concentration in the academic campus could exceed the permitted level, if so, how much it would exceed international benchmarks and what any recommended application is for cleaning indoor air pollutants.

This research problem results in experimental aims related to monitoring indoor and outdoor particulate matter sized 2.5 micron and investigating relationship between relative humidity and such particle in Songjiang, Shanghai, China. Also the relative humidity effect on PM2.5 concentration was taken into account and the results would show in at the end of this chapter. To specify case studies, Donghua University's residential and office buildings in Songjiang, Shanghai were monitored in terms of 24-hr indoor and outdoor PM2.5 concentration.

As mentioned previously, two international standards have specified average level of PM2.5 concentration in 24 hours such as WHO AQG and US NAAQS (Sarbu & Sebarchievici 2013). **Table 5-1** shows the limiting values of PM2.5 in 24 hours in indoor air. It can be seen that the US NAAQS standard allows a higher value of PM2.5 concentration than that in WHO limitation. However, these international standards have not specified climate condition and separated economic zone around the world. Therefore, this study uses both international standards to be criteria of indoor PM 2.5 concentration.

Table 5-1 International standards for monitoring PM2.5 throughout 24-hr period (Sarbu & Sebarchievici 2013)

Standards	PM2.5 concentration (24hrs) (μg/m^3)
WHO AQG	25
US NAAQS	35

After briefly literature of PM2.5 monitoring in terms of current situation in Songjiang, China and international standards, the next step will provide the hypothesis and objectives of this real-time experiment.

5.2 Hypothesis and objectives

The hypothesis of this real-time monitoring in Songjiang, China is to research the current situation of indoor PM2.5 in official and residential buildings in academic campus. Moreover, it is doubt whether indoor PM2.5 concentration relates to meteorological factors or not, if so, in what direction.

The objectives of this study Objectives:

- To monitor 24-hour real-time PM2.5 and environmental data in two types of buildings in Songjiang, Shanghai, China.
- To investigate the relationship between PM2.5 and environmental data and the directions of relationship.

5.3 Selective locations

In this 24-hour monitoring, research area is PM2.5 and meteorological factors in residential and official buildings in academic campus. The campus of Donghua University in Songjiang is 68.5 km from Shanghai Pudong International Airport. Two different functional buildings were selected to be sampling locations. The first building is Environmental Science College about 230 m from Guangfulin road. This building is the representative of office buildings in Donghua University with mixed use functions between research office and laboratory. Another sampling site is an U-shape domitory located 750 m from Guangfulin road, however, this building is near another main road around campus named Longteng road which brings possibly about transport pollution.

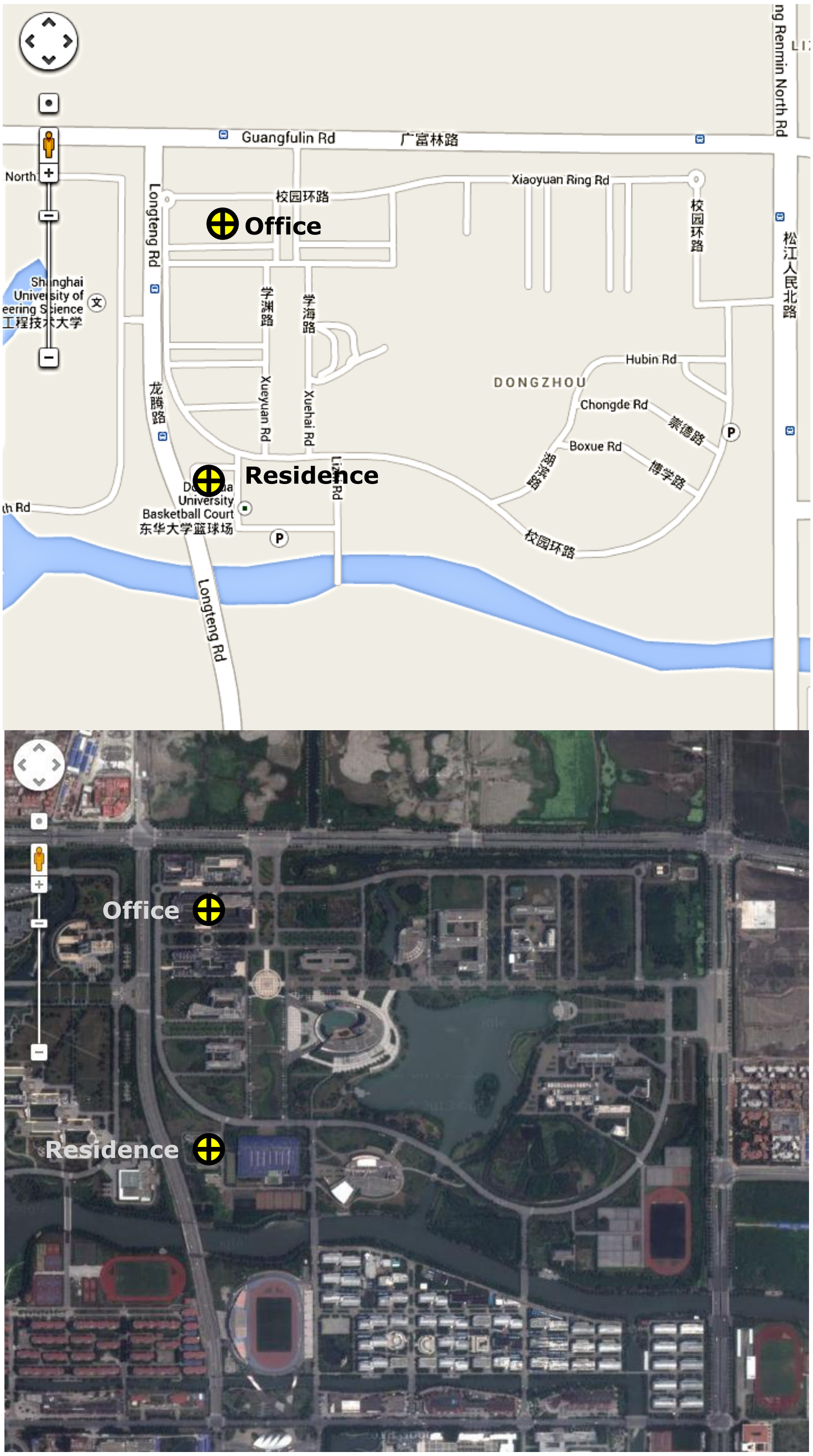

Figure 5-2 The layout of Donghua university, Songjiang, Shanghai, China (Google Maps. 2013)

Both office and residential building sites are located in Donghua University, Songjiang, Shanghai, China. Following **Figure 5-2**, office building is located closely the north entrance of university, while a residential area is located near river and student residence. According to university map, office building is in the north of university which is 100-m far from "Guangfulin road" and 40-m far from "Longteng road", so office building can be mainly affected from car traffic. However, this main road is considered adequate for the amount of cars and buses in rush hour, the pollution from traffic jam could not be dominantly indoor air quality effect in office building. Turning to the residence in Donghua Univesity, it can be bothered from boat transportation by noise pollution and air pollutant can also result from "Longteng road" which is 40-m far from site. To be noted, agriculture activities and new construction projects around Donghua University, Songjiang have become more popular. Across Guangfulin road near the north orientation of Donghua University, there is a large area of agriculture to grow corn and strawberry. Thus there activities such as fertilization and pesticide could affect indoor air. Also the construction process on east side and northern west side of university could be the main sources of indoor air pollution.

In case of office building, the sample room is on the 5th floor of environmental science college building that far from main public transportation road around 40 meters. In the building, corridor structure is arranged single line in the middle of building and office or laboratory arranged on two sides of corridor. The dimension of general laboratory and office is 8-m width and 12-m length which is separated inside with permanent or temporary particles as shown **Figure 5-3**.

The occupation of general office in this building is 12 hours from 8.00 am to 20.00 pm with central air conditioning system control. However, based on working culture, the openings in the room have been opened during work time. Moreover, there are 5-8 people per room depending on academic terms and student occupation. To be more comfortable in Shanghai, central air conditioning system has been installed to this building and it's reduced around 3-5 $^{\circ}$C throughout working period. This ventilated system affected directly indoor air quality because it provides generally indoor inhalable air.

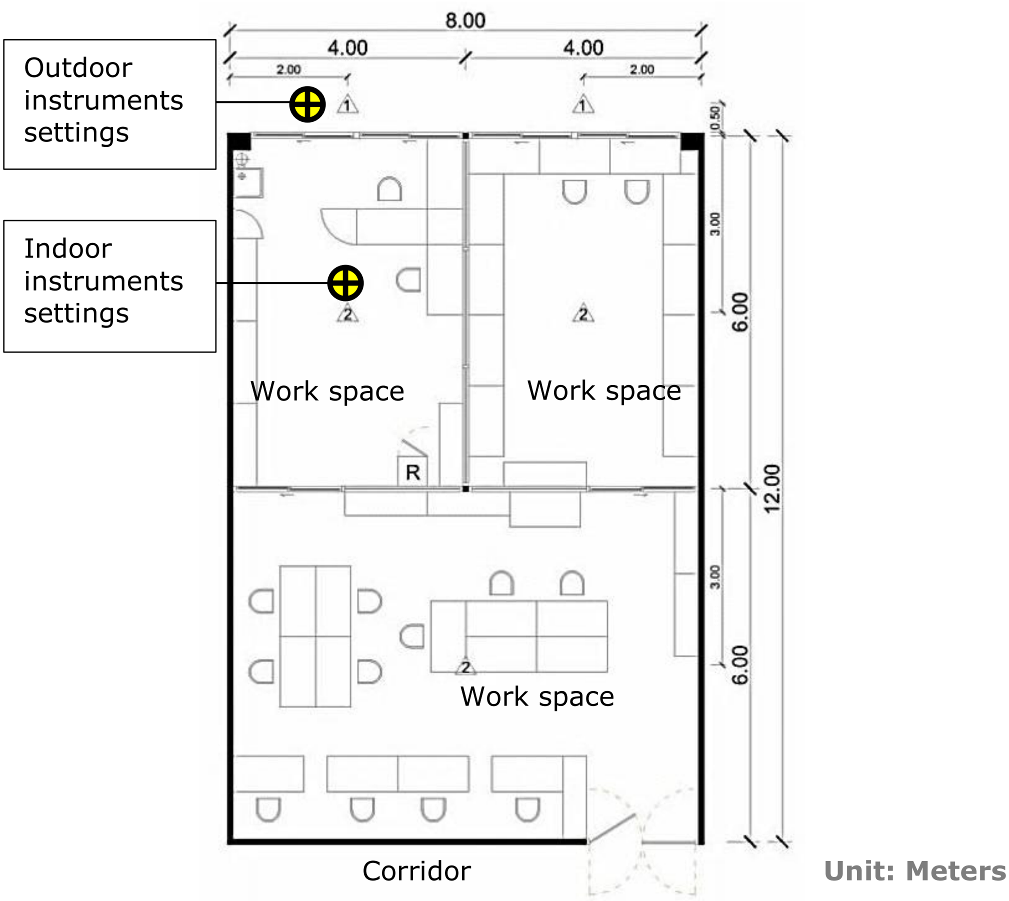

Figure 5-3 Office and laboratory building in Donghua university, Songjiang, Shanghai, China (Donghua University. 2013)

As the same areas of office buildings, outdoor environment of residence building is not differed from office building with high dust concentration, high temperature and high relative humidity. Donghua's residential building is standing away from main public road and it is also buffered by gymnasium or second functional buildings. The arrangement of corridor is also middle double corridor with both side of room sized 6 meters length and 5 meters width. In the 3rd floor room, personal bathroom is separated space around 2.00*2.00 m^2 in the corner of room and single bed is lay out in the room by length followed **Figure 5-4**. Single side of window is located opposite the door opening that is not related significantly to indoor dust concentration. This room is controlled temperature and humidity by single unit of air conditioner during 15 hours between 17.00pm and 8.00 am.

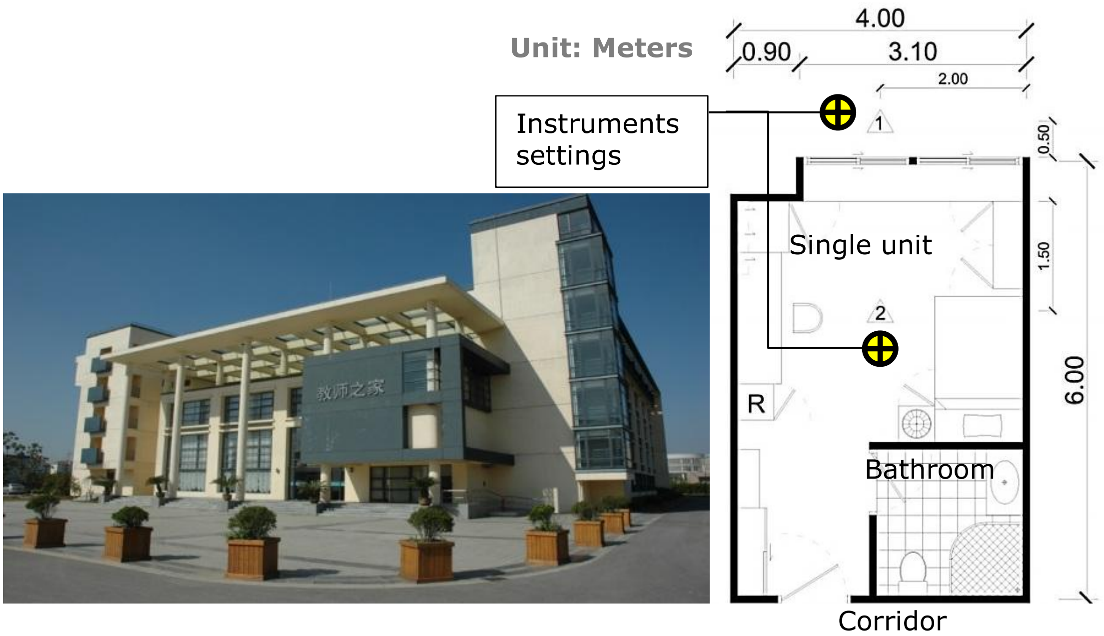

Figure 5-4 Residential building in Donghua university, Songjiang, Shanghai, China (Donghua University. 2013)

After indicating the locations of monitoring and setting the equipment, the experiment would be run for more than 24 hours and collected data by automatic data loggers and manual recording. Also all collected data would be rearranged and presented graphically later.

5.4 Experiments

According to the aim of this study, to monitor indoor PM2.5 in residential and office buildings, there are a few steps to prepare for real-time experiment. The research area is firstly specified to study in residential and office building in Sonjiang district. Secondly, three types of equipment are used to monitor four 24-hr data regarding air velocity, humidity, PM2.5 concentration and temperature. Thirdly two international standards are compared with the PM2.5 concentration result. Lastly, the current situation of PM 2.5 in 24 hours is discussed based on the benchmarks and the problems of experiment.

Table 5-2 Time frame for PM2.5 monitoring process in Songjiang, China

Week	1					2					3					4				
	July			August																
Research plan	29	30	31	1	2	5	6	7	8	9	12	13	14	15	16	19	20	21	22	23
Equipment and place preparation																				
Pre-monitor testing																				
1st time monitoring																				
2nd time monitoring																				
3rd time monitoring																				
Error experiment																				

To carry out the process, simple time frame is created in order to plan briefly experimental step throughout a month period. **Table 5-2** illustrates seven steps of experimental development including the arrival date, equipment preparation, pre-test data, 1^{st}-3^{rd} real-time monitoring PM2.5 and the time for some error in experiments. Also the time limitation of each step is separated in a month in order to arrange the importance of each experimental step. At the end of this plan shows the time for data analysis. After briefly observing experimental plan, the next session of this report will refer to equipment used in this experiment and descript some information of such equipment.

Table 5-3 Equipment for monitoring indoor PM2.5 in Shanghai, China

Type of meter	Description	Position	Quantity	Comparison
Anemometer	Monitoring velocity (m/s) and temperature (°C)	Indoor/ outdoor	2	velocity and temperature with humidity meters
Humidity meter	Monitoring relative humidity (%) and temperature (°C)	Indoor/ outdoor	2	
Dust meter	Monitoring air particle meter (mg/m^3)	Indoor/ outdoor	2	air particle meter

There are three main types of instrumentation to carry out research. **Table 5-3** shows the three types of equipment that could collect all four types of data with multi-functional instrument. Two anemometers are set for both indoor and outdoor environments to collect record (m/s) and temperature (°C). Also humidity meters are put in the same places as the anemometer to monitor relative humidity (%) and temperature (°C). Then indoor and outdoor dust meters are set to monitor PM2.5 concentration (mg/m^3).

After setting equipment and starting the experiment more than 24 hours, the data would be collected every 30 minutes in case of manual data collection for sampling velocity. For automatic collection, however, the data would be recorded every 10 seconds in order to study in detail of data such as PM2.5 concentration and relative humidity. The next part of this report will examine the results of this monitored experiment in office.

5.5 Results

Approximately 28 hours monitoring, the results are presented in terms of indoor and outdoor dust concentration, velocity, relative humidity, temperature before comparing to international standards. The all data in 28 hours will be discussed comparing to 24-hr air quality standards in the next session.

5.5.1 The dust concentrations

After reliably calibrating equipment, monitoring results show fluctuating dust concentration in both indoor and outdoor locations. However, average indoor PM2.5 concentration did not exceed WHO AGC and US NAAQS at 25 $\mu g/m^3$ and 35 $\mu g/m^3$ respectively as shown in **Figure 5-5** (Sarbu & Sebarchievici 2013). Moreover, velocity, relative humidity and temperature will be considered to study the relationship between dust and humidity and temperature. Also indoor velocity of this experiment is near zero throughout testing period. Another consideration of this 24-hour experiment is air conditioner turned on for 15 hours between 17.00 PM and 8.00 AM. So indoor temperature, humidity and dust concentration will be investigated value, effect and relationship during 24-hour monitoring.

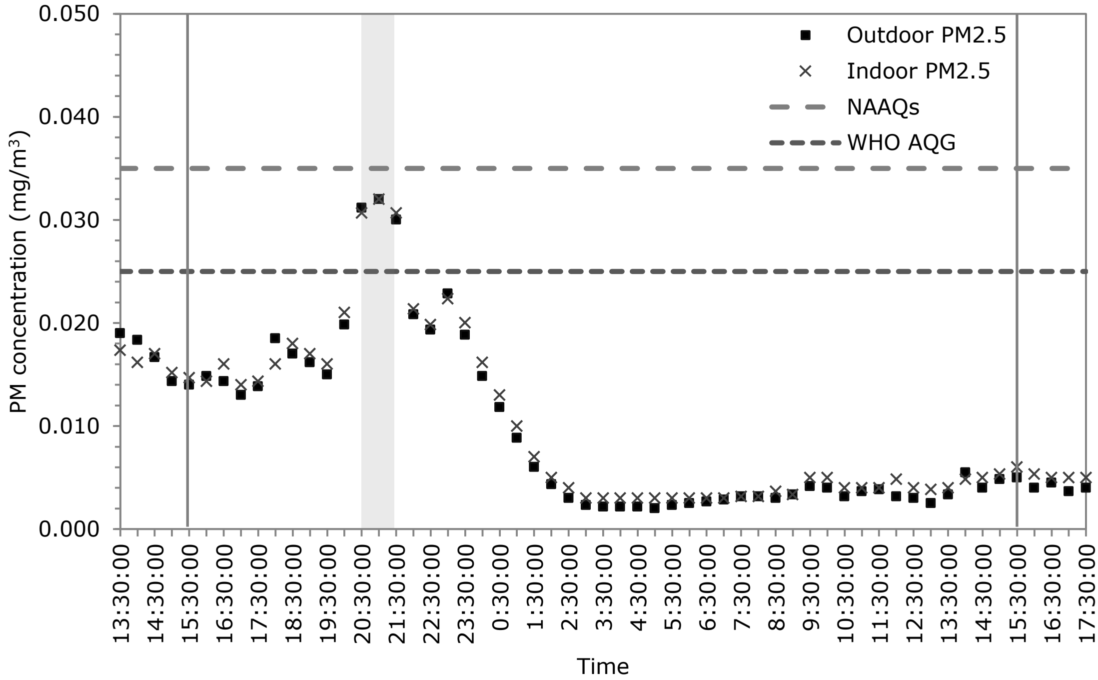

Figure 5-5 Particulate matter concentration in Songjiang's office building

As monitoring indoor PM2.5 concentration, **Figure 5-5** demonstrates the concentration of indoor PM2.5 over the period of 24 hours. It can be seen that indoor and outdoor PM2.5 concentrations change in the same direction with fluctuating and then reducing to lower than 0.006 mg/m^3 at midnight. The indoor concentration is mostly lower than those in outdoor condition throughout the 24-hr period. By the way, the averages of indoor and outdoor PM2.5 concentrations are at 0.010 mg/m^3 and 0.009 mg/m^3 respectively. To be noted, indoor and outdoor PM 2.5 concentrations exceeded WHO standard in the 1-hr period from 20:30:00 to 21:30:00.

According to the PM2.5 concentration, it is possible that dust concentration will affect respiratory system especially staff and students who have routinely worked until late night. So it is possible that purified application might be integrated to clean indoor air quality at this 1-hr period. Purification applications will be introduced in this report including fabric filters and dehumidifier application.

In residence, dust monitoring was set in single bedroom in the same academic campus and the period of monitoring was the same as office monitoring over the 24-hr period. However, the results differ obviously in case of indoor and outdoor dust concentration as showing in **Figure 5-6**.

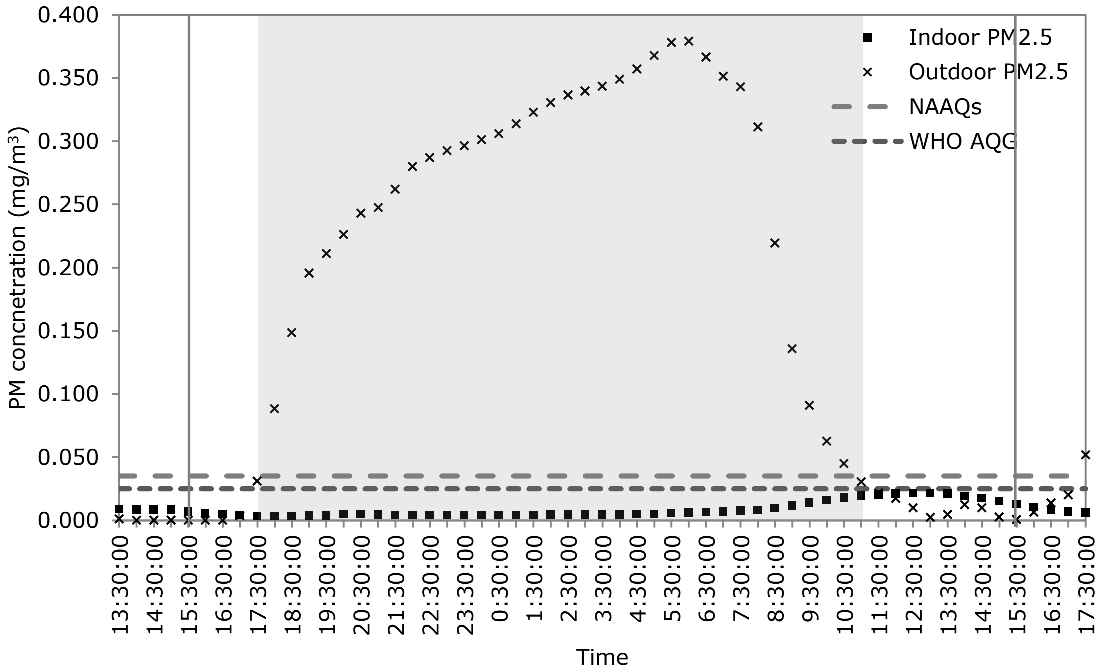

Figure 5-6 Particulate matter concentration in Songjiang's residence building

According to residence monitoring, **Figure 5-6** shows the concentration of indoor and outdoor particular matter diameter 2.5 micron during the 24-hour period. It is obviously seen that outdoor PM2.5 concentration reaches over 0.350 mg/m^3 or 10-time exceeding of NAAQs standards; while indoor air pollutant remains under both WHO and NAAQs standards during the whole period. The 24-hr average of indoor and outdoor PM2.5 concentrations are 0.008 mg/m^3 and 0.164 mg/m^3 respectively and those outdoor average dust still exceeds both air quality standards.

The reason of significant difference between indoor and outdoor PM2.5 results from variety types of air condition in both buildings. The package type air conditioner in office building is more difficult to clean indoor air than single unit in bedroom. Also another cause of variety of indoor dust is occupants' behavior such as movements, door and window openings. As a result, office monitoring data shows more relatively to outdoor condition because higher frequency of window and door opening. In this study the number of occupants in office is 5 regular workers and a few temporary visitors. The next step, environmental conditions of monitoring will be examined and then analyzed the relationship to indoor PM2.5.

5.5.2 *Environmental conditions*

Environmental conditions of experiment affect possibly indoor PM2.5 concentration and those data are demonstrated in terms of temperature, relative humidity and air velocity. Environmental data was collected in both indoor and outdoor; however, indoor air velocity was monitoring to be 0 m/s during the 24-hr period.

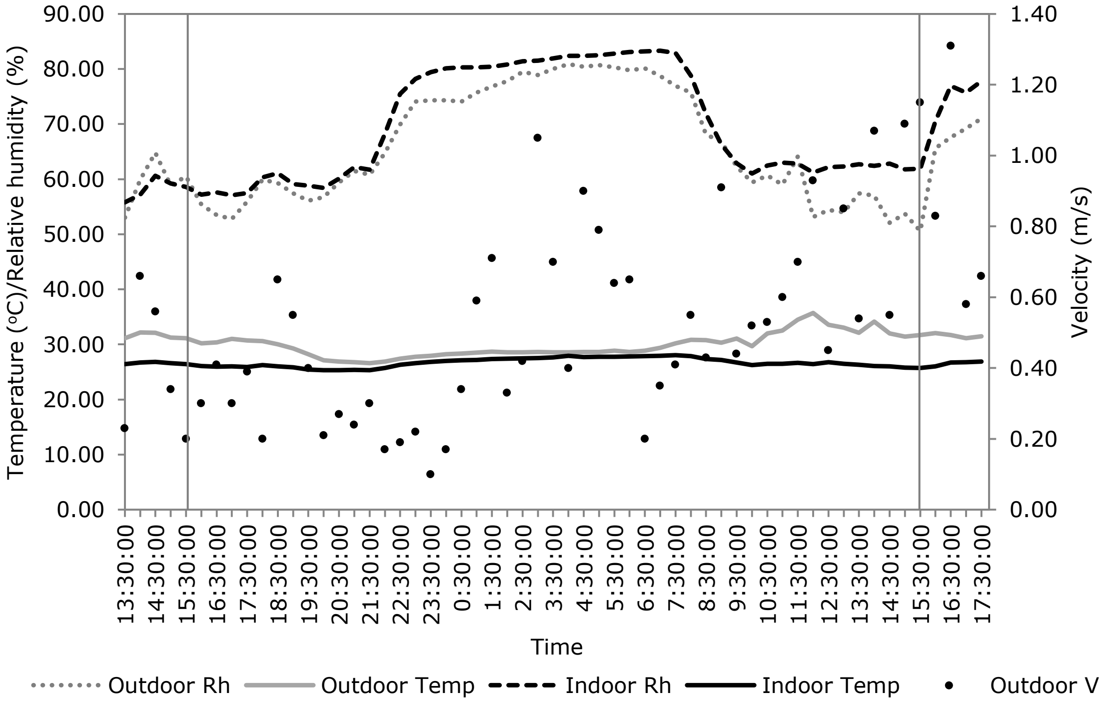

Figure 5-7 Environmental conditions in office building

In **Figure 5-7**, the chart shows indoor and outdoor environmental data of real-time experiment in Shanghai, China during the period of 24 hours. It can be seen that indoor temperature and relative humidity range in the period of 25.35-28.05 °C and 55.80-83.30% respectively. In outdoor condition, temperature and relative humidity range in the period of 26.60-35.70 °C and 50.60-80.90% respectively. Outdoor temperature drops slightly at night while outdoor relative humidity is higher at the same time. This is a common relationship between temperature and relative humidity based on psychometric chart. Also outdoor velocity fluctuates in the range of 0.10-1.31 m/s throughout the 24-hr period.

As mentioning room openings in office case, indoor relative humidity changes approximately as same to those in outdoor; while indoor temperature remains stable throughout the experimental period. So indoor environmental data varies nearly as same as outdoor condition but outdoor data fluctuates more dramatically.

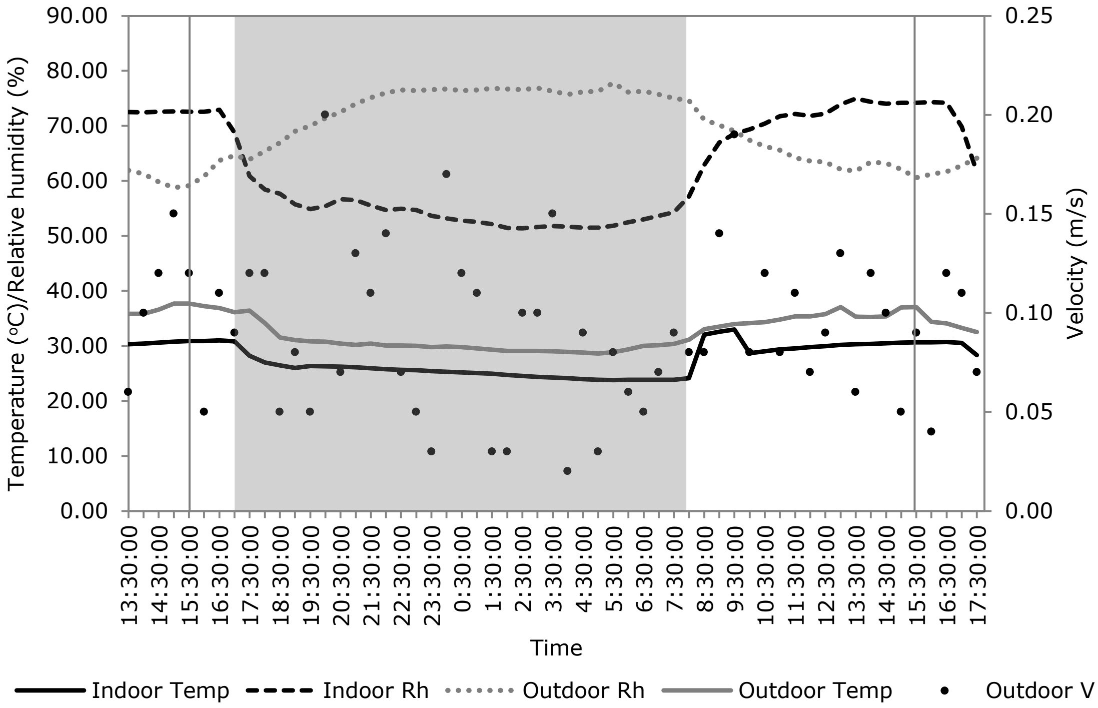

Figure 5-8 Environmental conditions in residence building

In residence case, **Figure 5-8** demonstrates environmental data of real time experiments in both indoor and outdoor condition during the period of 24 hours. It can be seen that outdoor temperature and relative humidity are in the range of 28.60-37.70 °C and 58.80-77.80% respectively throughout the 24 hours period. Also outdoor velocity fluctuates between 0.02 m/s and 0.2 m/s in the same period. On the contrary, indoor temperature and humidity swing in the range of 23.81-32.97 °C and 51.37-74.94%. Indoor temperature and relative humidity drop during the 17:00:00-8:00:00 period when turning on air conditioner.

5.5.3 The conclusion of monitoring results

Based on hot and humid climate, indoor PM2.5 concentration was monitored in residence and office buildings in Donghua University, Shanghai, China. In office building, average indoor PM2.5 level is at 0.010 mg/m^3 that does not exceed both WHO and NAAQs standards; while those peak reaches 0.032 mg/m^3 exceeding WHO for 2 hour. In case of residential building, the average and the peak of dust concentration are at 0.008 mg/m^3 and 0.022 mg/m^3 within both standards; while the peak of outdoor dust is at 0.379 mg/m^3 higher than 10-time NAAQs standard. Another consideration in experiment is the opening leakage between indoor and outdoor conditions that high leakage in office case can bring about high indoor dust; while indoor dust in residence with low leakage is obvious seen lower than 10-time outdoor dust concentration.

Turning to environmental results, outdoor temperature and relative humidity are in the range 25-38 °C and 50-81% respectively. The outdoor results of temperature in both office and residence buildings are same as night time reduction; while relative humidity gets reverse result following psychometric chart. As a result, indoor temperature and relative humidity change in the same trend with high leakage of openings. Due to night time air in residence is controlled by air conditioner and low opening leakage, indoor relative humidity drops at night. The next session of this study will examine the relationship between indoor PM2.5 and environmental factors.

5.6 Discussions

To consider free ventilation, ambient particle number concentration (PNC) relating to environmental factors in terms of rainfall, wind, temperature, relative humidity and traffic condition. Rainfall is well known to wash out all sizes of PNC from atmosphere. Higher wind speed can reduce environmental fine and ultrafine particles but does not relate evidently to coarse PCN. Temperature and relative humidity have mostly a negative correlation to PCN, however, relative humidity is sometimes found to have no effect on PNC. During all day activities, the peak of PCN is normally demonstrated in morning when the beginning of environmental change is found as a reduction in relative humidity, increases of day temperature and wind speed. Consequently, in the afternoon, the peak of wind speed and high air temperature with low relative humidity can encourage particle movement and eventually particle reduction. It is evidently found that individual meteorological factors are less influential than traffic variables especially traffic speed and traffic volume. Even both traffic speed and volume affects to PNC, but there are still argued in negative relationship between those two traffic variables (Price et al. 2014).

Based on multiple regression analysis in this study, PM2.5 concentration will be identified the association to environmental factors especially temperature, relative humidity, velocity and outdoor dust level. The results will be estimated relationship by P-value of each variable and then only significant result will be plotted in relationship chart.

5.6.1 The effect of environmental factors on indoor PM2.5 in office

According to statistical analysis, indoor PM2.5 shows significant relationship to indoor temperature and outdoor PM2.5 ($P<0.05$). Relative humidity, outdoor velocity and temperature are found insignificant effect to indoor PM2.5 concentration (more details in **Appendix D.1** to **D.3**).

In **Figure 5-9**, the chart demonstrates indoor PM2.5 related to indoor temperature in office building. There is negative trend of relationship between indoor PM2.5 concentration and indoor temperature. As the high opening leakage in office case, this relationship is same as the relationship between ambient particle number concentration (PNC) for nanoparticle size range and temperature. This is because colder temperature can enhance atmosphere particle formation (Price et al. 2014).

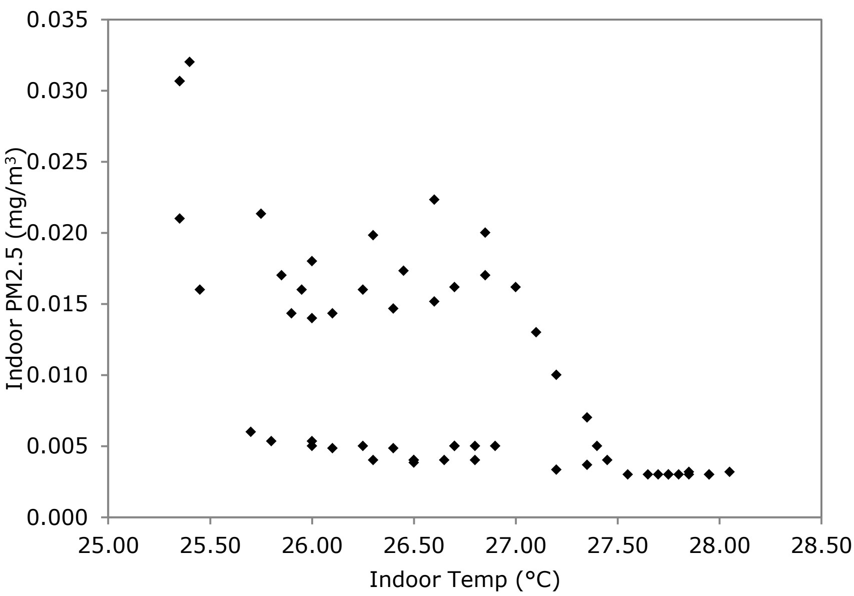

Figure 5-9 The relationship between indoor PM2.5 and indoor temperature in office building

According to **Figure 5-10**, the graph shows indoor PM2.5 concentration associating with outdoor PM2.5 level in office building during the 24-hr monitoring. It can be seen that indoor PM2.5 concentration relates significantly to outdoor PM2.5 as a linear trend with $R^2=0.99$ ($P<0.05$). This is because of high leakage of opening in working area, so indoor PM2.5 concentration is nearly the same as that in outdoor condition.

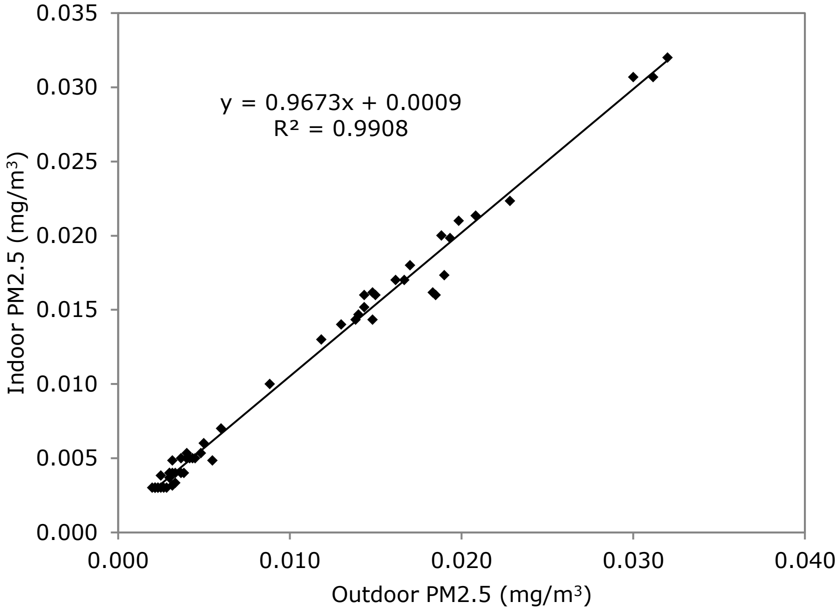

Figure 5-10 The relationship between indoor and outdoor PM2.5 in office building

5.6.2 The effect of environmental factors on indoor PM2.5 in residence

As multiple regression analysis in residence results, indoor PM2.5 shows significant relationship to indoor temperature, indoor and outdoor relative humidity ($P<0.05$). The outdoor environments such as velocity, temperature and PM2.5 are found insignificant effect to indoor PM2.5 concentration (more details in **Appendix D.4** to **D.6**).

In **Figure 5-11**, the chart illustrates particle concentration relating to indoor temperature in residence during the period of one day. The relationship trend should be divided into 2 sections; one is turning air conditioner condition and another is turning off air conditioner. When air conditioner is working, indoor temperature is ranged in 23.81-28.22 °C period. In this temperature range, the temperature is controlled and indoor air is purified by air conditioner. So the particle concentration can be very low in case of turning on air conditioner. Secondly, when turning off air conditioner, air temperature rises up to higher range at 28.22-32.97 °C and particle concentration show reducing trend at higher temperature. That associates with the relationship between particle concentration and temperature in office building.

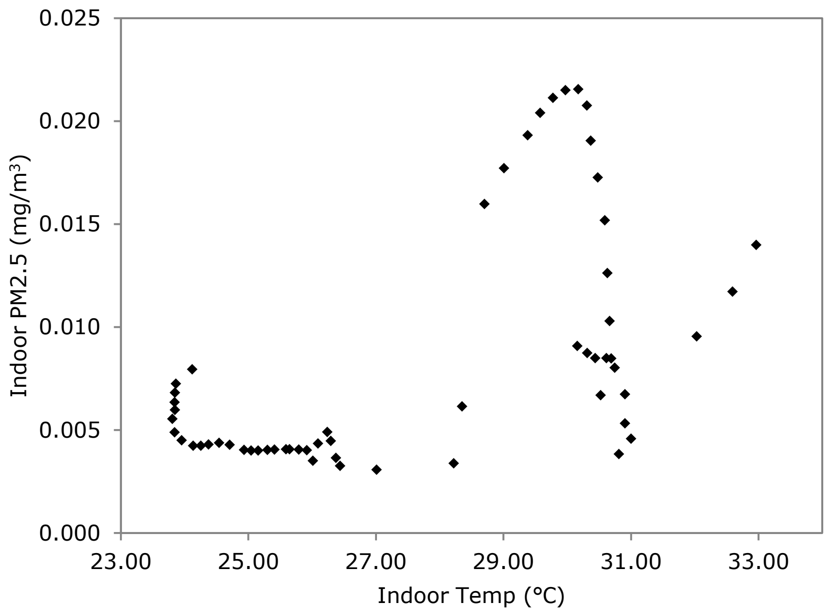

Figure 5-11 The relationship between indoor PM2.5 and indoor temperature in residence

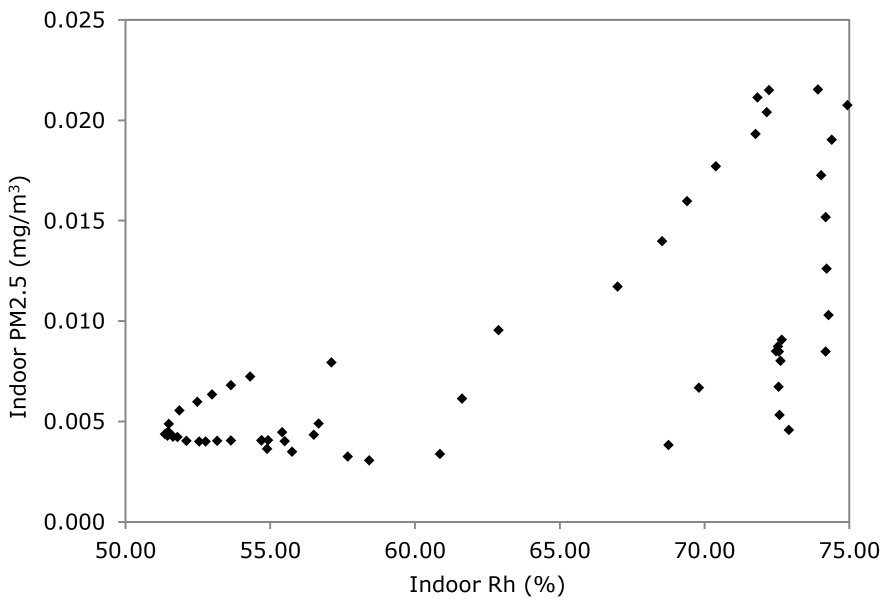

Figure 5-12 The relationship between indoor PM2.5 and indoor relative humidity in residence

With a low leakage through opening, it is possible that air conditioner affects relative humidity as same as air temperature and the result of relationship demonstrates in **Figure 5-12**. Under air conditioner working, relative humidity gets a trough at 51.37-60.87%. In this condition, indoor PM2.5 concentration is very low because of air conditioning filtration. When turning off air conditioner, relative humidity rises up to the range 60.87-74.94% and indoor particle relates positively to indoor relative humidity. This situation is not following regular negative relationship between outdoor relative humidity and outdoor particle (De Hartog et al. 2005).

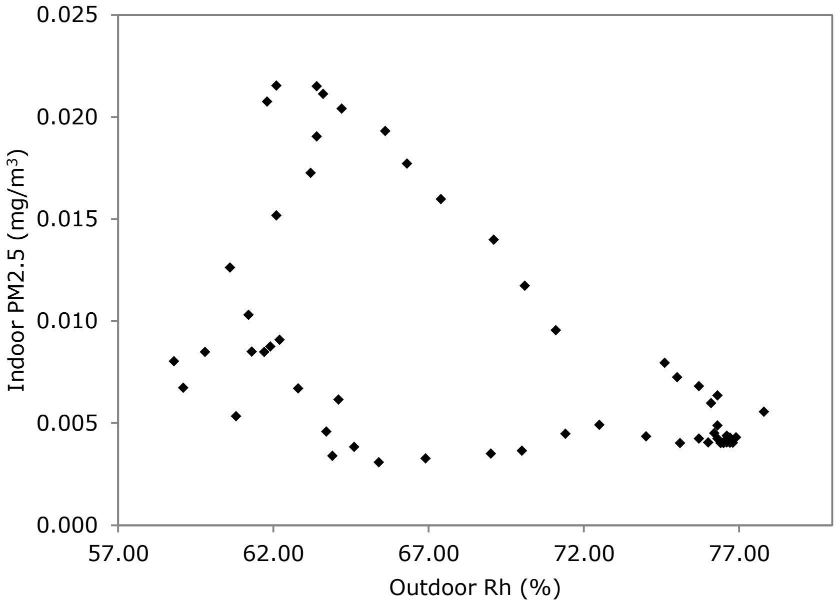

Figure 5-13 The relationship between indoor PM2.5 and outdoor relative humidity in residence

The relationship between indoor PM2.5 concentration and outdoor relative humidity in **Figure 5-13** is incidentally happened. This is because of low leakage and indoor environment is not affected by outdoor factors in single bedroom. However, an increase of outdoor relative humidity may bring about uncomforting perception to occupant and then turning on air conditioner.

5.6.3 The conclusion of indoor PM2.5 and environmental factors relationship

Based on real monitoring in academic office and residence in Donghua University, occupants were routinely behaving included opening windows even in air conditioning rooms. So number of occupants could affect the leakage between indoor and outdoor air. In case of office building, permanent workers had ordinary work on personal computer and meeting activities; while more ventilation was required when getting heat source from office cooking and more visitors. In case of residence, the leakage was lower because of only one occupant and less opening change.

This leakage in office building can imply to indoor air condition in office building that indoor environmental factors is changed as same as outdoor condition. As a result, the effects on indoor PM2.5 concentration are considered from indoor environment as a direct effect. Then the effects from outdoor weather were secondly considered with the leakage condition.

Table 5-4 The conclusion of relationships between indoor PM2.5 concentration and environmental factors

Building type	Opening leakage	Environmental factors on indoor PM2.5		Regression coefficients ($P<0.05$)
Office	High	Intercept		0.0165
		Indoor	Relative humidity	N/A
			Temperature	-0.0006
		Outdoor	PM2.5	0.9211
			Velocity	N/A
			Relative Humidity	N/A
			Temperature	N/A
Residence	Low	Intercept		-0.1014
		Indoor	Relative humidity	0.0013
			Temperature	-0.0011
		Outdoor	PM2.5	N/A
			Velocity	N/A
			Relative Humidity	0.0008
			Temperature	N/A

In **Table 5-4**, the conclusions of all environmental factors are demonstrated statistical coefficients which can inform how great of impact and the direction of relationship. It can be seen that indoor temperature has a negative relationship on indoor PM2.5 in both office and residence. This is the same trend as relationship analysis in other air pollutant monitoring (Price et al. 2014). In case of office, relative humidity has no significant effect on indoor PM2.5; while positive relationship between relative humidity and PM2.5 is found in residence. However outdoor relative humidity is accidentally related to indoor environment because low openings leakage and definitely different trend between indoor and outdoor relative humidity.

High leakage of office's openings could bring about strong correlation between indoor and outdoor PM2.5. This can affect directly to natural ventilation houses in industrial zone when indoor environment possibly exceeds air quality standard especially in the high risk of air pollutant locations as mentioning in 3-year statistical data in Thailand. Therefore, one way to protect occupants' health is air purifier which is normally too expensive for low income family. The findings of air purifiers' techniques will be identified and improved their efficiency for reducing cost based on hot and humid climate.

5.7 Recommendations

Due to time limitation of air monitoring in Shanghai, this study was done in only academic campus with lower impact of air pollutants from traffic and industrial zone. Further research may find out more in case of different air pollutant sources and their effects on local people in hot and humid climate. Also, the leakage of opening and occupant behaviours can directly affect to indoor air pollutants. So further study of buildings envelop developments for controlling air quality may concern more details on these topics.

According to real time monitoring test in July and August, the range of outdoor temperature was in 23.81-35.70 °C and outdoor relative humidity was in 50.60-80.90%. These environmental conditions were in summer season in Shanghai which was nearly similar to Bangkok, Thailand in the same moment. So this temperature and relative humidity would be used to control further experiments in this Thesis.

Chapter 6: Solid fibre mops evaluation for PM10 cleaning

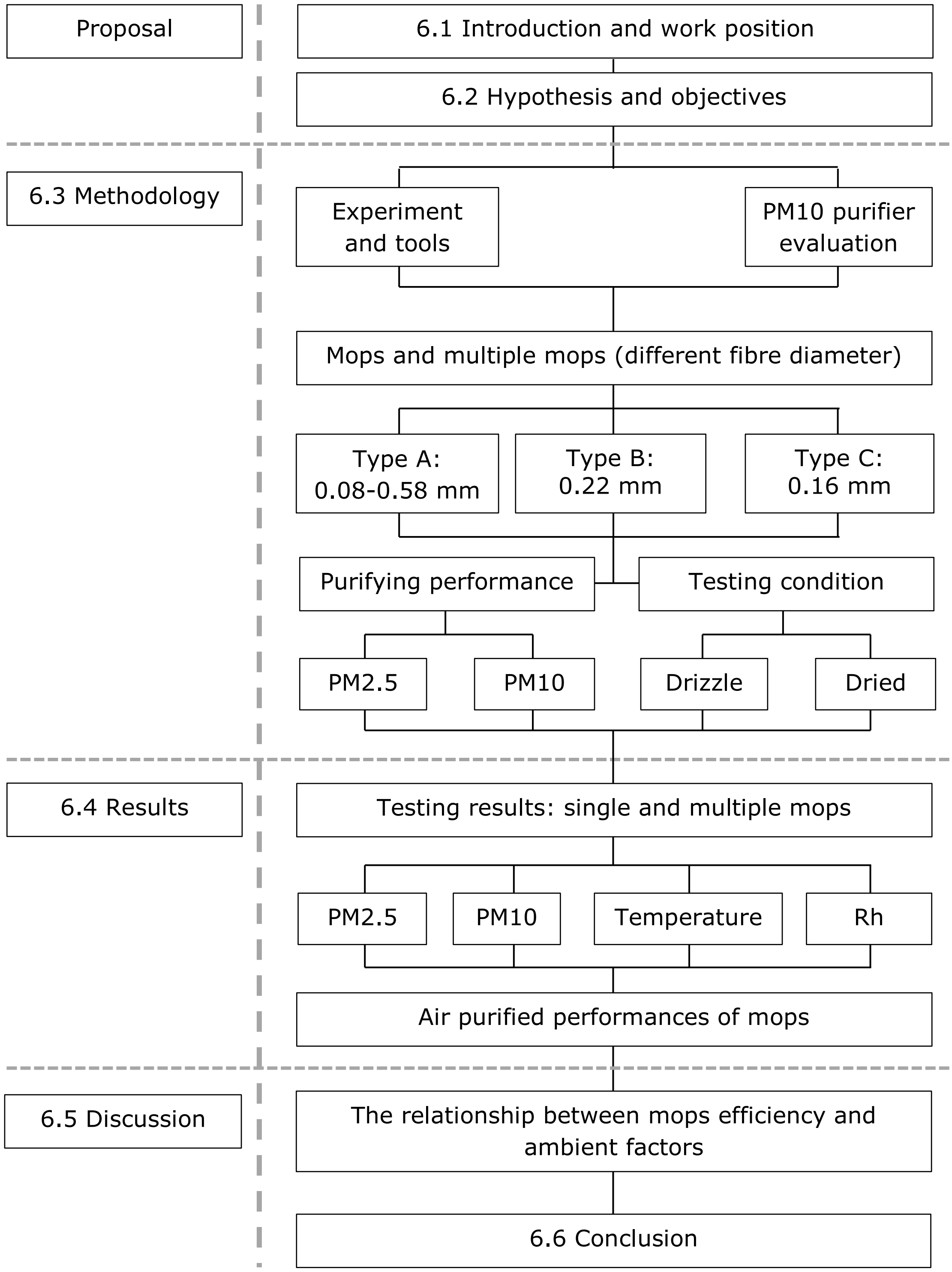

Figure 6-1 The diagram of chapter 6 issues

6.1 Introduction and work position

According to air PM2.5 monitoring in previous chapter, it was in doubt that other types of air contaminant affected building users such as inhalable dust. As noted sources of indoor air pollutant in China, some are from traffic combustion in terms of gases and smoke, but some are from construction factory such as cement dust and inhalable dust. Additionally, the 10-year statistic data of PM2.5, PM10 and TSP from Thai methodological station could be concluded high risk areas and the factors of particle exceeding in each parts of Thailand. This data conclusion would bring about more understanding real actual situation of particle in Thailand and the proper direction of particles reduction in each local area. For example, in Changmai, the northern part of Thailand, covering fume in the city could be happened when open burning activities and weather pressure were simultaneous high in winter time. So particle matter diameter sized 10 micron (PM10) would be another air pollutant suggested to study how it could be purified efficiently and economically. In this chapter, the experiment of air cleaning mop evaluation focused on PM10 and PM2.5 purification are investigated in term of dust cleaning efficiency.

From early research in mop experiment, it is suggested that fibre brunch of mop can remove air contaminant better than bladed fan resulted from larger surface of fibre (Riffat & Shehata 2001). So this testing mop will be formed from lots of polymer fibre brunch with a staggered tuft formation. Turning to fan specification, there was a static efficiency test on mop that proved mop efficiency in flow rate 0.12 m^3/s and motor speed of 1420 rpm (Riffat & Zhao 2007). However, 6 years later, there was found the optimum of fan specification for air cleaning by mop based on the reaction efficiency was at low speed rotation (1-5 Hz). Also the fan motor could be only 180W with rotation speed at 136 rpm in order to reduce energy consumption in experimental system (Riffat & Ma 2012). In this test, fan rotation could be adaptable for suitable system flow rate.

Even the result from chapter 3 showed no significant relationship between relative humidity and PM2.5 concentration, this experiment would estimate air purified performance based on wet and dry conditions. Not only in PM2.5 purification process, but PM10 cleaning would be investigated in drizzle box comparing to dehydrate condition. Before proceeding to examine mop experiment, it will be necessary to determine hypothesis and objectives appeared in next point.

6.2 Hypothesis and objectives

The hypothesis of this chapter research is whether solid mop can reduce effectively indoor air PM10 and PM2.5, if so, which size of solid fibre could be the highest efficient mop for cleaning air pollutant. Another question is whether water spray can increase the efficiency of air purification or not, if so, how much percentages of efficiency can rise up. Lastly, multiple mops can improve air cleaning efficiency, if so, in what way. The objectives following above hypothesis are:

- To monitor PM10 and PM2.5 concentrations and ambient data in mop purified systems in both drizzle and dried conditions.
- To examine PM2.5 and PM10 concentrations and ambient data in case of multiple mops' purified system.
- To evaluate the air cleaning efficiency of mops and state ranking of efficiency on international standard.
- To compare the efficient results between drizzle and dried conditions.
- To compare the particle removal rate of various types of mop.
- To investigate the relationship between mop efficiency and ambient data.

The following part is a full report of methodology and equipment used in this experiment to carry on above objectives. Also all standard and benchmark are examined for ranking air cleaning efficiency of mops.

6.3 Methodology

In this mop experiment, mop work process would be investigated how it effectively clean indoor air within water spraying and dry boxes. As a safety policy for researcher, salt is safe for PM10 laboratory test (NIOSH 1996) because some granulated salt can easily falls down and salted water can be drained out. Not only the reason of safety, but size of table salt is ranged between 5 to 10 micron as same as PM10 size. Also the same character of construction dust and automobile dust is appeared as droppable by higher precipitation. Even Sodium Chloride is hydrophilic, initial source would be assured to be dry and unable to directly reach water spray before dropping down to the bottom of box. So table salt is one type of source as PM10 and body spray can be PM2.5 source in this experiment.

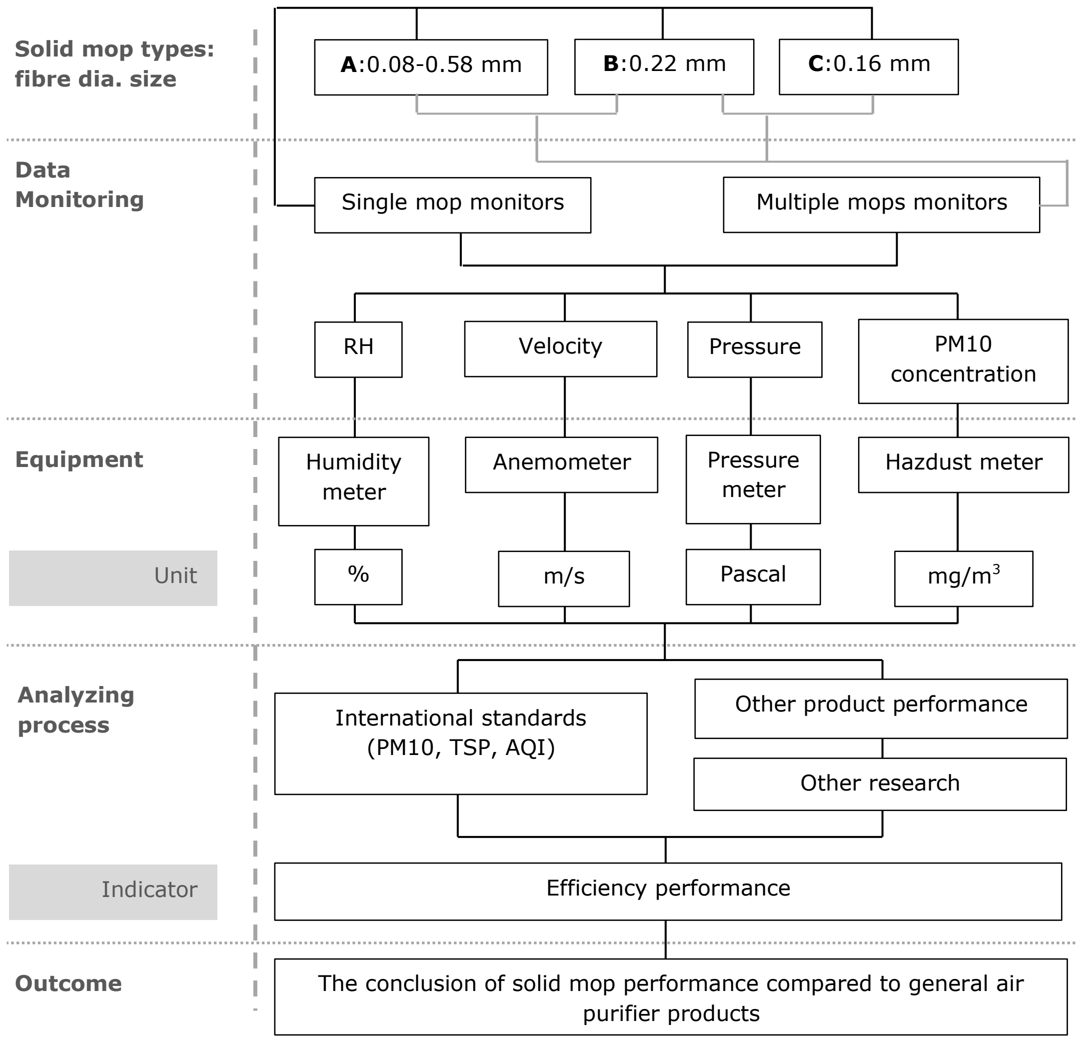

Figure 6-2 The diagram of solid mop evaluation process

According to **Figure 6-2**, three sizes of solid fibre were composed to be solid mop and installed to experimental box within water spraying and dry condition. Also fan blade was adapted into experimental box for controlling box flow rate and press. First of all, the initial samples consisted of three types of polymer fibre mops that could be called A, B and C in this experiment as the following **Figure 6-3**. The mop typed A was constructed by the main wooden core diameter 30 mm, length 50 mm as same as the specification in **Table 6-1**. Then 48 staggered tuft bunch of mixed polymer fibres would be stuck into wooden core by water proof glue. Each endurance brunch was a group of polymer fibres mixed between fibre diameter sized 0.08 mm and 0.58 mm. This resulted in thicker fibres that can support the physical construction of mop when thinner fibres help to increase surface for cleaning activity.

A:0.08-0.58mm B:0.22mm C:0.16mm

Figure 6-3 Three fibre sizes of each solid fibre mop type

In group B, fibres diameter sized 0.22 mm were casted with permanent glue into rubber core sized similar to A mop core. This type of fibre is adequately thick to support mop strength when rotating with motor. The single type of fibres diameter sized 0.16 mm were assembled into the third type of mop called C mop in this test. Because of strong enough fibres, staggered tuft formation of this fibre would be put into main wooden core as the same to A mop. However, one limitation of this test would be appeared in the number of fibre in each mop type. As a result of hand made in mop A and C, they got number of fibre less than mop B from factory made.

Table 6-1 Mop specification

Geometry	Type of mop		
	A	B	C
Fibre diameter (mm)	0.08-0.58	0.22	0.16
Number of fibre (n)	9,312	10,688	46,128
Mop Length (mm)	50	50	50
Core diameter (mm)	30	30	30
Mop diameter (mm)	160	160	160

To evaluate the potential of air PM10 cleaning, each mop was installed in the middle of experimental box with water spraying. Then salt would be mixed to inlet air as the source of PM10 until the system reaching the steady state. PM10 was monitored both from inlet and outlet in order to calculate the efficiency of particulate cleaning. Then another source of air pollutant, body spray, would be replaced in this experiment for investigating PM2.5 purified performance. As a result, the equipment of this experiment will be examined in the next session.

Table 6-2 Equipment for mops evaluating experiment

No.	Types	Model	Position	Data
1	Dust meter	DPM-4000™ Real-time Personal Diesel Particulate Monitor	Inlet and outlet of experimental box	$PM_{2.5}$, PM_{10} concentration (mg/m^3)
2	Pressure meter	Digitron 2000 Series Pressure Meters Manometers	Measuring the pressure between box inlet and outlet	Pressure (pascals)
3	Anemometer	Hot wire anemometer AVM 714	Inlet and outlet of experimental box	Velocity (m/s)
4	Data logger	Data Taker DT85 Data Logger	Connecting to Rh probes	-
5	Humidity probes	HMP45A Humidity and temperature probes	Connecting between Data logger and experimental box	Rh (%), Temperature (^oC)

To ensure reliability of the experimental results, the comparison of all equipment was in chapter 3 and then the results would be compared to other research. All equipment in mop experiment is appeared in **Table 6-2** as five types of parameter. Common installation of equipment is both inlet and outlet of experimental box and specific positions are in details explained as well. To control pressure and velocity in this testing, fan motor would be turned on until steady state before carrying on whole process of experiment. Humidity and temperature were dependent variables depended on water spraying, inlet air and velocity. To monitor dust concentration in this experiment, both PM2.5 and PM10 concentrations could be monitored by Hazdust particle monitor in unit mg/m^3. All equipment would be installed in poly carbonate vinyl box with water proof sealed lid.

In this experiment, the dimensions of plastic box were width 41 cm, length 51 cm and height 45 cm. Then each mop core would be connected directly to motor with main metal core diameter 8 mm. Even though the maximum ability of rotation in this motor was 1420 rpm, this experiment was set rotation at 340 rpm. That was fast enough to evaluate dust cleaning efficiency (Riffat & Ma 2012). After completing the mop, each type of mop would be installed in the same core with fan blade and motor controlled speed and rotating direction. To increase air cleaning performance for solid mop, water spraying set was installed to rise up relative humidity and helped novel mop to clean particulate matter as illustrating in **Figure 6-4**.

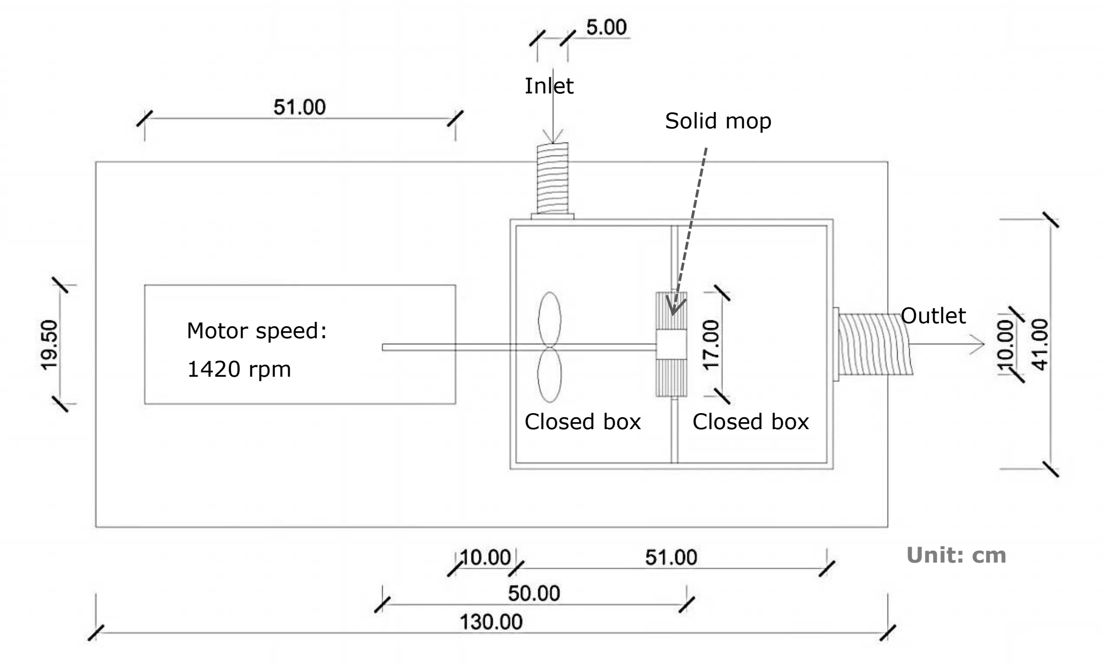

Figure 6-4 The experimental box of air purifier evaluation on mops

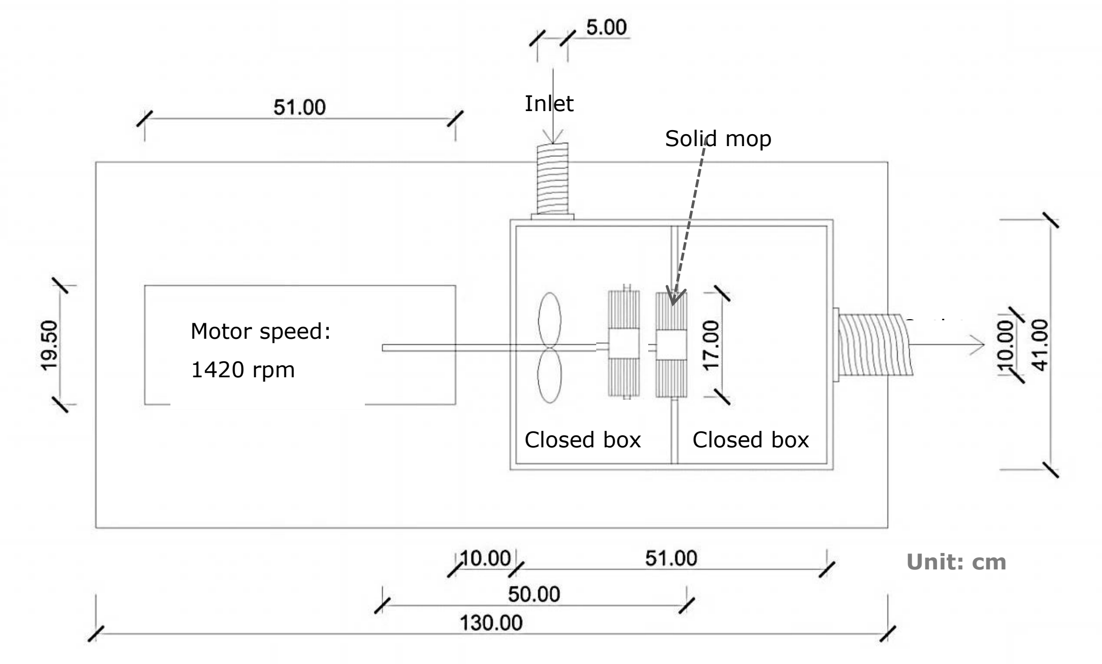

Figure 6-5 The extended experimental box of air purifier evaluation on multiple mops

According to **Figure 6-4**, to monitoring data from this experiment, there was separated into 2 sides in terms of inlet and outlet parts. Both parts will be monitored PM2.5, PM10, relative humidity, pressure, velocity and temperature in order to calculate MERV and compare air cleaning efficiency rank to international standards and other research. Also **Figure 6-5** was the model of experimental extension to clarify the efficiency of multiple mops at the end of this study.

From previous research, 160 minutes was adequate time for air cleaning test of photovoltaic mop (Riffat & Ma 2012). However, this experiment will be expanded period of air cleaning because of different air cleaning process by water spray rather than photovoltaic system. To compare dust removal rate, inlet dust concentrations were monitored in the same period of 900 seconds. Then the peak and lowest data would be calculated for comparing the performance of air cleaning.

As depending on monitor's memory, it is possible to set Hazdust monitoring for various short and long period depended on steady state of PM concentration level. Then steady state results in both inlet and outlet parts would be evaluated mops efficiency followed MERV process. The standard of PM2.5 concentration in 24-hour period should not exceed level at 35 μg/m^3 and PM10 concentration should not be higher than 150 μg/m^3 (EPA 1990, updated on Dec 14, 2012).

According to MERV ranking in chapter 3, PM2.5 and PM10 can be gathered into E2 and E3 groups respectively. So the calculation of air cleaning efficiency would be calculated differently by **Equation 3-1** and **3-2** depended on type of pollutant (Doty & Turner 2013). For PM2.5 cleaning, E2, air cleaning efficiency calculation in **Equation 3-1** would be the main process. Nevertheless, in terms of E3 or PM10 concerning, dust arrestance would be calculated as same as **Equation 3-2**.

For the purpose of investigating air cleaning performance, equipment and experimental box were set in order to collect dust concentration both inlet and outlet part of box. Then dust data from both inlet and outlet would be compared to NAAQs depended on type of dust. However, the condition of spraying water would be considered to be main factor of air cleaning performance and concluded to be a notification of mop adaptation in general purifiers. For the estimation of air cleaning efficiency, dust results would be calculated and compared to MERV level. All of results and estimated data will be demonstrated in the following section.

6.4 Results

In each type of mop, the results will be shown in PM2.5 concentration in case of dry and wet conditions, PM10 concentration in case of dry and wet conditions and ambient data. Then selective multiple mop results will be examined after single mop results. Lastly, relationship analysis will appear at the end of this chapter. The results of all data will be given in regime codes in **Table 6-3**.

Table 6-3 Data code in all experiments

Mop		PM	Condition	Code of experiment
Type	Fibre dia. (mm)			
A	0.08-0.58	PM2.5	Dry	A-D PM2.5
			Wet	A-W PM2.5
		PM10	Dry	A-D PM10
			Wet	A-W PM10
B	0.22	PM2.5	Dry	B-D PM2.5
			Wet	B-W PM2.5
		PM10	Dry	B-D PM10
			Wet	B-W PM10
C	0.16	PM2.5	Dry	C-D PM2.5
			Wet	C-W PM2.5
		PM10	Dry	C-D PM10
			Wet	C-W PM10
C,A	0.16, 0.08-0.58	PM2.5	Dry	CA-D PM2.5
			Wet	CA-W PM2.5
B,C	0.22, 0.16	PM10	Dry	BC-D PM10
			Wet	BC-W PM10

6.4.1 Mop A

To begin with mop typed A with solid fibre diameter sized 0.08-0.58 mm, the results will be illustrated in terms of removal performances of both PM2.5 and PM10 in dry and wet conditions as shown in **Figure 6-6** and **6-7**.

From **Figure 6-6**, line chart illustrates the PM2.5 cleaning performance of mop A within dry and wet condition. It can be seen that both PM2.5 concentrations in dry and wet conditions dropped dramatically from around 18.00 mg/m^3 to lower 0.40 mg/m^3 throughout the period of 900 seconds. Also PM2.5 concentration in wet condition was lower than those in dry condition as seen in average PM2.5 concentrations at 2.129 mg/m^3 and 2.623 mg/m^3 respectively. Dust removal rates of A-D PM2.5 and A-W PM2.5 were at 0.020 mg/sec and 0.019 mg/sec respectively. However, in shorter period, removal rate was possibly to higher

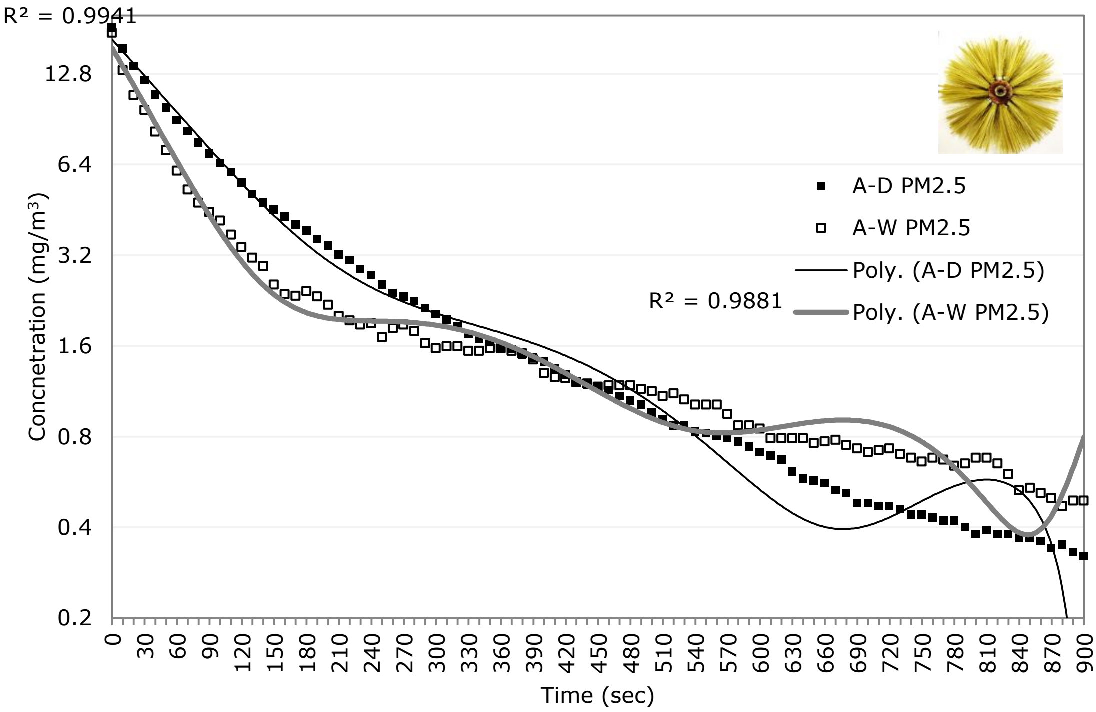

Figure 6-6 Fume cleaning performance in solid fibre mop typed A sized 0.08-0.58 mm

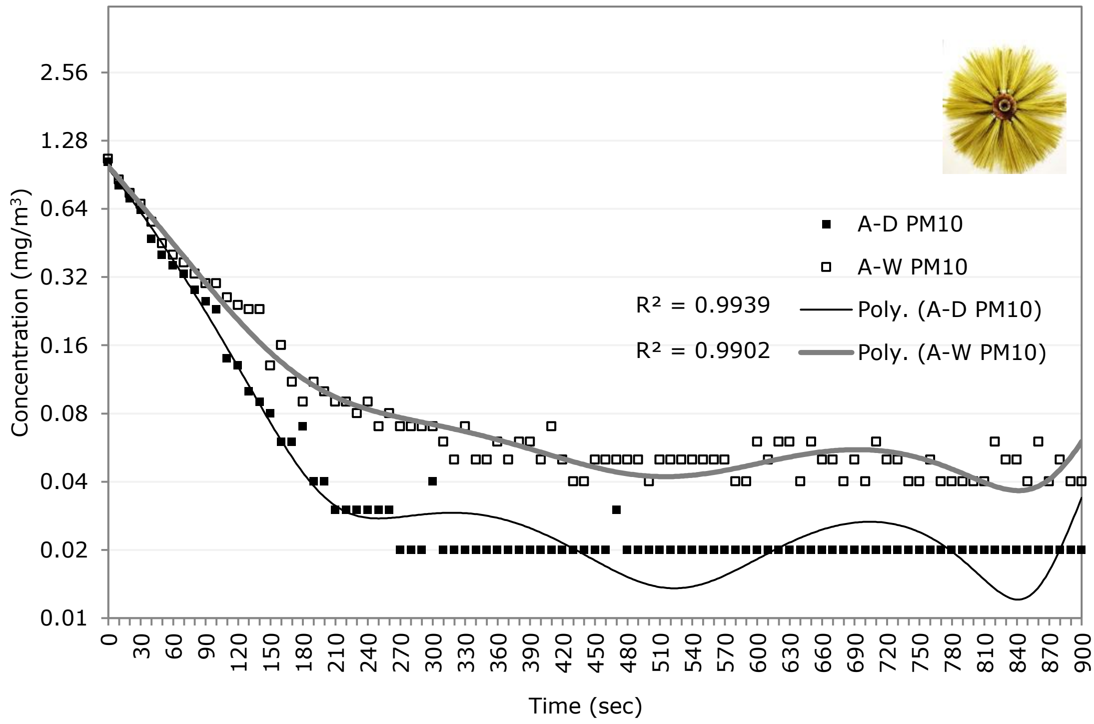

Figure 6-7 Salt cleaning performance in solid fibre mop typed A sized 0.08-0.58 mm

Turning to PM10 purification, salt was used to be source in experimental inlet and the test would be carried on in two conditions as dry and wet mop environment.

In **Figure 6-7**, line graph demonstrates PM10 concentration reduction in both dry and wet conditions. It can be seen that dust concentration reduced dramatically during the first 300 seconds before getting steady state until the end of 900-second period. PM10 concentration in dry condition was lower than those in wet condition with average concentration at 0.086 mg/m^3 and 0.126 mg/m^3 respectively. Averagely, removal rates of both dry and wet conditions were at 0.001 mg/sec during the 900-second estimation. For shorter period, air purification rate was possibly higher.

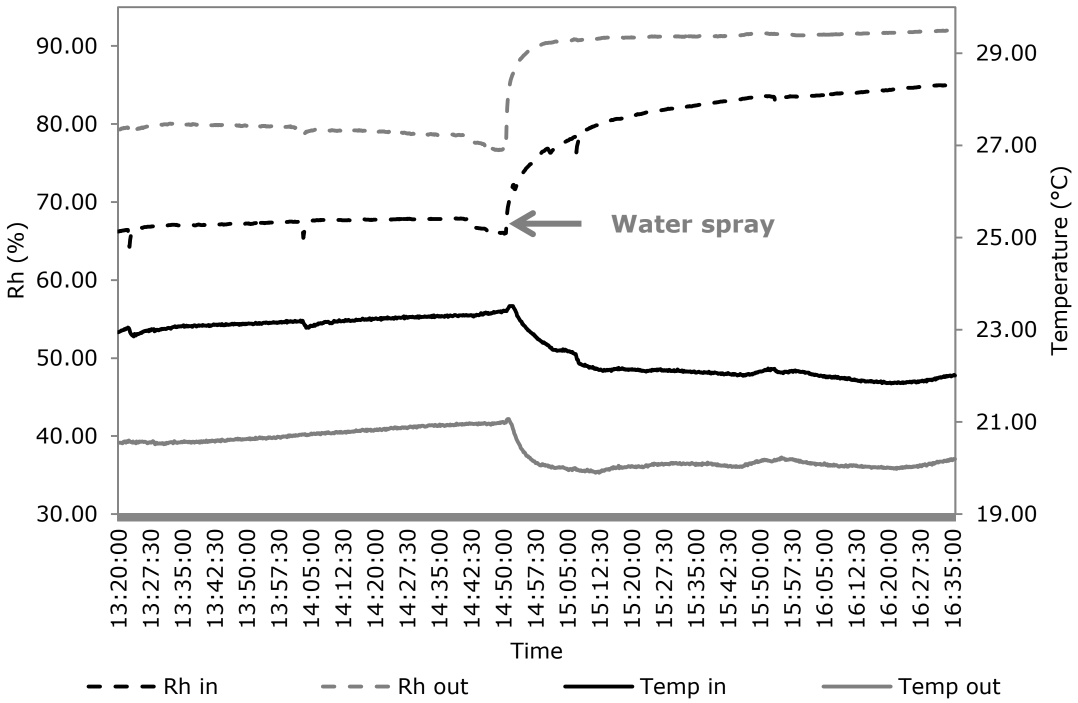

Figure 6-8 Ambient data in the experiment of solid fibre mop typed A sized 0.08-0.58 mm

In **Figure 6-8**, line chart shows level of relative humidity (Rh) and temperature both inlet and outlet of testing box throughout the period of 3.12 hours. It can be seen that Rh level related conversely to temperature level both in and out of box. When spraying water at 14:48:50PM, the relationship between Rh and temperature stood still contrasting as increasing relative humidity and reducing temperature.

6.4.2 Mop B

Another type of fibre mop is mop B composed with polymer fibre diameter sized 0.22 mm. To clarify mop B dust removal performance, above process of experiment would be repeated in dry and wet condition. The results of mop B dust removal performance will be show in **Figure 6-9 to 6-10** and meteorological data will be demonstrated in following **Figure 6-11**.

According to **Figure 6-9**, line graph illustrates PM2.5 monitoring in both dry and wet conditions throughout the 900 second period. It is apparent from the chart that entry and exit PM2.5 concentrations decreased moderately from around 18.0 mg/m^3 to 1.0 mg/m^3 at the end of period. The average of dust concentrations in dry condition was lower than those in wet condition at 5.51 mg/m^3 and 6.36 mg/m^3 respectively. Moreover, the average dust reductive rate of both dry and wet cases were at 0.019 mg/sec in 900-second estimation; while these rate could be higher in shorter period based on chart slope.

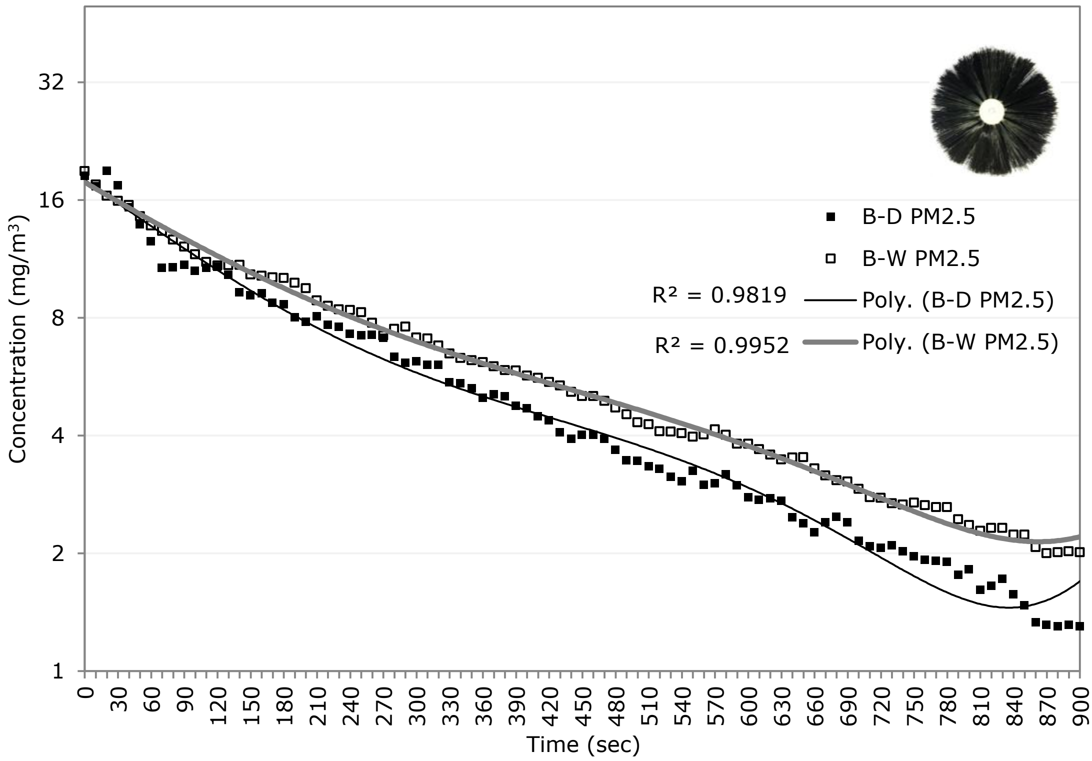

Figure 6-9 Fume cleaning performance in solid fibre mop typed B sized 0.22 mm

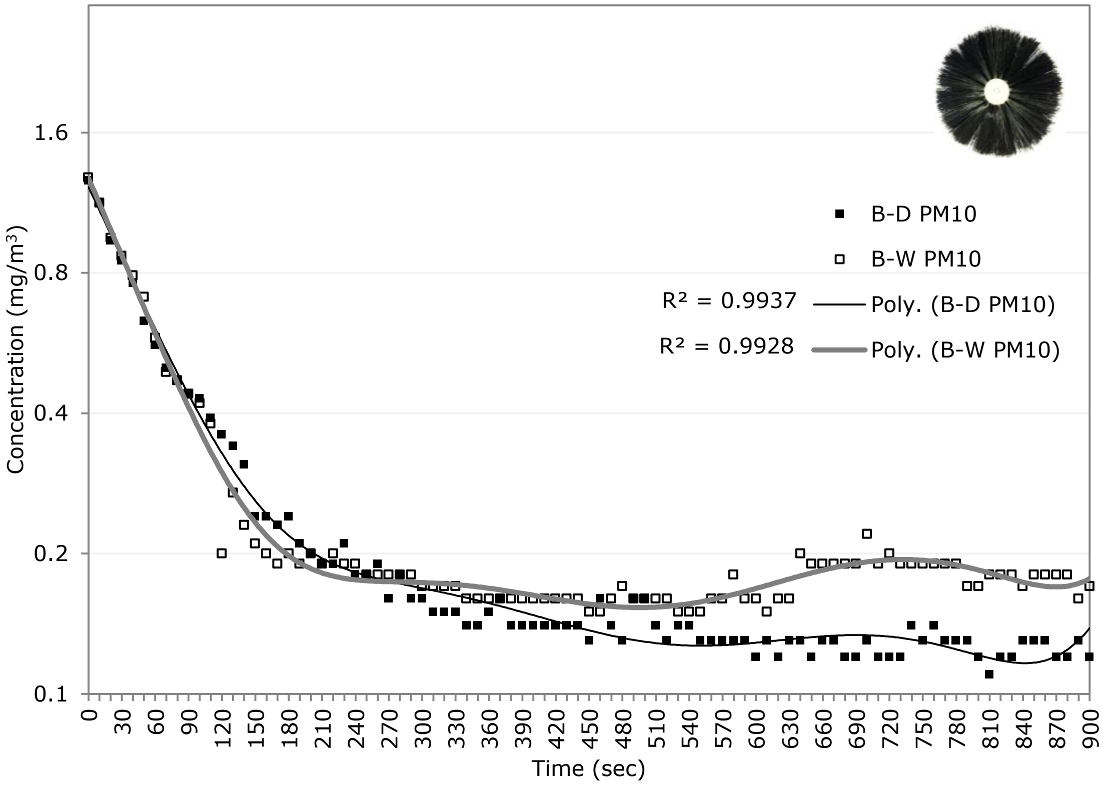

Figure 6-10 Salt cleaning performance in solid fibre mop typed B sized 0.22 mm

Having investigated PM2.5 cleaning by mop B already, PM10 purifying will be now focused cleaning performance in dry and wet circumstances. **Figure 6-10** provides PM10 monitoring of mop B monitoring throughout the 900-second period. It can be seen that inlet PM10 concentration dropped rapidly to approximate 0.13 mg/m^3 until the end of test. The average of PM10 concentration in both dray and wet environments were 0.22 mg/m^3 and 0.24 mg/m^3 respectively. Also the averages of dust reductive rate of dry and wet conditions were same at 0.001 mg/sec within 900 second monitoring.

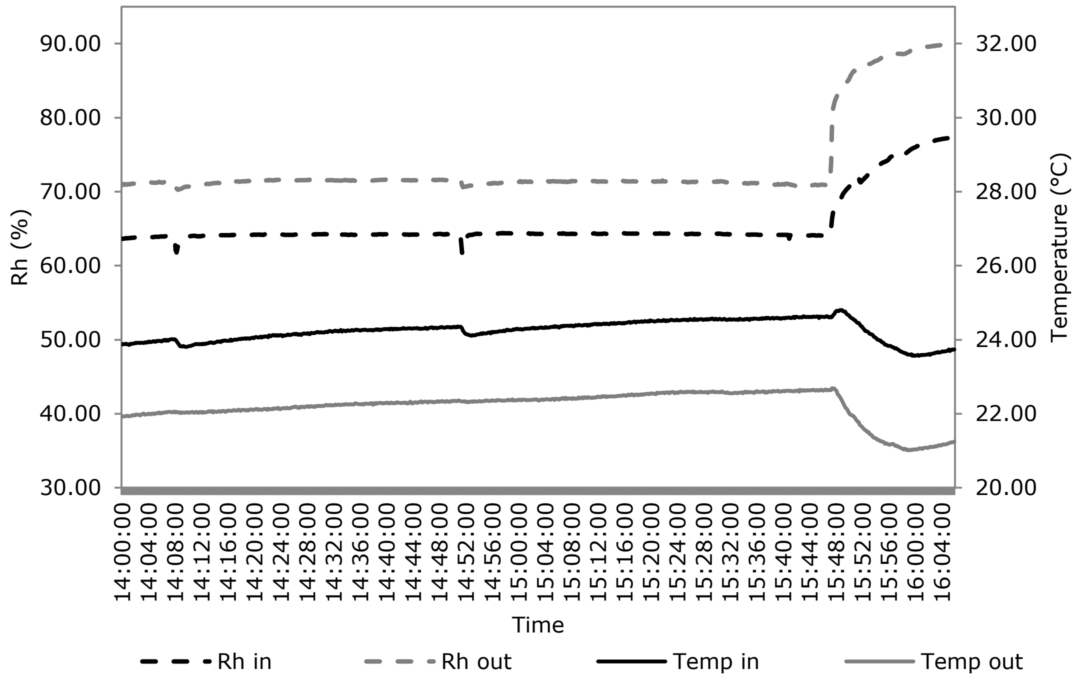

Figure 6-11 Ambient data in the experiment of fibre solid mop typed B sized 0.22 mm

In **Figure 6-11**, histogram demonstrates relative humidity (Rh) and temperature both in and out of testing box throughout 2.06 hours period. It can be seen that Rh level related contrastively to temperature level both inlet and outlet. When spraying water at 15:48:00PM, the relationship between Rh and Temperature stood still contrasting as increasing Rh and reducing temperature.

6.4.3 Mop C

Turning now to another fibre mop type, mop C composed with 46,128 fibres diameter sized 0.16 mm. The efficiency experiment would be carried on in dray and wet conidition in both PM2.5 and PM10 purification as followed **Figure 6-12 to 6-13**. Then testing ambient data will be demonstrated in **Figure 6-14** after mop C evaluating results. In **Figure 6-12**, line chart indicates the levels of inlet PM2.5 reductive concentration when evaluating air cleaning performance of mop C in dry and wet conditions in the period of 900 seconds. It is evident that both PM concentrations in dry and wet conditions declined dramatically to 0.40 mg/m^3 and 0.18 mg/m^3 respectively. The average dust concentrations of dry and wet environments were at 1.84 mg/m^3 and 1.12 mg/m^3 respectively. Also the dust reductive rates in case of dry and wet conditions were at 0.017 mg/sec and 0.016 mg/sec.

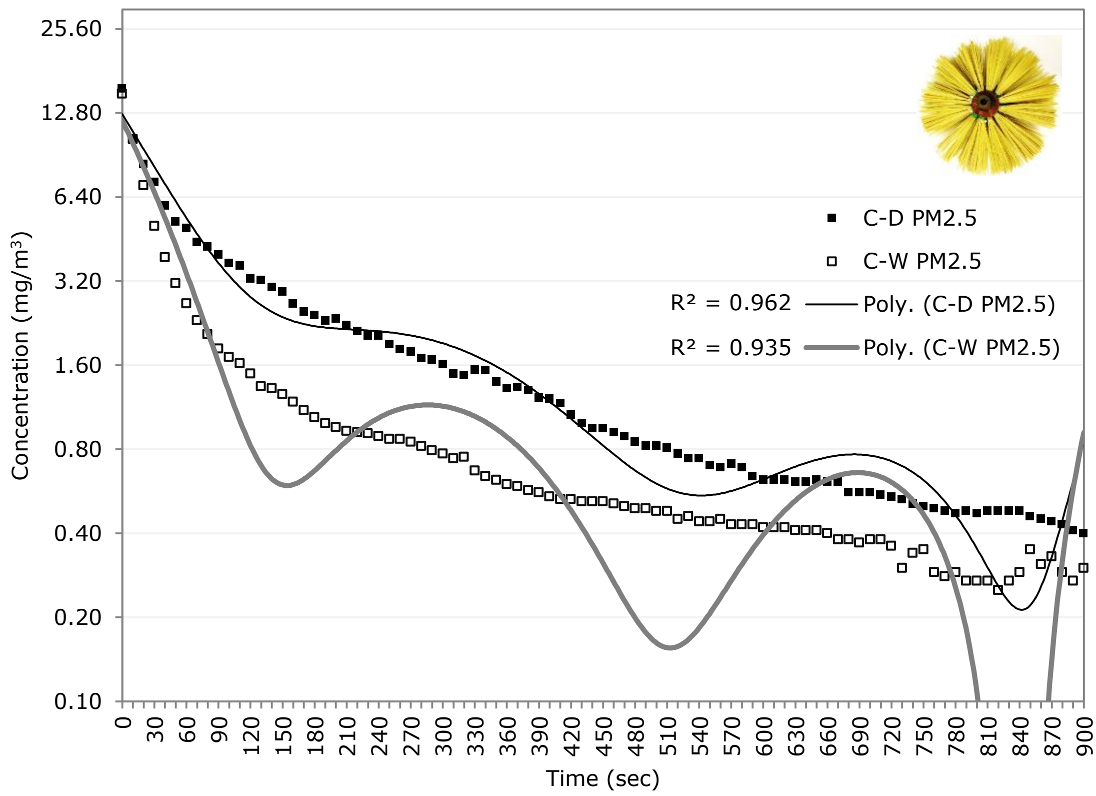

Figure 6-12 Fume cleaning performance in solid fibre mop typed C sized 0.16 mm

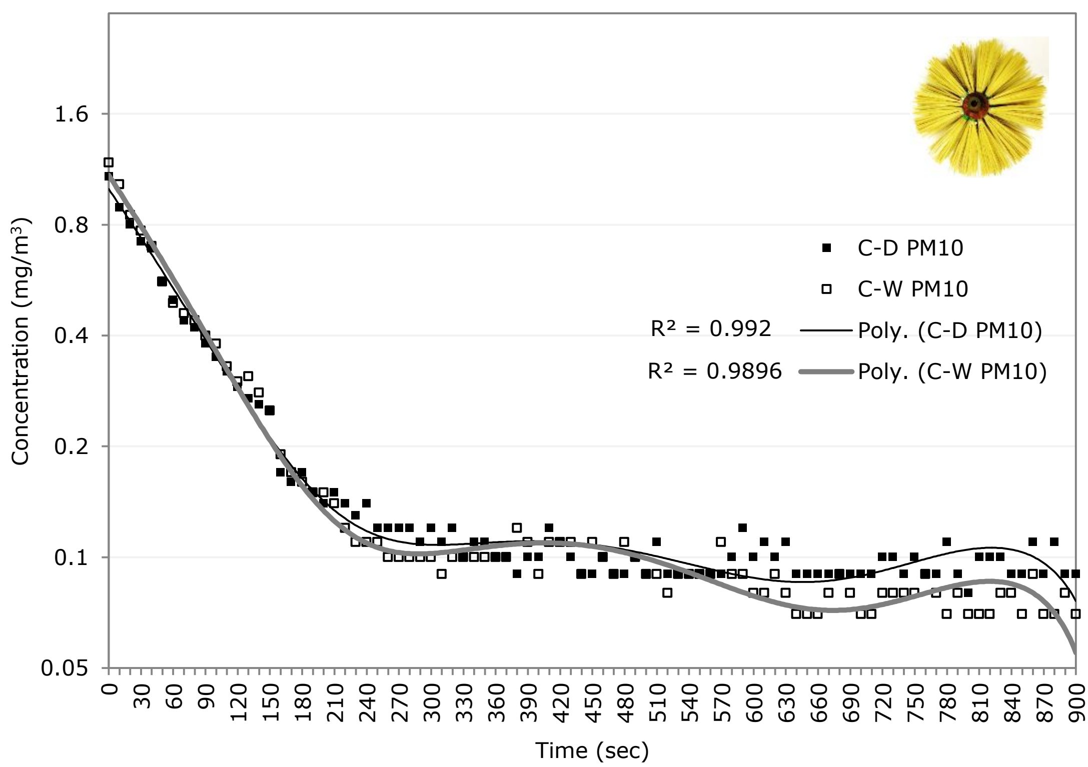

Figure 6-13 Salt cleaning performance in solid fibre mop typed C sized 0.16 mm

To evaluate PM10 purification, line chart in **figure 6-13** demonstrates the level of salt concentration by solid fibre mop C in both dry and wet conditions throughout 900 second. It is apparent that dust concentrations in dry and wet conditions dropped intensely to nearly 0.10 mg/m^3 in the first 200 seconds. The average of duct concentration of mop C cleaning in dray and wet conditions were at 0.18 mg/m^3 and 0.17 mg/m^3 respectively. The average dust reductive rates in dry and wet conditions were similar at 0.001 mg/sec.

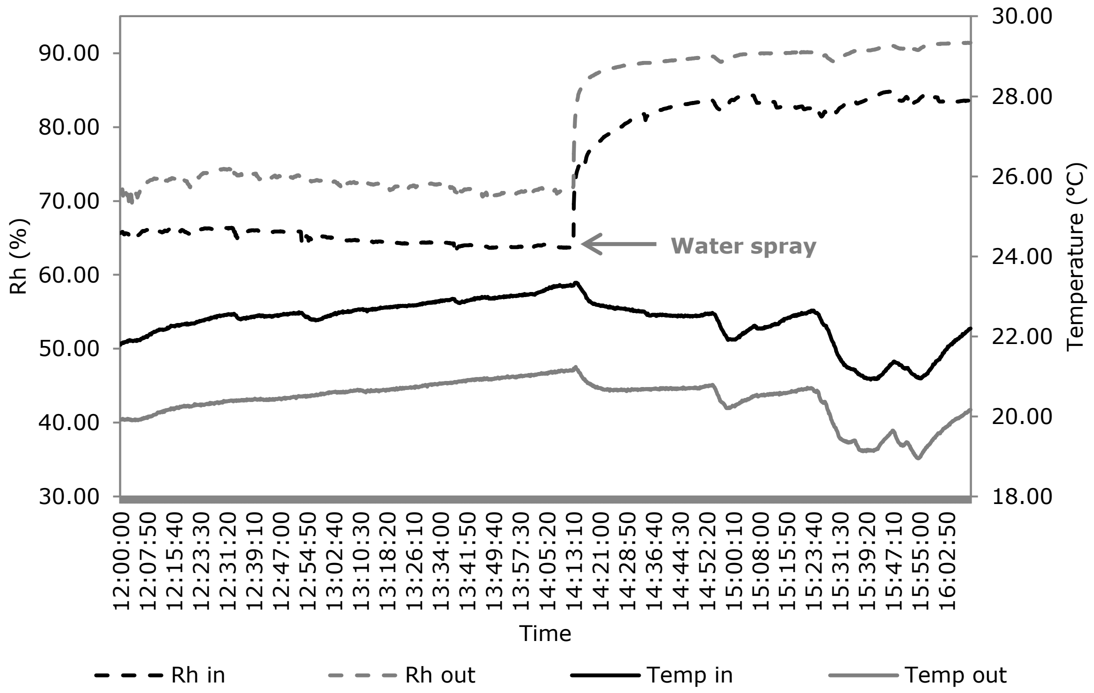

Figure 6-14 Ambient data in the experiment of solid mop typed C sized 0.16 mm

As **Figure 6-14**, line graph shows relative humidity (Rh) and temperature both in and out of testing box in mop C experiment throughout the 4.03-hour period. It can be seen that Rh level related oppositely to temperature level both inlet and outlet. After spraying water at 14:10:00PM, the relationship between Rh and Temperature stood still contrasting as increasing Rh and decreasing temperature.

6.4.4 A combination of mop A and C for cleaning PM2.5

As the combination of mop C and A, **Figure 6-15** demonstrates the reductions of PM2.5 concentration in both dry and wet conditions throughout the period of 900 seconds. It is evident that respiratory dust concentration dropped moderately from approximately 18 mg/m^3 to 0.50 mg/m^3 in dry condition and 0.27 mg/m^3 in wet condition during the 900 seconds period. The average of PM2.5 concentrations in dry and wet conditions were 2.99 mg/m^3 and 2.36 mg/m^3 respectively. Also the average of dust removal rates in dry and wet conditions were at 0.020 mg/sec and 0.021 mg/sec respectively during the 900-second monitoring.

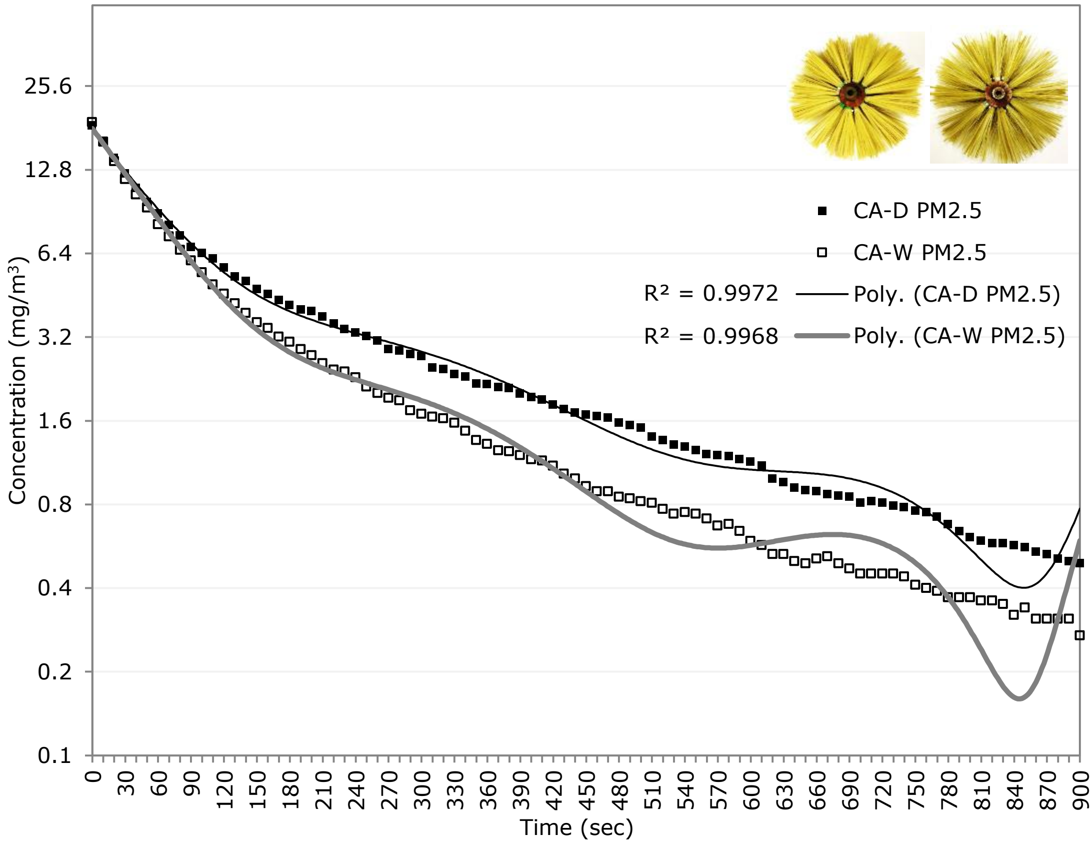

Figure 6-15 Fume cleaning performance in multiple fibre mops C and A

The ambient data monitors in multiple mops to purify PM2.5 are in **Figure 6-16** as air relative humidity and temperature over 2.25 hours period. It is apparent that reverse relationship was happened between relative humidity and temperature as higher humidity affecting lower air temperature.

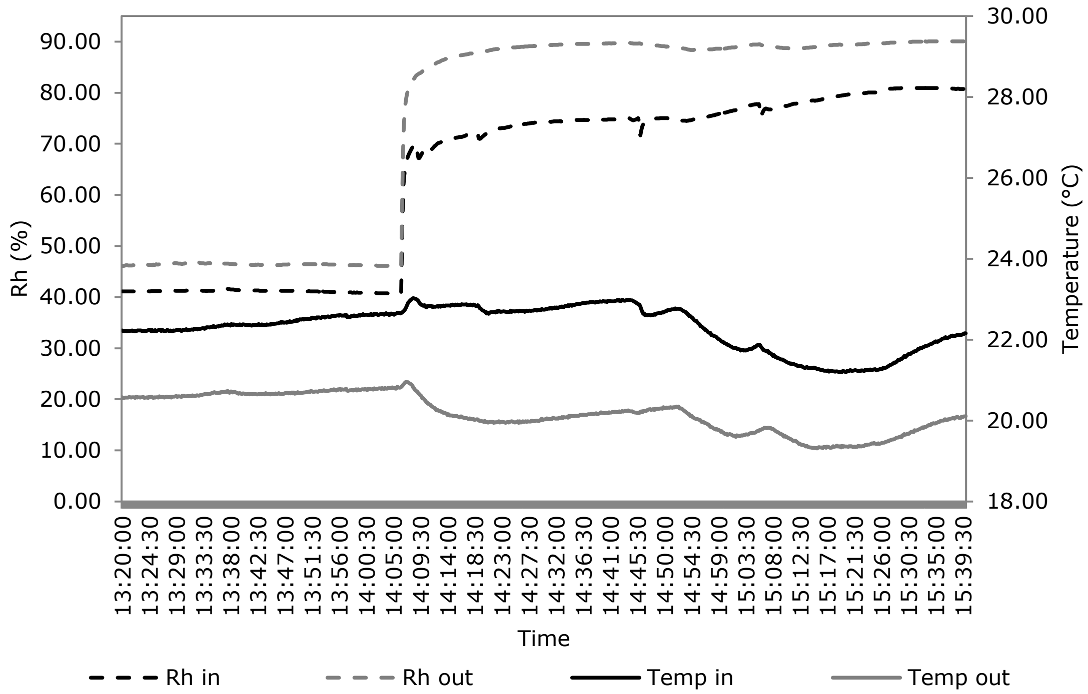

Figure 6-16 Ambient data in the experiment of multiple fibre mops C and A

6.4.5 A combination of mop B and C for cleaning PM10

The next extended experiment was multiple mops evaluation in PM10 cleaning performance mixed between mop B and C. As can be seen from **Figure 6-17**, line chart reported PM10 concentration both in dry and wet conditions throughout 350 seconds period. It is clear that PM10 concentration dropped dramatically in wet condition and decreased moderately in dry condition. The average PM10 concentrations in dry and wet environments were at 0.19 mg/m^3 and 0.38 mg/m^3 respectively. Also the reductive rates of PM10 in dry and wet conditions were at 0.003 mg/sec and 0.005 mg/sec in the period of 350 seconds.

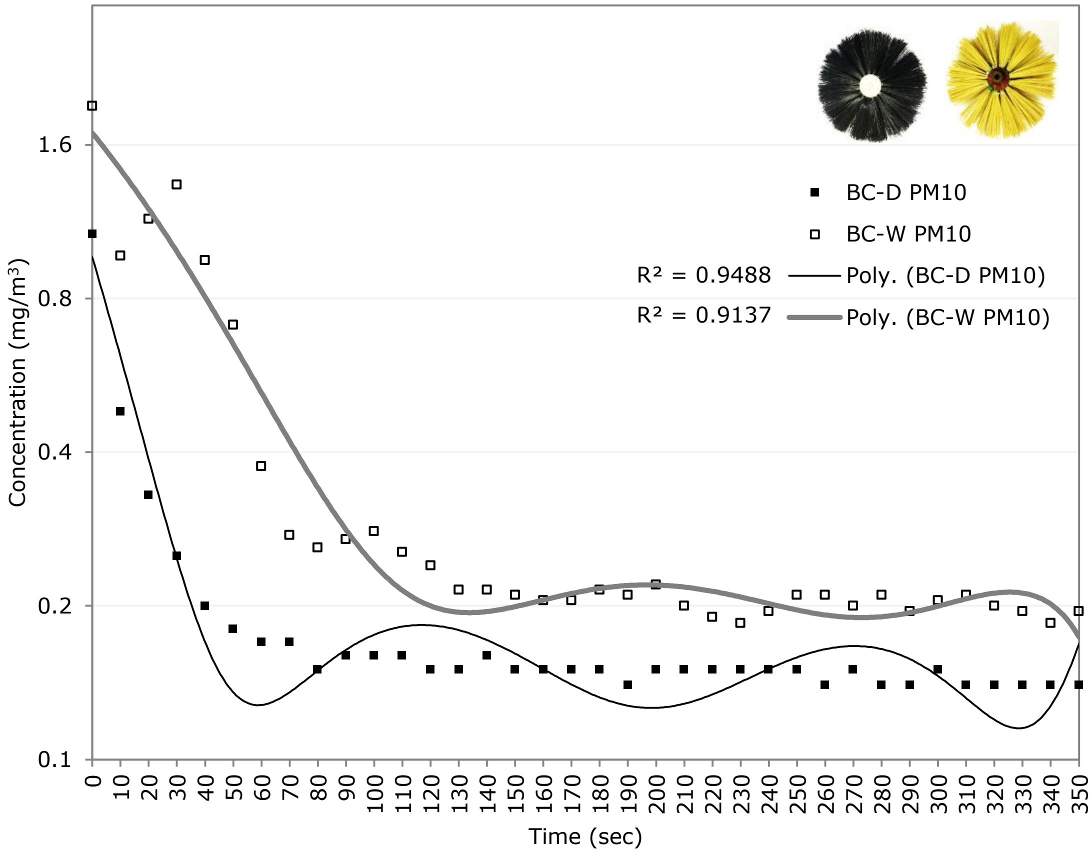

Figure 6-17 Salt cleaning performance in multiple fibre mops B and C

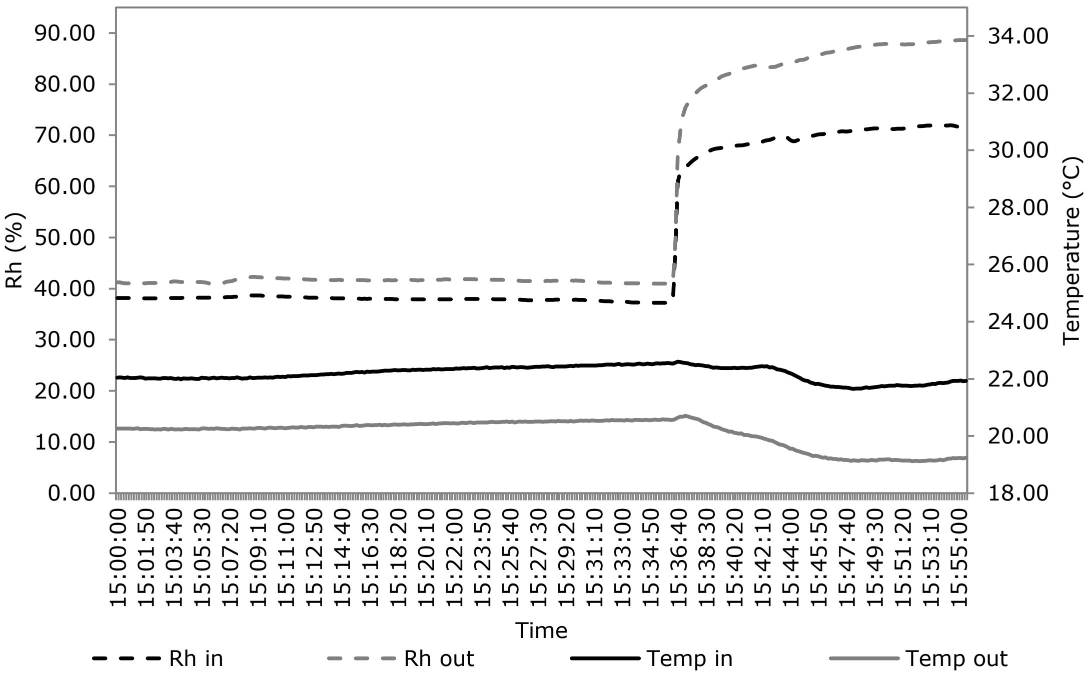

Figure 6-18 Ambient data in the experiment of multiple fibre mops B and C

The ambient data monitoring of multiple fibre mops B and C are in **Figure 6-18** as air relative humidity and temperature over 1hours period. It is apparent that reverse relationship was happened between relative humidity and temperature as higher humidity affecting lower air temperature. According to limitation of laboratory close, this experiment was done in shorter period than other fibre mop tests.

6.4.6 The validation of solid fibre mop evaluation

As all results of PM purifier evaluation, it can be seen that PM10 dropped more dramatically than PM2.5 throughout the 900 seconds period. This can be explained by the same result in heavier ions falling down faster because of weight gravity (Černecký et al. 2015). To concern reductive trend, this inlet PM2.5 purification could be compared to the study case testing photovoltaic mop in **Figure 6-19** (Riffat & Ma 2012) as exponential reduction. For validation, this comparable trend of dust removal would confirm all above experimental results in this study. However, this comparative result did not concern the different thickness and diameter of mop.

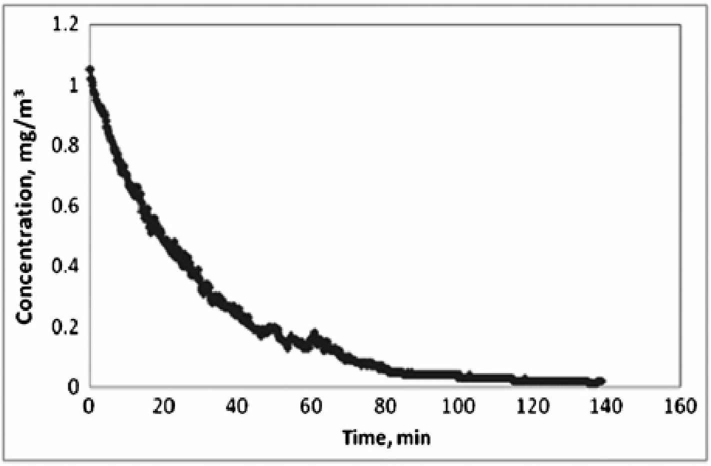

Figure 6-19 The diesel dust purification in a photovoltaic mop (Riffat & Ma 2012)

6.4.7 The conclusions of dust removal performance

After repeating experiment for three times in each case and collecting data as showing above, the conclusion of air cleaning performance is briefly showed in **Table 6-4** in terms of dust removal concentration (mg/m^3), dust removal rate (mg/sec) and dust average concentration (mg/m^3). In part of inlet, it can be seen that dust removal performances relate directly to size of particle and removal time. In every mop test, the removal concentrations of PM2.5 in 900 seconds were obviously higher than those in 350 seconds; while PM10 removals were quite similar between 900 and 350 seconds. This is because PM10 is heavier than PM2.5 that can bring about shorter time to fall down bottom box. Also dust removal rates in PM2.5 and PM10 were higher in shorter period that resulted from dramatic reductions at early testing period.

As steady state of PM10 concentration after first 350 second, removal rates of PM10 could be compared in the period of 350 seconds. Also the result of mop B and C combination was done in only 350 seconds as an accidental close in laboratory. However, in case of PM2.5, the removal rate should be fixed on estimation in 900 seconds for getting steady state.

Table 6-4 Dust removal performances of various types of solid fibre mops

Code	Dust removal				Avg. concentration (mg/m^3)
	Concentration (mg/m^3)		Rate (mg/sec)		
	900 sec	350 sec	900 sec	350 sec	
A-D PM2.5	17.88	16.55	0.020	0.047	2.62
A-W PM2.5	16.98	15.98	0.019	0.045	2.13
A-D PM10	1.01	1.01	0.001	0.003	0.09
A-W PM10	1.02	1.01	0.001	0.003	0.13
B-D PM2.5	17.10	13.13	0.019	0.038	5.52
B-W PM2.5	16.95	12.74	0.019	0.036	6.37
B-D PM10	1.14	1.12	0.001	0.003	0.23
B-W PM10	1.11	1.12	0.001	0.003	0.25
C-D PM2.5	15.25	14.26	0.017	0.041	1.84
C-W PM2.5	14.67	14.35	0.016	0.041	1.12
C-D PM10	0.99	0.97	0.001	0.003	0.18
C-W PM10	1.11	1.08	0.001	0.003	0.17
CA-D PM2.5	17.97	16.29	0.020	0.047	2.99
CA-W PM2.5	**18.70**	17.61	**0.021**	0.050	2.36
BC-D PM10	-	0.93	-	0.003	0.19
BC-W PM10	-	**1.71**	-	**0.005**	0.38

The highest of PM2.5 cleaning is demonstrated as a combination of mop C and A in wet conditions with dust removal concentration and removal rate at 18.70 mg/m^3 and 0.021 mg/sec respectively in the 900 seconds period. While in case of PM10, the highest performance of removal is shown as a combination of mop C and A in wet condition with dust removal concentration and removal rate at 1.71 mg/m^3 and 0.005 mg/sec respectively during the period of 350 seconds. However, these evaluating results may be resulted from system flow.

6.4.8 The efficiencies of fibre mops cleaning PM2.5 and PM10

After evaluating mop performance of dust removal in only inlet part, this section aims to evaluate mop efficiency to clean PM2.5 and PM10 in dry and wet condition. The efficiency was calculated from steady state of inlet and outlet dust concentrations following **Equation 3-1** and **3-2**.

Table 6-5 Air cleaning efficiency of various mops

Code	Avg. dust concentration in steady state (mg/m^3)		Avg. efficiency (%)
	Inlet	Outlet	
A-D PM2.5	0.99	0.98	1
A-W PM2.5	1.17	1.16	0
A-D PM10	0.02	0.02	0
A-W PM10	0.04	0.04	0
B-D PM2.5	3.67	3.31	10
B-W PM2.5	4.77	4.63	3
B-D PM10	0.13	0.12	6
B-W PM10	0.16	0.12	**25**
C-D PM2.5	0.94	0.61	**36**
C-W PM2.5	0.55	0.54	0
C-D PM10	0.10	0.09	13
C-W PM10	0.09	0.09	0
CA-D PM2.5	0.74	0.74	0
CA-W PM2.5	0.76	0.75	1
BC-D PM10	0.17	0.17	0
BC-W PM10	0.26	0.24	8

The mop evaluation based on steady state could identify real performance of fibre mop with same system flow. It can be seen in **Figure 6-5** that the highest efficiency of PM2.5 cleaning is mop C in dry condition and the highest efficiency of PM10 cleaning is mop B in wet condition. This is definitely different from the results of inlet dust removal as the highest performance shown in single solid fibre mop. Even cleaning efficiencies of mops could be estimated, but those efficiencies are still low comparing to MERV level in the next section.

6.5 Discussions

According to consider dust reductive rate in inlet part, the efficiency of fibre mop was not related to the period of reductive performance. In case of dust reductivity, an increasing number of mops could improve dust removal rate for both PM2.5 and PM10 cleaning. On the contrary, the steady state of dust concentration in inlet and outlet part was identified air cleaning performance of each mop. The results of cleaning efficiency did not show relating to the number of mop, but the diameter size of mop fibre and box aridity affected to mop efficiency.

Table 6-6 The efficiencies of air particle cleaning in various types of mop in dry and wet experimental conditions

Code	Avg. efficiency (%)	Standards	Avg. geological data	
			Rh (%)	Temp (°C)
A-D PM2.5	1	-	73.28	21.78
A-W PM2.5	0	-	85.51	21.08
A-D PM10	0	-	72.14	22.14
A-W PM10	0	-	80.95	21.80
B-D PM2.5	10	-	67.65	23.04
B-W PM2.5	3	-	87.36	22.33
B-D PM10	6	MERV1	67.57	23.59
B-W PM10	25	MERV5	80.03	22.78
C-D PM2.5	36	-	68.65	21.59
C-W PM2.5	0	-	83.52	21.72
C-D PM10	13	MERV1	83.80	21.36
C-W PM10	0	MERV1	84.68	21.31
CA-D PM2.5	0	-	79.44	21.81
CA-W PM2.5	1	-	82.19	21.15
BC-D PM10	0	MERV1	50.89	20.87
BC-W PM10	8	MERV1	75.00	20.87

After evaluating air cleaning efficiency, all types of mop can be ranked by MERV level in **Table 6-6** with geological data in experimental box. Based on 20 levels of MERV, for cleaning PM10, mop B in wet condition can reach MERV5 ($20 \leq E_3 < 35$) as the highest efficiency performance among study mops. Moreover, PM10 cleaning efficiency was identified at MERV 1($E_3 < 20$) in case of mop C, a combination of mop B and C, and mop B in only dry condition. To be noted, the rank of efficiency for PM2.5 was obligated to get high efficiency of PM10 cleaning ($85 \leq E_3$). So the efficiency of PM2.5 cleaning in this study could not ranked by MERV standards.

Turning to geological factors consideration, lower temperature results generally in higher relative humidity as a common behaviour in psychometric chart. So improving relative humidity would reduce temperature as shown data in **Table 6-6** and **Figure 6-20**. However, there were only few exceptions that air temperature in PM2.5 purification in mop C testing was higher in case of wet condition and temperature remained the same in multiple mops B and C test.

In **Figure 6-20**, the graph demonstrates air cleaning efficiency of various mops based on average temperature and relative humidity. It can be seen that drizzle spray brought about higher air humidity but it could improve air cleaning efficiency in some types of mop only. In details, air cleaning performances could improve in drizzling condition such as PM10 purification in mop B and a combination of mop B and C and PM2.5 purification in a combination of mop C and A. Also arid condition of test brought possibly about better results in air particle purifying of mop A, mop C and PM2.5 purifying of mop B.

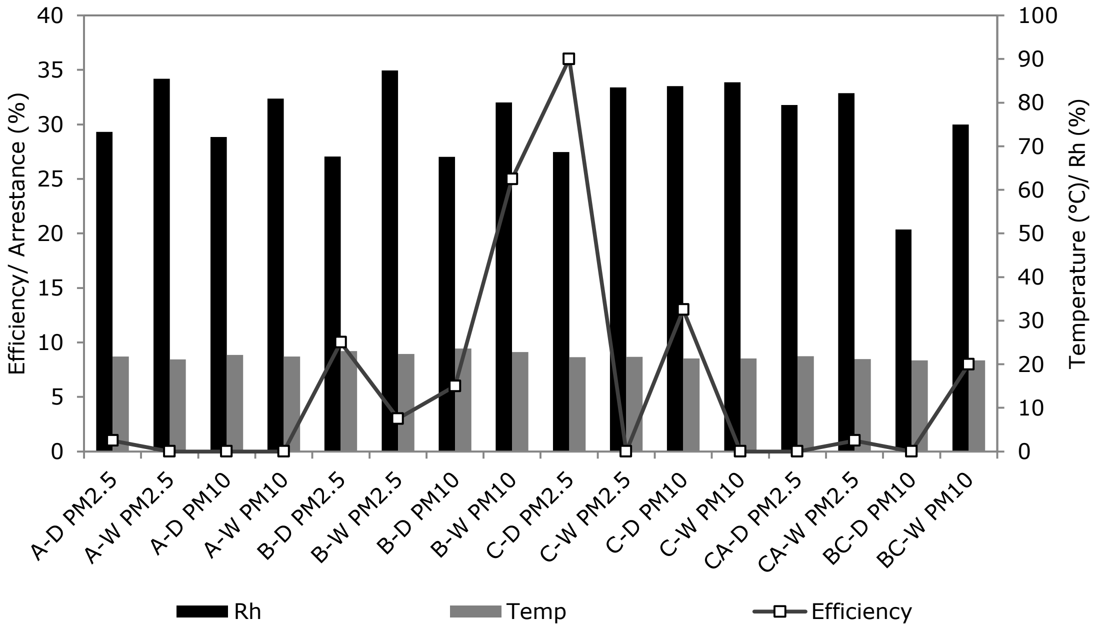

Figure 6-20 The efficiency/arrestance of dust cleaning in different types of mop

Even no significant statistical relationship between mop efficiency and ambient data, **Table 6-7** shows four groups of relationship related to spraying water on mops. The first group of higher relative humidity condition demonstrated negative effects on cleaning efficiency of mop and box temperature especially PM2.5 purifying tests in mop A and mop B and PM10 purifying tests in mop C. Secondly, the results changed to positive relationship between humidity and dust cleaning efficiency in case of PM10 purifications in mop A and mop B and PM2.5

purification in the combination of C and A. Thirdly, negative relationship between relative humidity and PM2.5 cleaning efficiency in mop C evaluation. Lastly, uncommon relationship was found in case of PM10 cleaning by the combination of mop B and C that humidity related positively to air temperature and air cleaning efficiency. These last two situations were rarely happened relied on other geological factors such as saturation pressure and dew point temperature.

Table 6-7 Three groups of relationship between air cleaning efficiency and ambient data in mop evaluative tests

Group	Mop code	Average data			Direction of change		
		eff. (%)	Rh (%)	Temp (^oC)	eff.	Rh	Temp
1	A-D PM2.5	1	73.28	21.78	-1.00	12.23	-0.70
	A-W PM2.5	0	85.51	21.08			
	B-D PM2.5	10	67.65	23.04	-7.00	19.70	-0.71
	B-W PM2.5	3	87.36	22.33			
	C-D PM10	13	83.80	21.36	-13.00	0.88	-0.05
	C-W PM10	0	84.68	21.31			
2	A-D PM10	0	72.14	22.14	0.00	8.81	-0.35
	A-W PM10	0	80.95	21.80			
	B-D PM10	6	67.57	23.59	19.00	12.46	-0.80
	B-W PM10	25	80.03	22.78			
	CA-D PM2.5	0	79.44	21.81	1.00	2.75	-0.66
	CA-W PM2.5	1	82.19	21.15			
3	C-D PM2.5	36	68.65	21.59	-36.00	14.87	0.13
	C-W PM2.5	0	83.52	21.72			
4	BC-D PM10	0	50.89	20.87	8.00	24.11	0.00
	BC-W PM10	8	75.00	20.87			

6.6 Conclusions

Following the objectives of this study, PM2.5 concentration monitor was found averagely to decrease moderately from more than 15 mg/m^3 to below 1.0 mg/m^3 in 900 second period, while PM10 concentration dropped more dramatically from approximate 1.15 mg/m^3 to around 0.10 mg/m^3 in very short period as the first 350 seconds. This resulted from higher mass and weight of PM10 that gravity force would let them down faster than PM2.5. This reason and the limitation of accident in laboratory could compare PM10 reductive results in shorter period at 350 seconds.

As dust removal rate concerning, the rapidity of PM10 reduction was faster than those in PM2.5 reduction because of particle weight, so the estimation of dust reductive rate would be separately estimated. For PM2.5 concentration, the highest dust reductive rate was shown in case of the combination of mop C and A at 0.047 mg/sec in the period of 900 second. While the highest removal rate of PM10 was at 0.005 mg/sec by the combination of mob B and C in the period of 350 second.

If turning now to efficiency evaluation in single mop, PM2.5 purification in mop C in dry condition was the best rank at 36% of air cleaning efficiency and mop B in arid laboratory hold the second rank of mop efficiency at 10%. In case of PM10, spraying water on mop B was the best solution with the efficiency at 25%. This was the evaluation based on single mop purification only, so the rank would be changed after testing multiple mops. The ranking priority of mop purification had be changed in PM10 purification that multiple mop B and C in wet condition got second rank at 8% of air cleaning efficiency.

Based on ASHRAE handbook 2012, this study could classify various type of mop into 3 levels of Minimum Efficiency Reporting Value (MERV). For PM2.5 as E2 particle type, it is obligated that PM10 cleaning efficiency of mop must be higher than 85% when PM2.5 cleaning efficiency is possibly evaluated. So PM2.5 cleaning efficiency could not be estimated MERV level for comparing purpose. For PM10 cleaning efficiency, mop B in wet condition reached the highest rank at MERV5 with $20 \leq E_3 < 35$; while mop B in arid condition, mop C and the combination of mop B and C could be ranked in MERV1 with $E_3 < 20$.

To investigate the relationship between mop efficiency and ambient data, there were four groups of relationship in this study based on increasing air humidity. Firstly, negative relationship was found in both dust cleaning efficiency and temperature. Secondly, negative relationship was found only in temperature change and the third relationship was negative change in only dust cleaning efficiency. Lastly, positive relationship was found in both dust cleaning efficiency and temperature.

Various types of above mops are cheaper element of purifiers to clean indoor PM2.5 and PM10 if the mop installation is in controlling such as high enough pressure system, ambient controlling method and types of mops. With low cost element, solid fibre mop might be developed in commercial part and be in use in developing counties. The recommendation for further research is model location that this mop element seems to be suitable for hot and humid climate with high relative humidity but higher temperature as in Chapter 5 monitoring data. Further research is possibly to be tested in tropical climate and developing countries such as Southeast Asia zone and South China etc. Moreover, as being an element, solid fibre mop should be developed in full-scale purifier and then real test monitoring should be done in each local climate. If getting higher efficiency, it is possible to adapt this mop being pre-filter part of high efficient purifiers.

With lower efficiency of air purification, mop B with solid fibre diameter 0.22 mm is selected to integrate with floor lamp in order to pre-filter of room particle. Also the solid fibres of mop are coated by TiO_2 solution in order to adjust photocatalytic system to this lamp. So the next chapter will inform the process of air purifier lamp design, the methodology of TiO_2 coating and lamp evaluating tests.

Chapter 7: An adaptive filter lamp methodology

7.1 Introduction and work positions

According to literature reviews, it is evident that PM2.5 and PM10 concentrations in Thailand exceed 24-hr standards of NAAQs and WHO in industrial and traffic areas. This air pollutant problem has become more important in Southeast Asia. However, the solutions to air cleaning which have adequate efficiency to clean air pollutant are still expensive for low income people. The findings of air purifying solutions in this study are fabric filter and solid fibre mop because these elements can be adapted to various devices. Also the preliminary tests in fabric filter and solid fibre mop demonstrate their performance of air cleaning.

After evaluating air purifying elements' performances, this section shows the integration of fabric filter and solid fibre mop to room device such as a floor lamp. For more effectiveness, photo catalytic process is adjusted to this lamp as TiO_2 coating on mop. It is also suitable for environmental conditions in tropical climate based on Köppen-Geiger classification (Kottek et al. 2006) as high humidity supporting photocatalytic process. Then this application was evaluated for air cleaning performances as a general use in bedroom.

7.2 Hypothesis and Objectives

To develop air purifying device, fabric filter and solid fibre mop are integrated to floor lamp for the purpose of low cost and more general use in local accommodation. Also TiO_2 coating on mop is applied for supporting air purification in hot and humid climate. The hypothesis in this study is that multiple techniques of air purifications can improve air cleaning performance or not, if so, how it improves. Based on this hypothesis, the objectives are informed as below points.

- To develop an air filter lamp for cleaning PM2.5 and apply for real time test in bedroom and then to advocate TiO_2 coating on solid fibre mop and ultra violet lamp for improving air purifying performance.
- To investigate PM2.5 cleaning performance of fabric filter after integrating to lampshade and to compare the performance of fabric filter lamp at different flow speeds in filter lamp system and to identify air cleaning efficiency rank of filter lamp.

- To identify the most effective option of PM2.5 air cleaning performance in fabric filter lamp and the best condition of using TiO_2 filter lamp for indoor air purification.

Following hypothesis and objectives, the methodology for filter lamp improvement is identified in the section. Then the method of TiO_2 coating is demonstrated and the application is real-time tested in a bedroom.

7.3 Real time test in bedroom

The process of real time test would be set in bedroom throughout the afternoon period of 4.30 hour to avoid interrupting existing users and all data was collected every 2 minutes. Moreover, collected data would be averaged from 3-time collections of monitoring for reliability.

7.3.1 Equipment

Regarding to real time monitoring in bedroom, the location was selected in Nottingham, United Kingdom environmental climate. The room was separated from outside low temperature by shutting down windows throughout the period of experiment. So the room temperature and humidity were not followed outside fluctuation. In this situation, the relationship between outdoor ambient and indoor PM2.5 was not significant as shown in Shanghai residence case in chapter 5, then outdoor environmental factors were not collected in this experiment.

To create hot and humid conditions, indoor environment was set with a boiler to increase air humidity and temperature. The boiler was set to turn on every time that relative humidity was lower than 70% until boiler was automatically cut out after boiled water. Room temperature was in the range 24-30 °C from heater and portable boiler.

Table 7-1 Equipment for monitoring indoor PM2.5 in accommodation in Nottingham, United Kingdom

Model	Description
Anemometer	Monitoring velocity (m/s) and temperature (°C)
Portable humidity meter	Monitoring relative humidity (%) and temperature (°C)
Dust meter	Monitoring respiratory particulate meter (mg/m^3)

As **Table 7-1** demonstration, there are 2 meters in the middle of room to monitor respiratory dust, temperature and wind speed. For respiratory dust, dust meter modelled HAZ-DUST IV monitored 3 times and then the data was averaged for more stable data collection. In this study, an anemometer was flexibly used for testing the air speed at the fan unit and monitoring ambient temperature in the room.

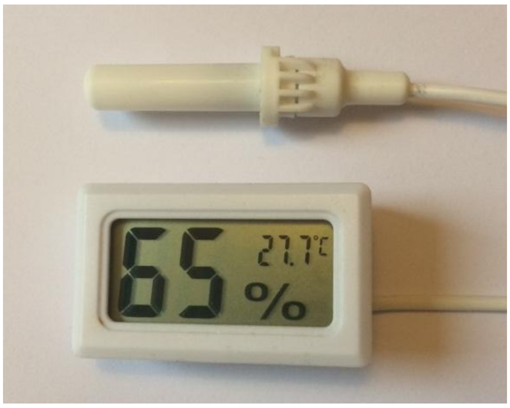

Figure 7-1 Mini portable humidity meter set

Instruments in real time monitoring in bedroom were the same as those for chapter 3 excepted mini portable humidity meter set as shown in **Figure 7-1**. This mini humidity set was compared to air humidity probes with data logger in chapter 3 and the collected results were adjusted for more reliability of environmental data.

7.3.2 Location and bedroom environmental condition

Figure 7-2 The experimental location in Nottingham, United Kingdom (Google Maps. 2016)

The location of real time experiment in bedroom is the house number 87, City road, Dunkirk, United Kingdom NG7 2JL where is far from “A6005 road” by 40 m. The capacity of house is for 4 different bedrooms and the smallest bedroom in the house was selected to be experimental room. For the reason of dust removal performance of filter lamp, the smallest room will provide fastest rapidity of PM2.5 removal and it is easier to control room temperature and relative humidity.

To scope the area of this research, one small bedroom was installed fabric filter lamp and the equipment for real time test. The small room is cubic shape with the width, length and height at 2.50 meters in each side. The openings in this bedroom are one high window sized 0.50x0.35 m^2, one normal window sized 0.50x0.95 m^2 and one door sized 0.75x2.00 m^2. There are 4 pieces of furniture in the room especially in bed, shelves and table. As the limitation of small space in the room, it is possible to locate lamp and various probes as the following **Figure 7-3**. Then all data was monitored and manually collected in the period of 4.30 hours. The results and discussion will be examined in the next section.

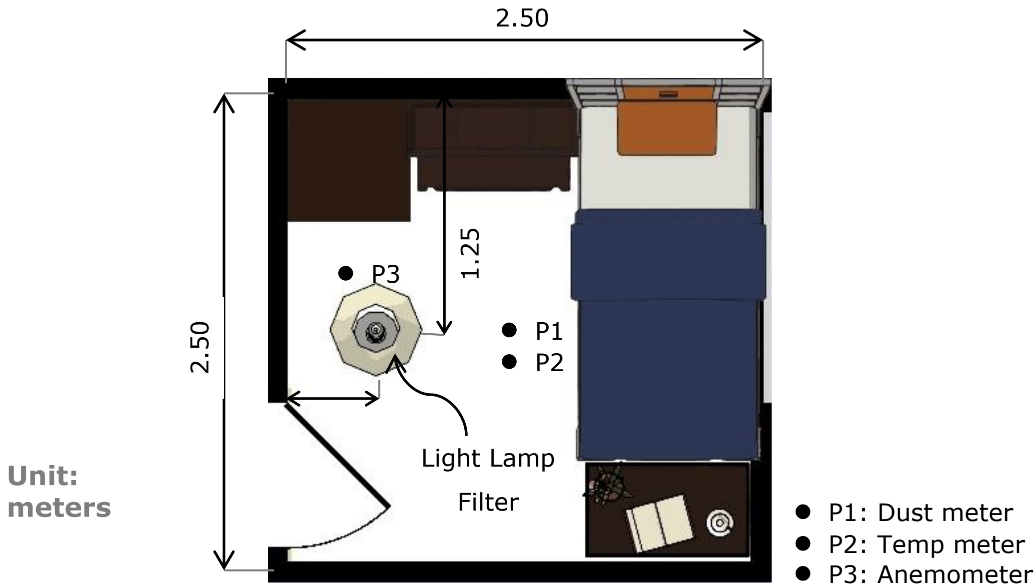

Figure 7-3 The position of ground lamp and various probes in testing room

In bedroom, environmental conditions were assured similarly to hot and humid climate by a portable boiler, so the temperature and humidity were getting high throughout experimental period. Also the results of temperature and humidity during experimental period will be demonstrated in the next chapter.

7.3.3 Filter lamp design

Figure 7-4 Four-layer fabric filter applied for lamp shade

Lamp design process began with the construction of floor lamp combined from 1.15 m height metal core and cylinder shape metal branch with diameter 0.18 m on top and 0.24 m at bottom. With this construction dimension, shading envelop area is 0.27 m^2. Normally, shading material of lamp is made from opaque paper to avoid light glare. This study used selective 4-layer fabric filter as shown in **Figure 7-4** replacing lamp shade.

Figure 7-5 SES light bulb used in experiment

Two light bulbs (E14/SES, standard 630 lumens, and 42 watts) in **Figure 7-5** were installed within the middle core. The light could pass though fabric filter shade as normal shade for general activities, however the intensity may be not high enough for reading activities. The high temperature of light bulb may result in buoyancy effect in filter lamp. However this study was the system with flow driven by fan unit in **Figure 7-6**.

Figure 7-6 Fan unit as “Sunon Fans” model

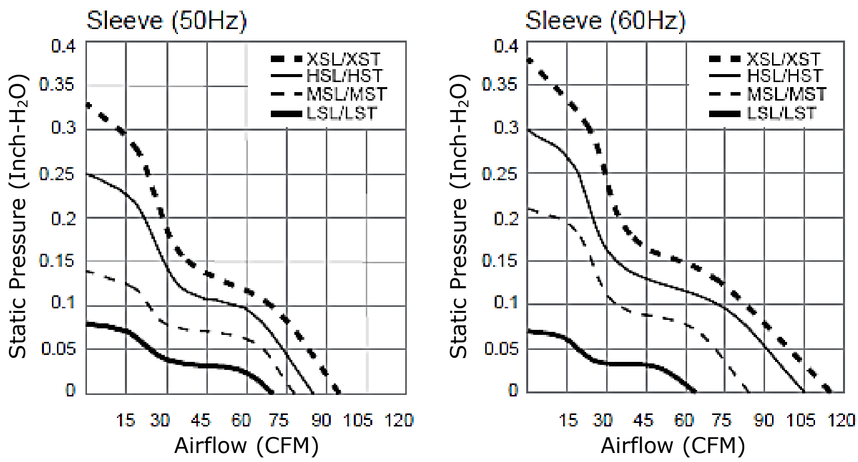

Figure 7-7 Airflow and static pressure characteristics of “Sunon Fans” model

A dimmer fan unit *(model: DP200A*-2123XST.GN/259-1632-ND) based on **Figure 7-7** was located at lamp bottom to increase the system flow rate for air pollutants to pass through purifying gadget (Zhong & Haghighat 2015). In **Figure 7-8**, all components show the dimension of lamp, lamp construction and the connection of each element in filter lamp. As a part of air purifying lamp, cumulative filtrate volume of the fabric filter was calculated to identify its performance before combining to lamp shade. This fabric filter lamp was used in a bedroom to identify air cleaning performance before adding UV light bulb set and TiO_2 coating mop.

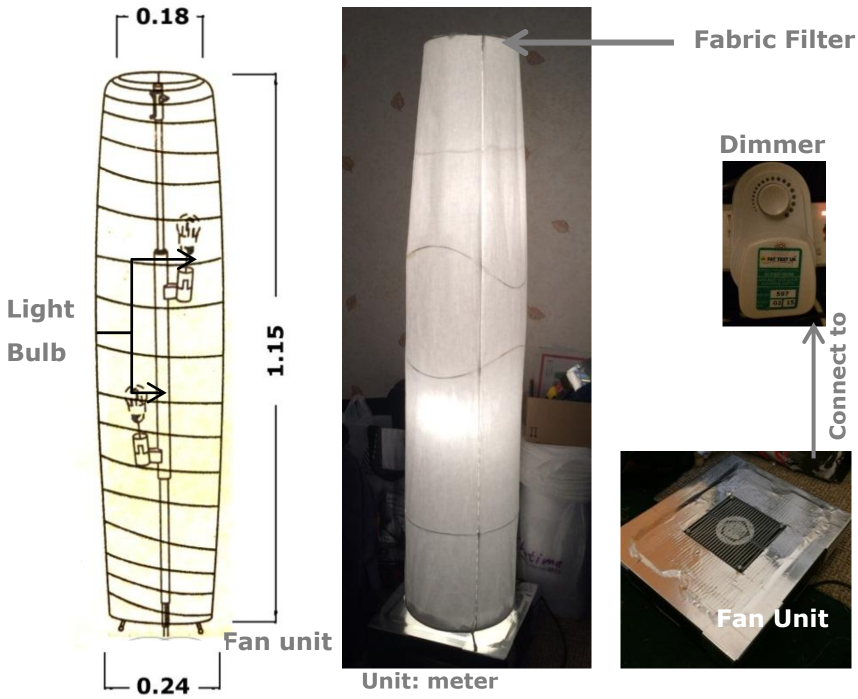

Figure 7-8 Ground lamp after applying fabric filters and fan unit

To extend experiment to photocatalytic process, UV light bulb in **Figure 7-9** would be separately installed in the middle core of lamp. This UV light with air humidity would enable TiO_2 function as a photocatalytic oxidative process (Murakami & Fujishima 2010). For this purpose, solid fibre mop would be coated by solvent with a concentration of TiO_2 2.0% (PCX-S2 by CristalAcTiv^{TM}) in **Figure 7-10**. Based on manufacturing process, titania sol was prepared in a weight % of 17.5±2.5 at a pH of 11.5±1 and an alkaline peptizing agent was used as a baffled mixing container. This solvent could be proved for excellent antibacterial activity in exposing light time (Kerrod & Wagstaff 2013).

Figure 7-9 UV light bulb used in experiment

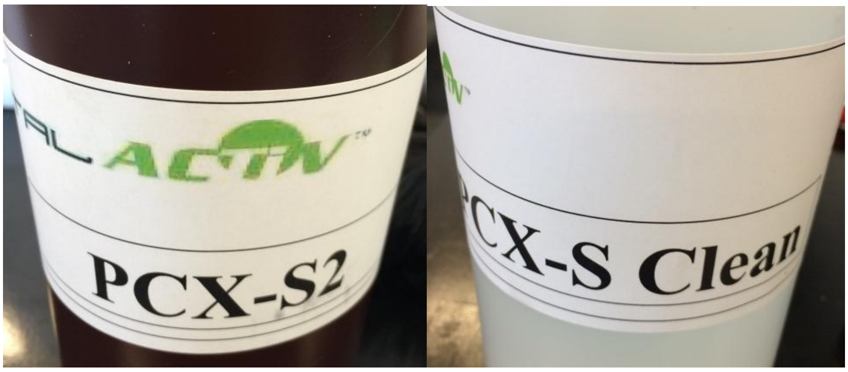

Figure 7-10 TiO_2 solvent and cleaning surface solvent used in experiment

For preparing surface before TiO_2 coating, the PCX-S Clean in **Figure 7-10** was used to clean surface of solid fibre mop. For more details, TiO_2 coating process is examined exhaustively later. The next session will identify several testing regimes and the results will be clarified in the next chapter.

7.3.4 Filter lamp testing process

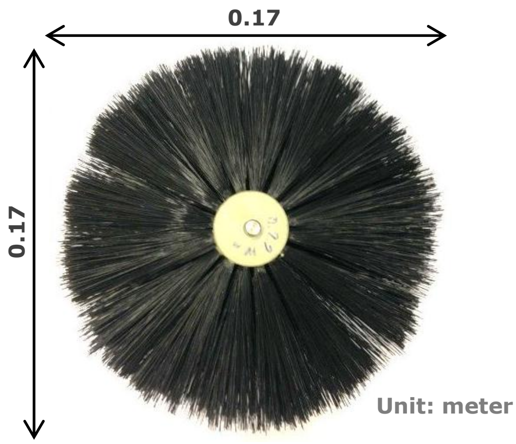

Figure 7-11 Fibre mop typed B for TiO_2 coating

According to preliminary tests of air purifier media, the integration of floor filter lamp would be done with fabric filter and solid fibre mops. Fabric filter would be integrated as lamp shade to cover floor lamp and mop B as in **Figure 7-11** would be selected to clean indoor PM2.5 in bedroom. Mop B consisted of 167 solid fibres per bunch with fibre diameter sized 0.22 mm and fibre length 0.08 m. To rotate the bunch around the core, there were 64 bunches of solid fibre in one core. The solid fibre surface in this type of mop was around 0.59 square meters per one mop.

Based on research objectives, the tests of fabric filter lamp evaluation were monitored in 4 regimes. Firstly, existing case of bedroom monitoring collected indoor PM2.5 concentration, indoor relative humidity and indoor temperature during the period of 4:30 hours; however, the comparative data would be based on 24 hours standards of WHO and NAAQs. Secondly, buoyancy effect case from light bulb heat was monitored by turning on light bulb but turning off fan unit. Thirdly, normal fan speed case was done in the same bedroom with fan speed 3 m/s in filter lamp system. Lastly, reducing fan speed to 2 m/s was used rather than normal fan unit. The results of indoor particle will be demonstrated in the next chapter.

Then the extension of photocatalytic process would be done in more 3 regimes after TiO_2 coating on solid fibre mop. The experiments in cases of normal fan speed and reduced fan speed would be repeated and compared the air purification results with existing room. All experimental regimes are summarized in **Table 7-2**.

Table 7-2 All experimental regimes for evaluating filter lamp

<table>
<tr><th colspan="2" rowspan="2">Applications</th><th colspan="3">Flow speed</th></tr>
<tr><th>Buoyancy</th><th>Fan (3m/s)</th><th>Fan (2m/s)</th></tr>
<tr><td colspan="2">(1) Existing</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">Filter lamp</td><td>Normal mop</td><td>(2) Turning on light bulb</td><td>(3) Turning on light bulb and fan speed</td><td>(4) Turning on light bulb and fan speed</td></tr>
<tr><td>(5) TiO_2 coating</td><td>-</td><td>(6) Turning on light bulb and fan speed</td><td>(7) Turning on light bulb and fan speed</td></tr>
</table>

After monitoring all regimes, PM2.5 concentrations were compared to WHO and NAAQs in chapter 3 as 24-hr PM2.5 level at 25 $\mu g/m^3$ and 35 $\mu g/m^3$ respectively. Then the equations used to calculate air cleaning efficiency rely on EPA method in **Equation 3-1**. The air purifying performances are ranked by Minimum Efficiency Reporting Value (MERV1-20) and British standard (BS EN 799:2012) to compare with others results.

7.4 TiO_2 coating process

Based on air cleaning solution, TiO_2 coating is another technique for air purification in this study. With TiO_2 photocatalytic process, air humidity and light intensity are important factors. After activated band gap energy by UV light, TiO_2 would release electrons for superoxide anions (O_2^-) creation and capture electrons for hydroxyl radicals ($^{\cdot}OH$). Then both products from above actions would chemically arrest air pollutants for oxidative decomposition to CO_2 and H_2O (Murakami & Fujishima 2010). For achieving the benefit of this technique, thin TiO_2 coating (Danish et al. 2015) on fibre mop increases chemical process on fibre surface and then mop is installed within filter lamp. This integrated device is tested for its performance of indoor PM2.5 degradation.

Before coating TiO_2 on solid fibre mop, solid fibre mop diameter sized 0.22 mm and a few bunch of this fibre type were rinsed in PCX-S clean solvent. Then fibre mop and separate fibre bunches would be dipped in PCX-S2 solution with a concentration of TiO_2 2.0% and left them to dry in room temperature without light. This could be assumed that solid fibre surface area of 0.59 m^2 was coated by TiO_2. Also a few separate bunch of solid fibre would be scanned by a scanning electron microscope (SEM) to assure TiO_2 coating on fibre surface. This TiO_2 coating fibre mop would be installed to fabric filter lamp for assessing the performance of indoor PM2.5 cleaning in experimental regimes 5-6.

7.5 Summary

After preliminary test of fabric filter and solid fibre mop, the solution of indoor air cleaning techniques are integrated as a floor lamp based on low cost and simple use in hot and humid climate. Air purifying techniques used to develop filter lamp are fabric filter, solid fibre mop and TiO_2 photocatalytic process.

To refurbish floor lamp, existing wire construction is high 1.15 m in cylinder shape and the main core of lamp structure is also the branch of 2 SES light bulbs. Top and bottom diameters of cylinder are 0.18 m and 0.24 m respectively. Then fabric filter would cover all cylinder structure with the area of 0.78 m^2. After covering lampshade, fan unit was installed at the bottom base of lamp with speed dimmer.

Also an optional mop coated TiO_2 was installed and estimated air cleaning performance in last two experiments. To clarify TiO2 on fibre surface, some samples of fibre bunches coated TiO2 in the same time with experiment mop are scanned by a scanning electron microscope (SEM) and the results are demonstrated in the next chapter.

There are seven experimental regimes to identify indoor PM2.5 cleaning performance of filter lamp included (1) existing, (2) filter lamp with buoyancy effect, (3) filter lamp with fan speed, (4) filter lamp with dimming fan speed, (5) TiO_2 coating on mop, (6) TiO_2 coating on mop with fan speed and (7) TiO_2 coating on mop with dimming fan speed.

The next chapter will examine the results of all experimental regimes based on this methodology and experimental preparations. Then the results will be discussed comparing to single air purifying technique and ranked to MERV and British standard levels. Moreover the discussion will identify air cleaning performance of application in high risk of intensive air pollutants in hot and humid climate.

Chapter 8: Results of fabric filter tests in bedroom

8.1 Introduction and work positions

According to literature reviews, the problems of exceeding air pollutants in hot and humid climate in Southeast Asia have expanded to urban industrial zone. The solutions in this study pointed to air purifier techniques especially fabric filter and solid fibre mop. Based on preliminary tests, fabric filter had adequate efficiency but had high cost for production and air purifier integration. Solid fibre mop had lower cost but offered lower efficiency in both PM2.5 and PM10. For solid fibre mop, mop B was selected for fabric filter lamp development as a result from (1) high number of fibre surface area at 0.59 m^2, (2) getting the highest efficiency at 25% for PM10 cleaning among all testing mops. So mop B could be developed for pre filtration and TiO_2 coatings on fibre surface in fabric filter lamp.

After fabric filter lamp installation in bedroom as same as in **Figure 7-3**, real time monitoring results are examined as six regimes in particular (1) existing, (2) buoyancy effect, (3) fan speed 3 m/s, (4) fan speed 2 m/s, (5) TiO_2 coating mop, (6) TiO_2 coating mop and fan speed 3 m/s and (7) TiO_2 coating mop and fan speed 2 m/s. Then the evaluating discussion will be identified at the end of this chapter.

8.2 The results of fabric filter lamp tests

As real time monitoring in bedroom, the results are shown in terms of PM2.5 concentration in 7 different regimes in **Table 8-1**. For existing environment, monitoring process was set on routine using included timing fan heater. In case of locating fabric filter lamp, bottom fan was set flow speed at 3 m/s as a normal speed and 2 m/s as reduced speed.

Table 8-1 All experimental regimes in fabric filter tests

Regimes	Conditions		Light bulb		Fan speed	
	Application	System fan	SES	UV light	3 m/s	2 m/s
A	Existing		-	-	-	-
B	Filter lamp	Buoyancy	on	-	-	-
C		Normal fan	on	-	on	-
D		Dimming fan	on	-	-	on
E	Filter lamp with TiO_2 mop	No fan	-	on	-	-
F		Normal fan	-	on	on	-
G		Dimming fan	-	on	-	on

8.2.1 Existing

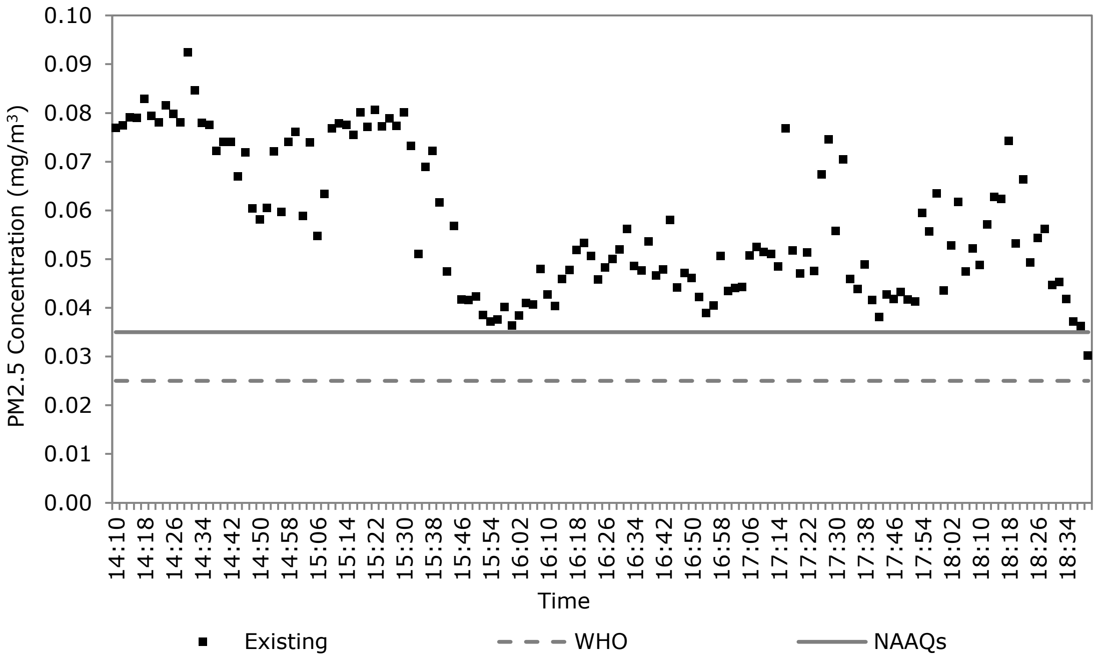

Figure 8-1 Indoor PM2.5 concentration in existing bedroom (Regime A)

During the period of 4.30 hours, real time monitoring is demonstrated in terms of indoor PM2.5 concentration and temperature in existing bedroom as regime A in **Figure 8-1** and **8-4** respectively. The existing PM2.5 concentration reduced from 0.09 mg/m^3 to 0.03 mg/m^3 and the average concentration was at 0.06 mg/m^3. It can be seen that PM2.5 concentration throughout the period of 4.30 hours exceeded WHO and NAAQs standards.

This fluctuating concentration occurred in case of real time monitoring as a result of occupants' activities such as opening door/window or cooking activities. In this bedroom monitoring, the fluctuation was from door opening and individual activities. In **Figure 8-2**, Dimitroulopoulou et al (2000) found very high peak indoor air particle concentration during the cooking period based on TEOM recording and GRIMM portable dust monitoring throughout a week. This was also related directly to simultaneous results in the same research. However indoor secondary organic aerosol (SOA) was different depending on various species between indoor and outdoor particle concentrations as reactive organic gases (ROGs) study in Beijing in **Figure 8-3**.

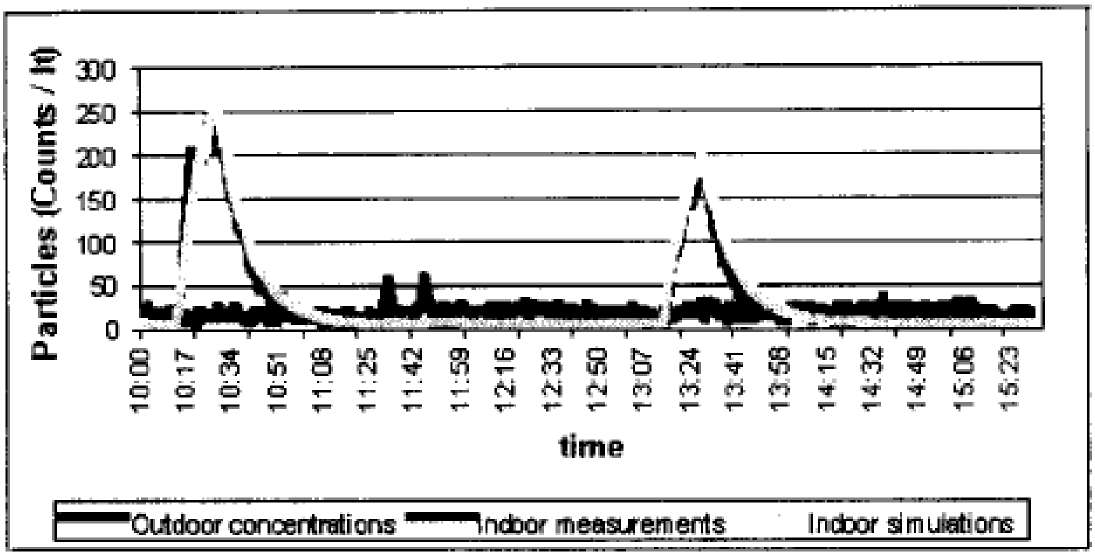

Figure 8-2 Comparative indoor particle concentration in living room (Dimitroulopoulou et al. 2000)

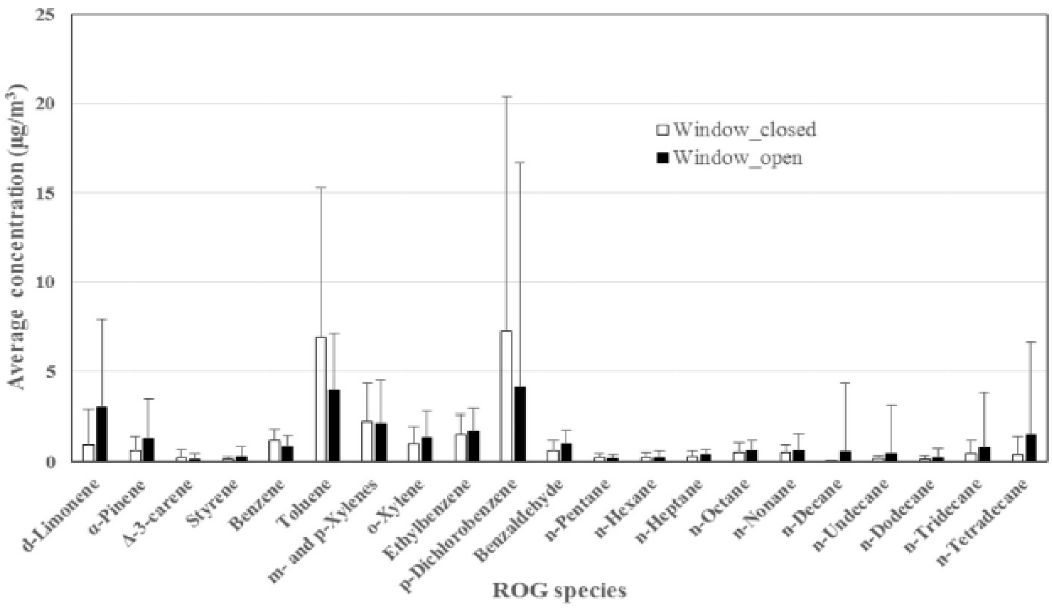

Figure 8-3 The 90-room average particle concentration by various species collections (Ji & Zhao 2015)

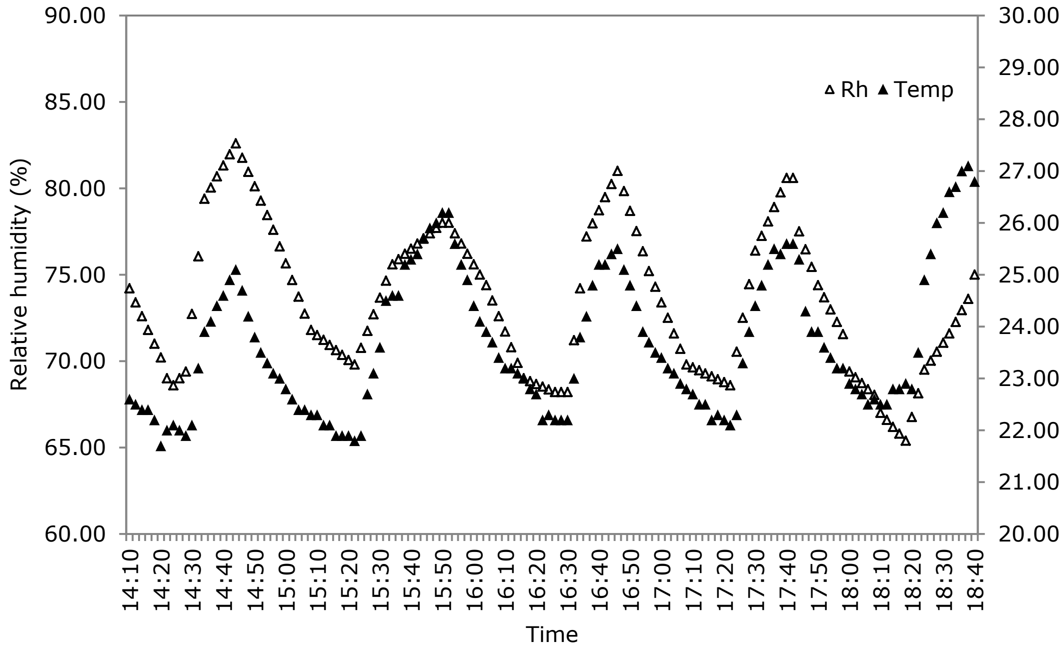

Figure 8-4 Room temperature during regime A experiment

In **Figure 8-4**, relative humidity in bedroom was assured to range between 65% and 83%, while temperature was ranged in 21.70-27.10 °C in experimental period. As relative humidity forced in that range, boiler was used to increase ambient relative humidity when the room relative humidity was lower than 70%. This affected to increase temperature for modeling hot and humid environment in bedroom. So the temperature fluctuated and increased slightly during the testing period. The ambient velocity in bedroom was averaged at 0 m/s, even low velocity no more than 0.05 m/s was found when boiler work.

8.2.2 Fabric filter lamp with buoyancy effect

In the period of 4.30 hours, real time monitoring is demonstrated in terms of indoor PM2.5 concentration and temperature in bedroom after turning on two light bulbs as regime B in **Figure 8-5** and **8-6** respectively. PM2.5 concentration of regime B fluctuated between 0.00 mg/m^3 and 0.07 mg/m^3 and the average concentration was at 0.03 mg/m^3. It can be seen that most of PM2.5 concentration still exceeded WHO and NAAQs standards at 0.025 mg/m^3 and 0.035 mg/m^3.

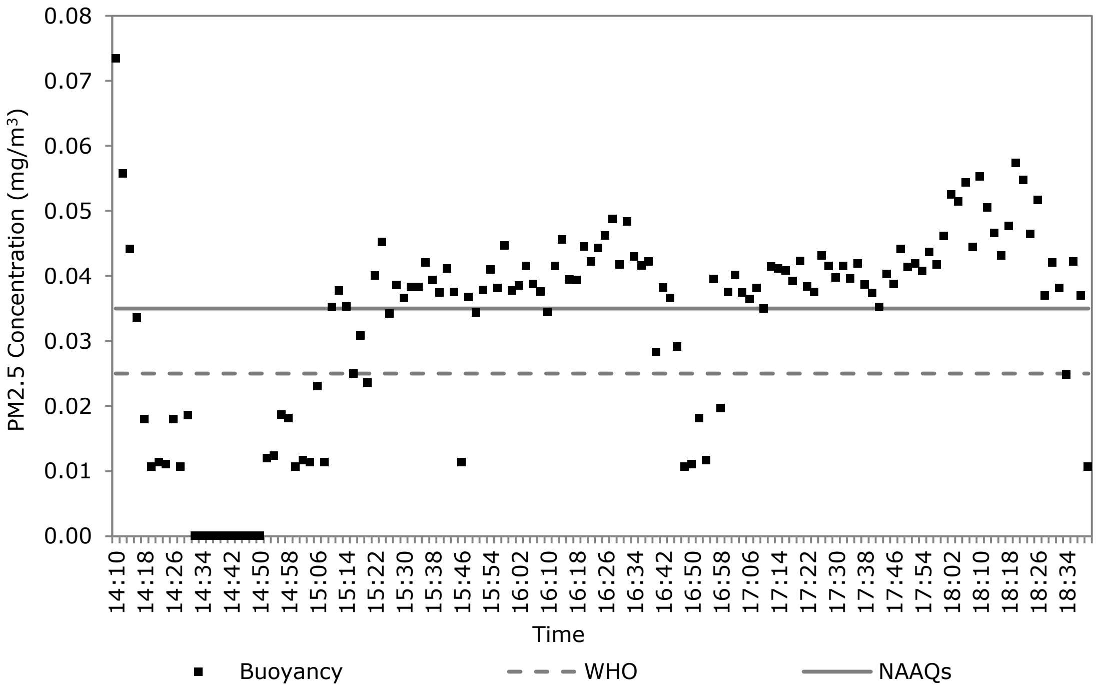

Figure 8-5 Indoor PM2.5 concentration in bedroom with fabric filter lamp and buoyancy effect (Regime B)

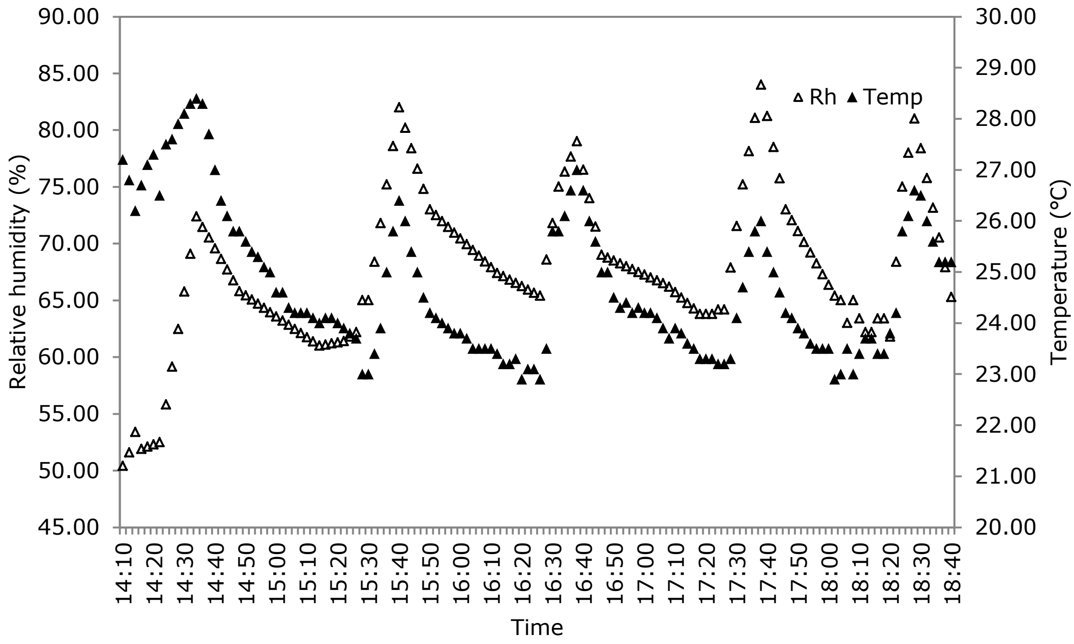

Figure 8-6 Room temperature during regime B experiment

In **Figure 8-6**, the chart demonstrates room temperature and relative humidity during the period of regime B experiment in 4.30 hours. It can be seen that temperature ranged in 22.90-28.40 °C; while relative humidity fluctuated between 50% and 84%. During the experiment boiler was used to increase relative humidity when it was nearly or lower than 70% in order to create hot and humid conditions in this experiment. Room velocity was same as existing case as very low speed and average velocity was 0 m/s.

To compare average PM2.5 concentration, PM2.5 in regime B is lower than those in regime A by 0.03 mg/m^3 with the buoyancy effect from light bulbs heat. However, only buoyancy effect could not effectively clean all PM2.5 in bedroom. The efficiency of air cleaning in this system will be calculated from the average concentration and demonstrated results in discussion part.

8.2.3 Fabric filter lamp with normal fan speed

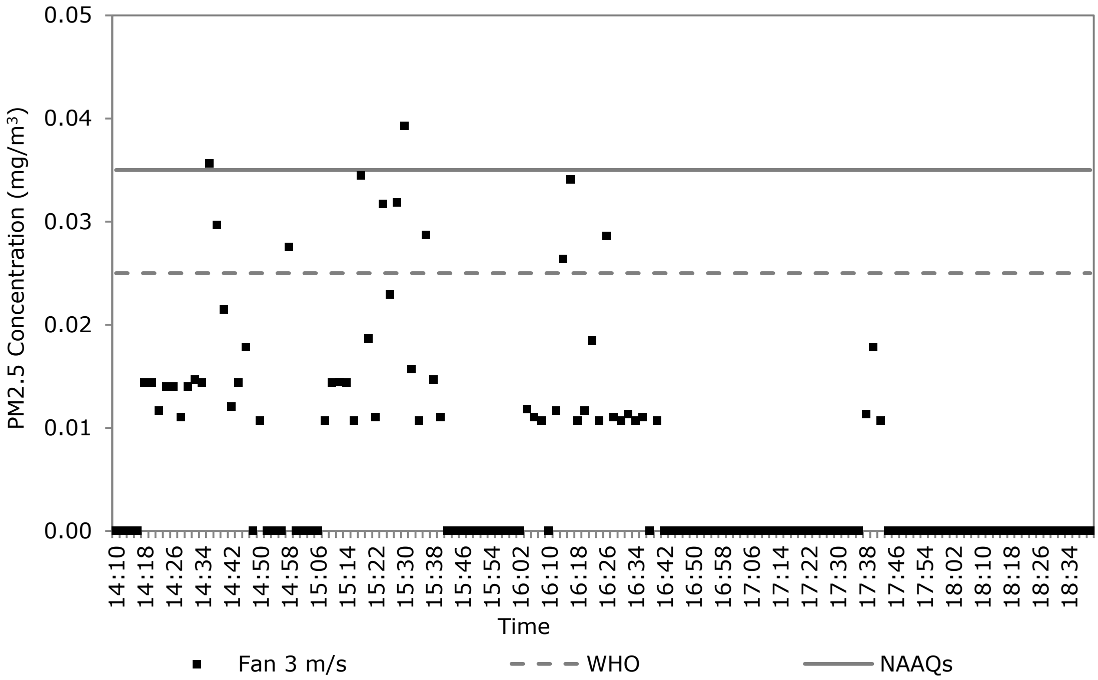

Figure 8-7 Indoor PM2.5 concentration in bedroom with fabric filter lamp and normal fan speed (Regime C)

As regime C in the period of 4.30 hours, real time monitoring is demonstrated in terms of indoor PM2.5 concentration and temperature in bedroom after turning on two light bulbs and fan unit as normal speed in **Figure 8-7** and **8-8** respectively. PM2.5 concentration in regime C fluctuated between 0.00 mg/m^3 and 0.04 mg/m^3 and the average concentration was at 0.01 mg/m^3. It can be seen that seldom PM2.5 concentration still exceeded WHO and NAAQs standards at 0.025 mg/m^3 and 0.035 mg/m^3, average concentration was lower than both standards.

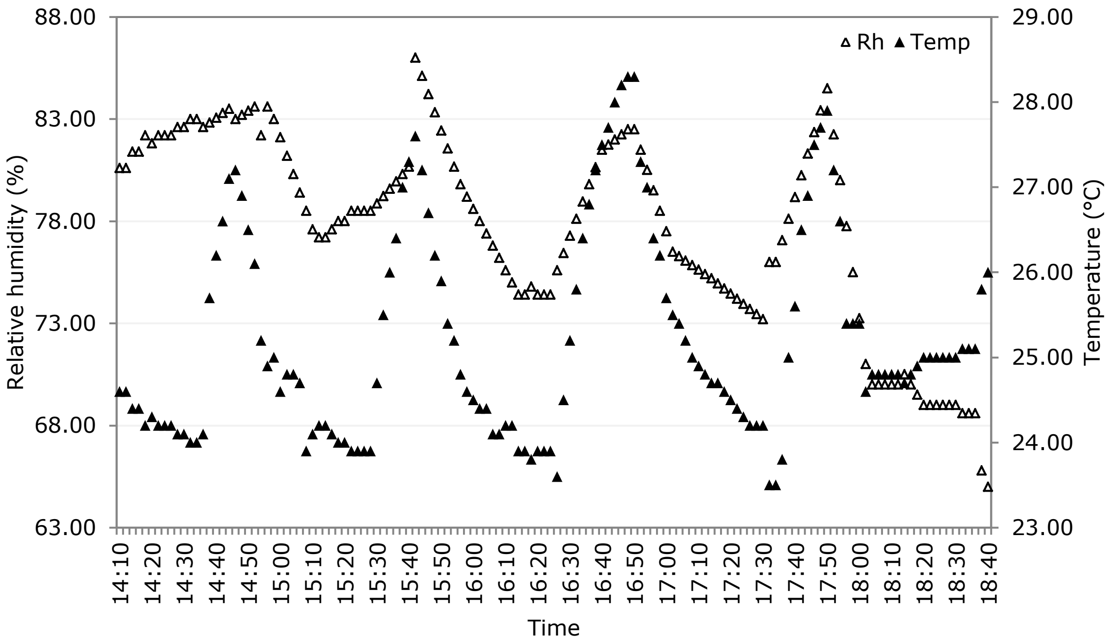

Figure 8-8 Room temperature during regime C experiment

In **Figure 8-8**, the graph shows indoor relative humidity and temperature during regime C experiment. It can be seen that room temperature fluctuated from 23.50 °C to 28.30 °C and relative humidity ranged into 65%-86% throughout the period of 4.30 hours. The boiler was set to work when relative humidity was nearly or lower than 70%. Even boiler could not work accidentally after 18.00, however, indoor PM2.5 concentration was removed nearly 0 mg/m^3 at the end of period.

Turning to comparison purpose, average PM2.5 concentration in regime C with turning on normal speed fan unit is lower than dust concentration in regime A by 0.05 mg/m^3. This regime C can effectively reduce indoor PM2.5 concentration and the efficiency of air cleaning in this system will be calculated from the average concentration and demonstrated results in discussion part.

8.2.4 Fabric filter lamp with dimming fan speed

As regime D in the period of 4.30 hours, real time monitoring is demonstrated in terms of indoor PM2.5 concentration and temperature in bedroom after turning on two light bulbs and fan unit as dimming speed at 2 m/s in **Figure 8-9** and **8-10** respectively. PM2.5 concentration in regime D fluctuated between 0.00 mg/m^3 and 0.08 mg/m^3 and the average concentration was at 0.02 mg/m^3. It can be seen that early state of PM2.5 concentration still exceeded WHO and NAAQs standards at 0.025 mg/m^3 and 0.035 mg/m^3, average concentration was lower both standards.

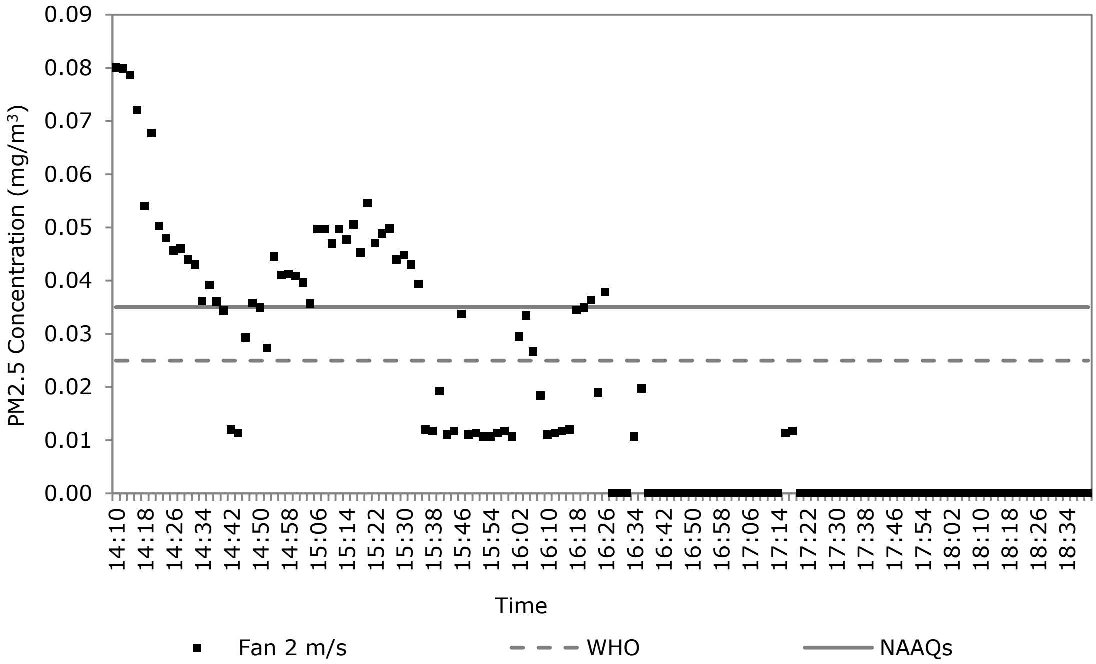

Figure 8-9 Indoor PM2.5 concentration in bedroom with fabric filter lamp and dimming fan speed (Regime D)

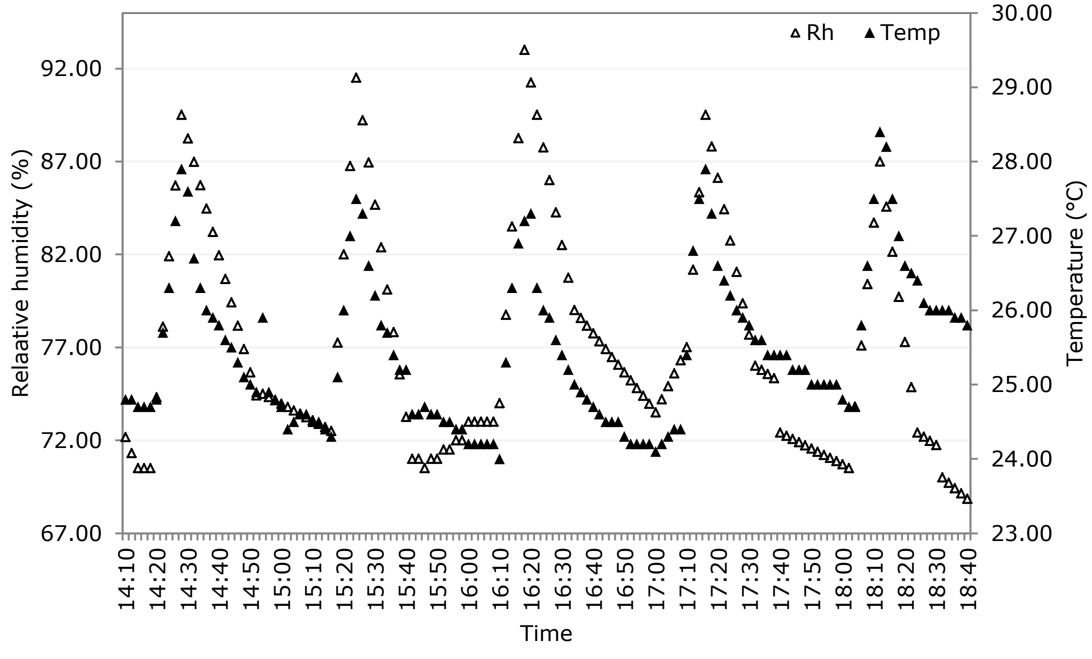

Figure 8-10 Room temperature during regime D experiment

In **Figure 8-10**, the chart illustrates room temperature and relative humidity during the experiment of regime D. It can be seen that temperature varied in 24.00-28.40 °C and relative humidity ranged between 68% and 93% over the period of 4.30 hours. The condition of boiler working was the same as existing regime when relative humidity was nearly or lower than 70%.

For comparison, average PM2.5 concentration in regime D is lower than those in regime A by 0.04 mg/m^3 with turning on normal speed fan unit. This regime D could highly reduce indoor PM2.5 concentration and the efficiency of air cleaning in this system will be calculated from the average concentration and demonstrated results in discussion part.

8.2.5 Fabric filter lamp with TiO_2 coating mop

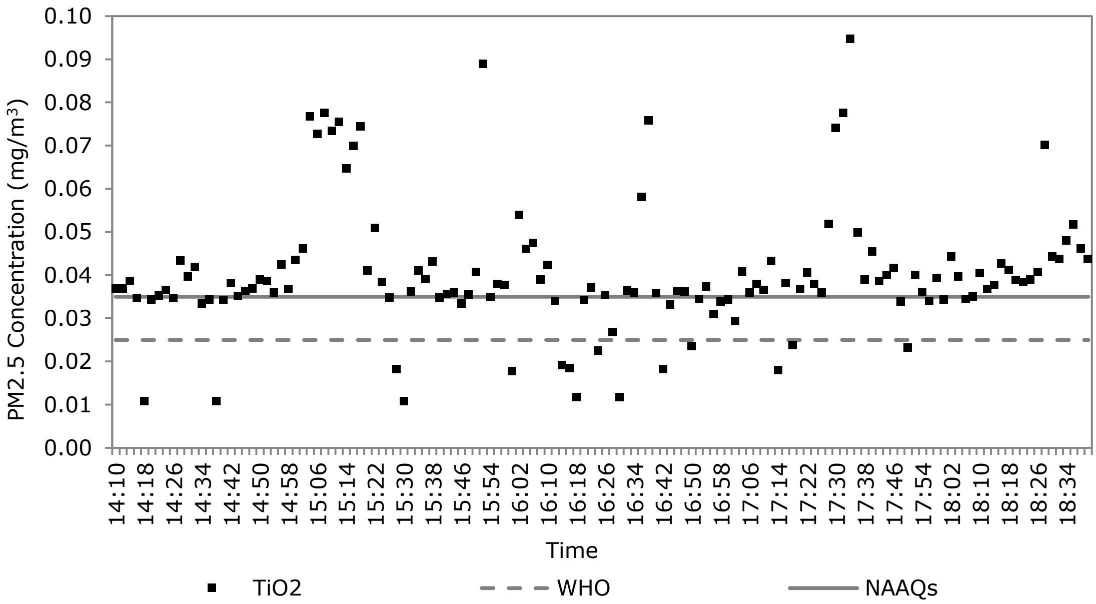

Figure 8-11 Indoor PM2.5 concentration in bedroom with fabric filter lamp and TiO_2 coating on mop (Regime E)

More extended research was done in photocatalytic process as a TiO_2 coating on solid fibre mop. In regime E, line chart in **Figure 8-11** illustrates indoor air PM2.5 concentration in bedroom with fabric filter lamp and TiO_2 coating on mop fibre. Turning on UV light would catalyse photocatalytic process and brought about air cleaning performance in filter lamp. It can be seen that indoor PM2.5 fluctuated between 0.01 mg/m^3 and 0.09 mg/m^3 during the period of 4.30 hours. Also the average indoor air particle was at 0.04 mg/m^3 which still exceeded NAAQs and WHO standards.

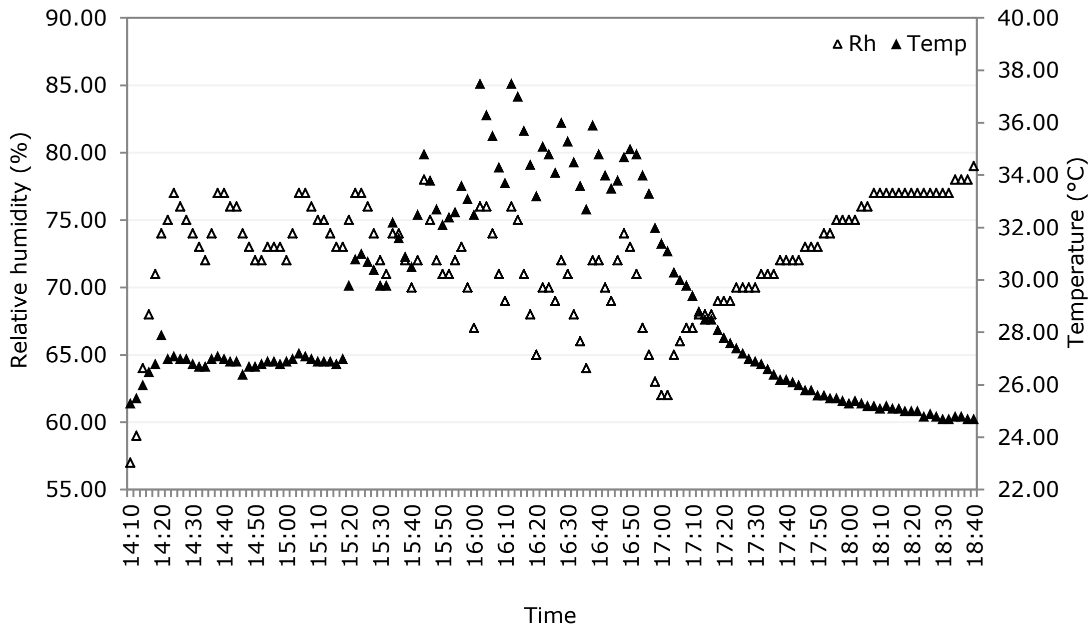

Figure 8-12 Room temperature and relative humidity during regime E experiment

During regime E testing period, the temperature varied from 24.70 °C to 37.50 °C and relative humidity fluctuated between 57% and 79% as shown in **Figure 8-12**. Because temperature and relative humidity were naturally high as in hot and humid climate, the boiler was not used in this case. With comparing to regime A, the average of indoor PM2.5 concentration in regime E lamp was lower than those in regime A by 0.02 mg/m^3.

8.2.6 Fabric filter lamp with TiO_2 coating mop and normal fan speed

With the effect of TiO_2 coating and normal fan speed at 3 m/s as a regime F, line graph demonstrate a dramatic reduction of indoor PM2.5 concentration over the period of 4.30 hours in **Figure 8-13**. It can be seen that PM2.5 concentration reduced rapidly from 0.04 mg/m^3 to 0.00 mg/m^3 in the first 10 minutes. Then the concentration was stable at 0.00 mg/m^3 until the end of test. The average of indoor PM2.5 concentration was at 0.001 mg/m^3 that lower than WHO and NAAQs standards. To be noted, more decimal unit in average dust concentration will be used for calculate air cleaning efficiency later. Also, in very low dust concentration, dust meter could not measure concentration lower than 2 decimals and the result would be appeared in zero.

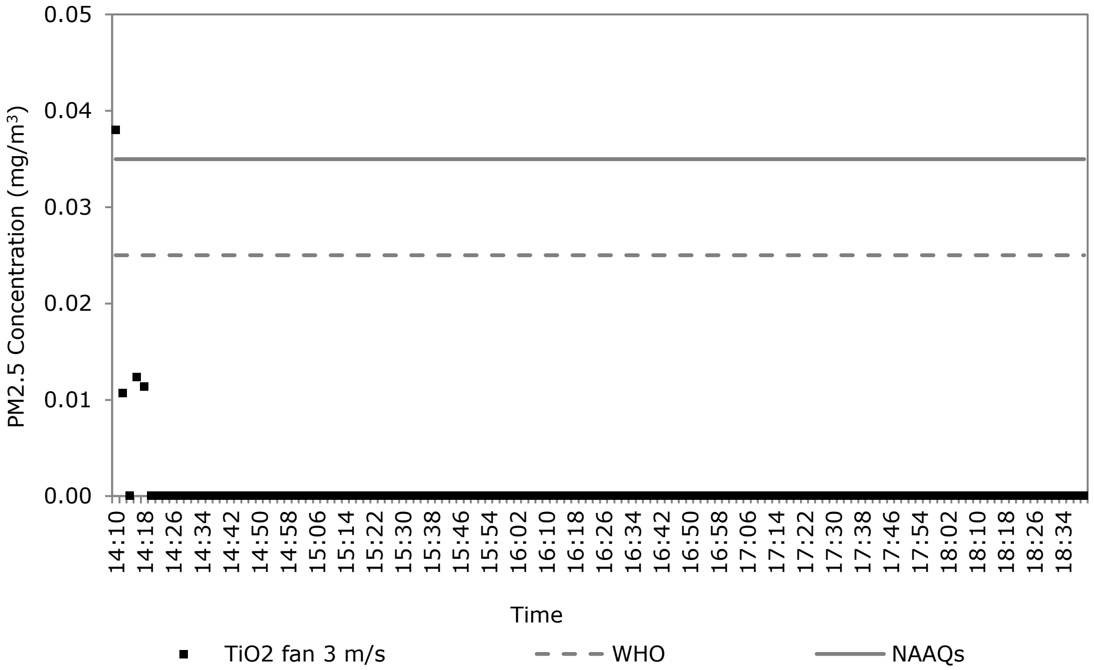

Figure 8-13 Indoor PM2.5 concentration in bedroom with fabric filter lamp TiO_2 coating on mop and normal fan speed (Regime F)

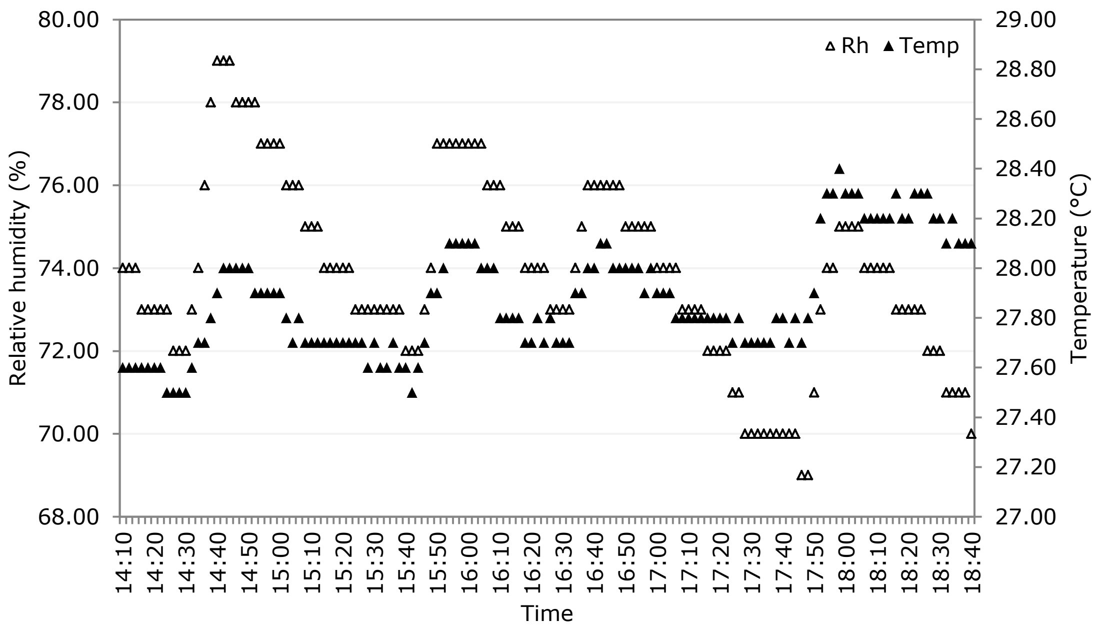

Figure 8-14 Room temperature and relative humidity during regime F experiment

To monitor dust concentration of regime F, temperature fluctuated from 27.20 °C to 28.10 °C and relative humidity ranged into 71%-79% during the period of 4.30 hours in **Figure 8-14**. This fluctuation was resulted from room boiler to increase temperature and air humidity as same as in hot and humid condition. Even fan unit was installed in filter lamp, but fan speed of system did not bother room velocity as a close sealing case of fan unit. So the room velocity was similar to existing case as average speed was at 0 m/s when occupant activities could bring about 0.03 m/s in the middle of room.

For comparison, it can be seen that regime F has higher performance to reduce indoor PM2.5 than all above regimes. The average PM2.5 concentration from regime F was obviously lower than those in regime A with 0.059 mg/m^3. The air cleaning efficiency in this regime will be calculated and demonstrated in the discussion part.

8.2.7 Fabric filter lamp with TiO_2 coating mop and dimming fan speed

To reduce fan speed to 2 m/s, indoor PM2.5 concentration shows a rapid reduction with TiO_2 coating on mop and filter lamp throughout the 4.30-hour period as showing in **Figure 8-15**. It can be seen that indoor PM2.5 concentration decreased immediately from 0.12 mg/m^3 to 0.00 mg/m^3 in the first 10 minutes and remained stable until the end of 4.30 hours period. The average dust concentration was at 0.001 mg/m^3 that were lower than both WHO and NAAQs standards. To compare, average PM2.5 concentration in regime G was lower than those in regime A by 0.057 mg/m^3.

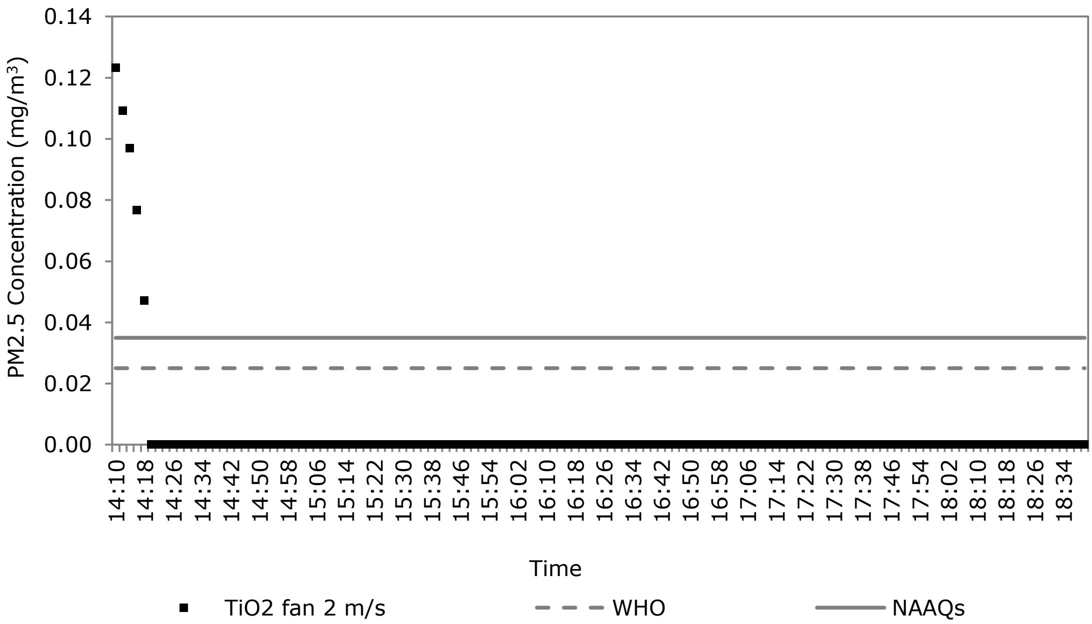

Figure 8-15 Indoor PM2.5 concentration in bedroom with fabric filter lamp TiO_2 coating on mop and dimming fan speed (Regime G)

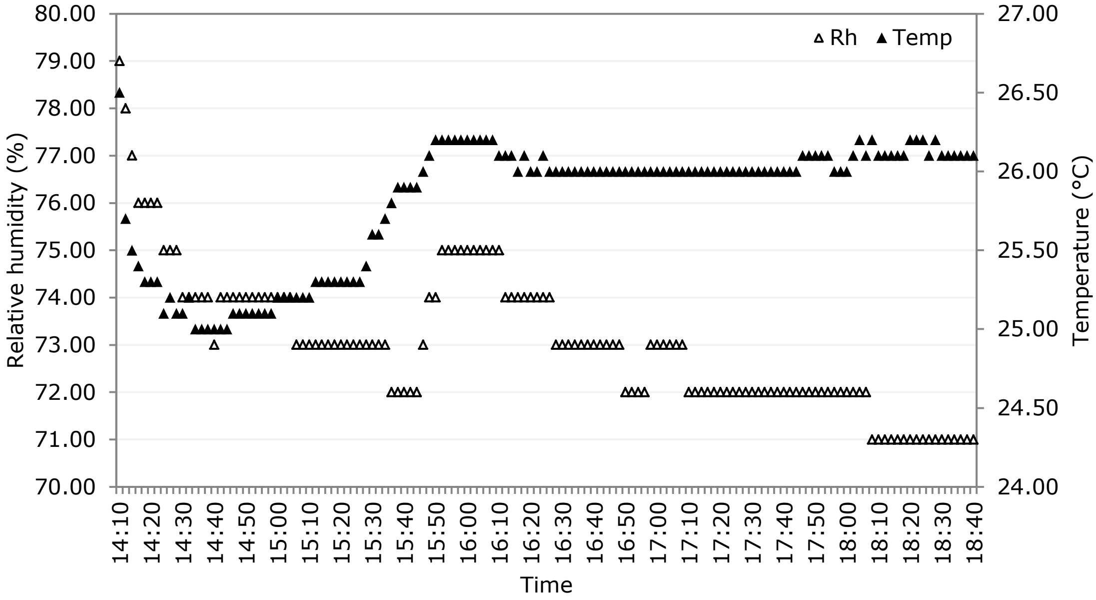

Figure 8-16 Room temperature and relative humidity during regime G experiment

Throughout the testing period, room temperature ranged in 25.00 °C -26.20 °C in **Figure 8-16** and relative humidity were increased by portable boiler to 70%-75% as same condition as hot and humid climate. Moreover, room velocity was at 0 m/s over the whole testing period.

8.2.8 The validation of fabric filter lamp tests

Based on PM2.5 removal tests of filter lamp, the results demonstrated exponential curve throughout the period of 4.30 hours. For validation, the results are compared reductive trend to PM2.5 removals in fabric filter test, general purifier test in Shanghai, China and diesel dust removal trend of mop test (Riffat & Ma 2012) in **Figure 8-17**. The dust removals show similar trends in all regimes of fabric filter lamp test that imply to reliable results. In case of different slopes of removal curve, it is possible that rapidity of dust removal result from various fan speed in this study. Also SEM results can prove TiO2 coating on mop fibres which is another method to guarantee Photocatalytic process in filter lamp. Then average dust concentrations are calculated for ranking into MERV level and BS EN standard.

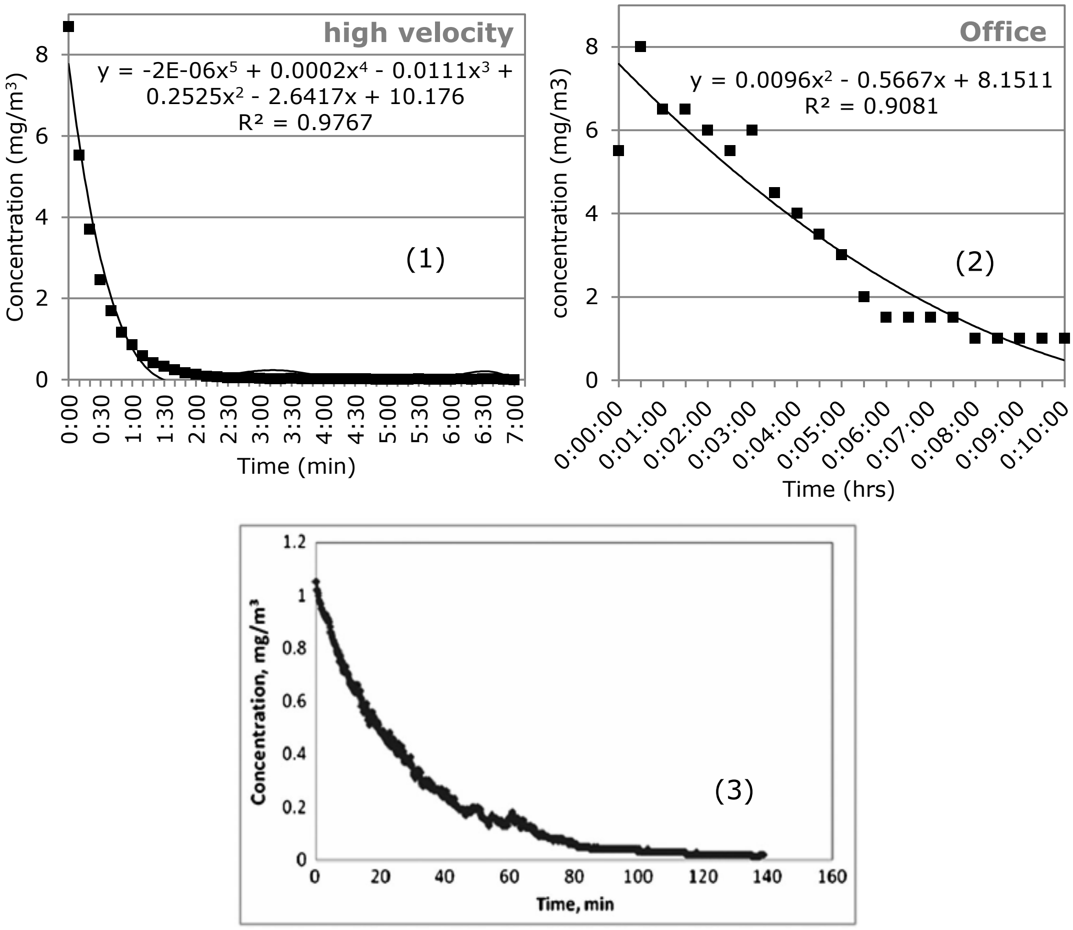

Figure 8-17 PM2.5 removal trends of (1) fabric filter test, (2) general purifier test and (3) a photovoltaic mop (Riffat & Ma 2012)

8.2.9 The conclusive results of all testing regimes

Table 8-2 PM2.5 concentration resulted from 7 experimental regimes

Regime		PM2.5 concentration (mg/m^3)				
		Max.	Min.	Avg.	NAAQs	WHO
A	Existing	0.09	0.03	0.06		
B	Buoyancy	0.07	0.00	0.03		
C	3 m/s	0.04	0.00	0.01		
D	2 m/s	0.08	0.00	0.02	0.035	0.025
E	TiO_2	0.09	0.01	0.04		
F	TiO_2+3m/s	0.04	0.00	0.00		
G	TiO_2+2m/s	0.12	0.00	0.00		

As a result of all regimes monitoring, indoor PM2.5 concentrations are concluded in **Table 8-2** in order to compare maximum, minimum and average of dust concentration with air quality standards. It can be seen that the average dust concentrations in regime C, D, F and G were lower than both WHO and NAAQs standards. Those all regimes resulted from increasing system velocity. However in buoyancy effect and only photocalytic process in regime B and E could reduce indoor air particle but the reductions were not adequate comparing to indoor air quality standards.

This result conclusion is not included the rapidity of each dust reduction yet. So, as another performance of dust removal, the rapidity will be discussed later. The next section will be assurance process of TiO_2 coating on fibre mop surface. This can confirm the photocatalytic activities in filter lamp too.

To be noted, occupant activities before experiment were dressing, make-up, hair drying, using body spray, opening the door and folding clothes and blanket. These activities could source high PM2.5 concentration in the bedroom. When the experiment started, occupant activities were reduced to writing, working on computer, walking and temporary opening the door. The PM2.5 concentration from activities during the experiment was very low level and the condition of bedroom environment was nearly close from outdoor environment as close windows. So the dust concentration seemed to be fixed high level from the beginning of experiment. Then, without filter application, PM2.5 concentration fluctuated from aggregated sources; while the PM2.5 concentration in application test would be eliminated.

8.3 SEM results

To promote photocatalytic process, solid fibre was dipped into TiO_2 solvent in room temperature, and then left it for dry in dark place. Based on thin film coating on fibres surface, an electron scanning microscope (SEM) was used to assure TiO_2 component being on surface in **Figure 8-18** and **8-19**.

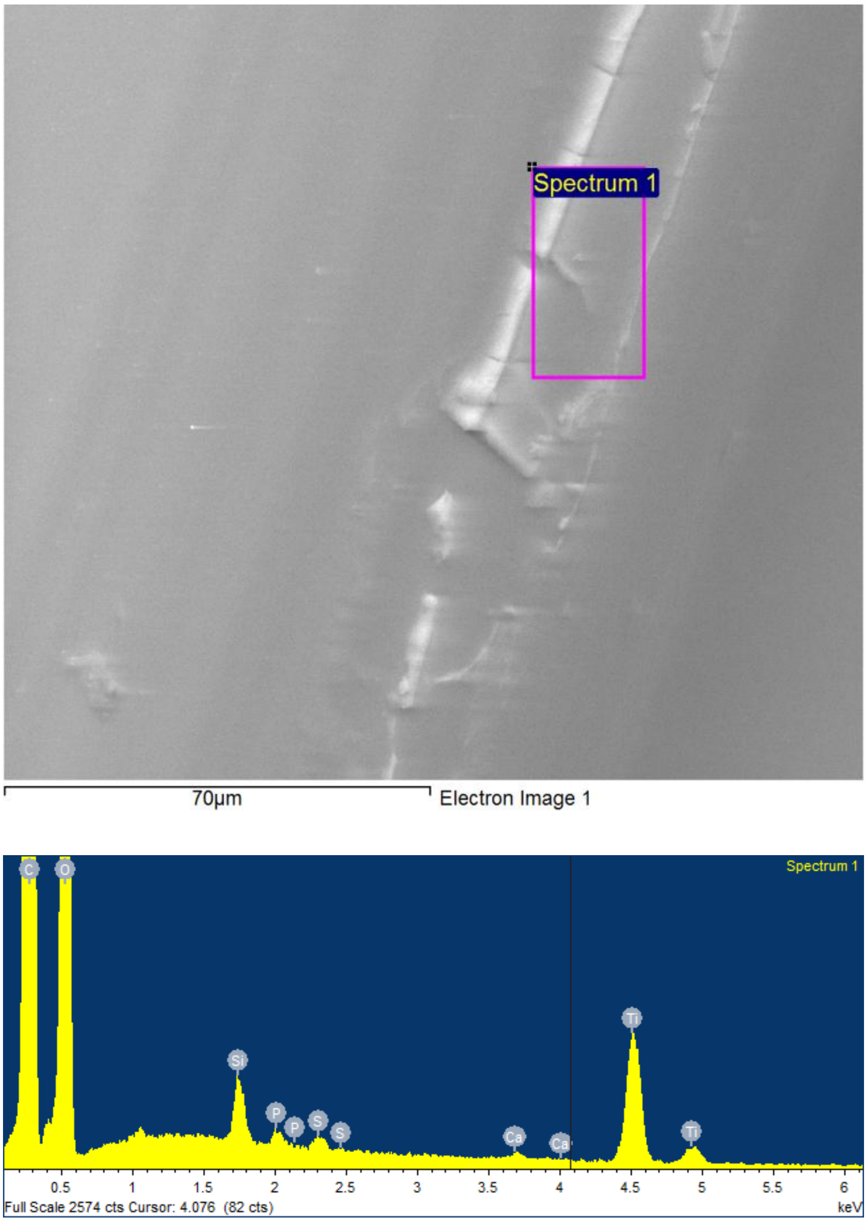

Figure 8-18 SEM and chemical analysis of TiO_2 coating on fibre surface 1

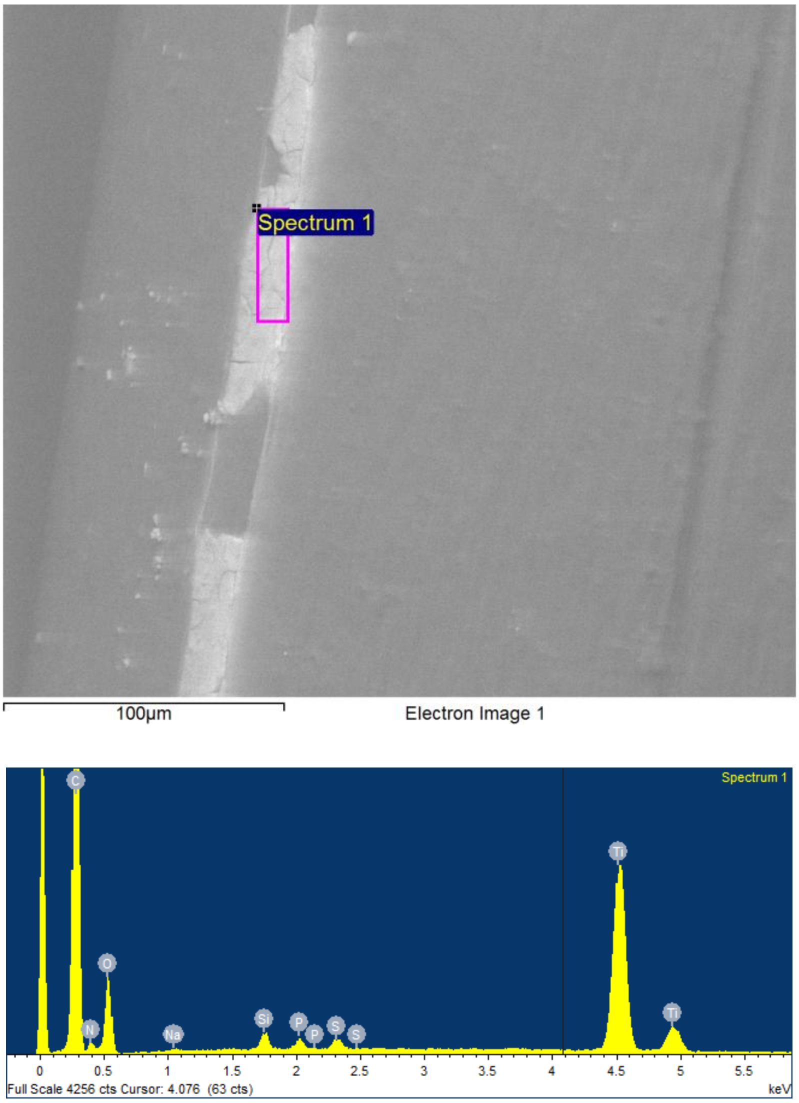

Figure 8-19 SEM and chemical analysis of TiO_2 coating on fibre surface 2

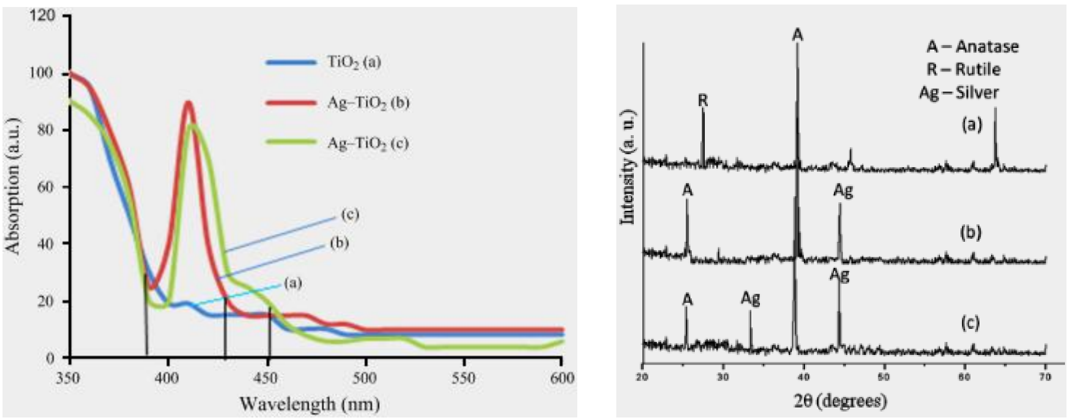

Figure 8-20 XRD pattern of TiO_2 and UV-vis absorption spectra of annealed TiO_2 (Gupta et al. 2013)

An X-ray diffraction (XRD) would be used to synthesize TiO_2 crystal phase on mop surface and then the wavelength of spectra in **Figure 8-18** and **8-19** would be compared to the band gap energy in **Figure 8-20** (Gupta et al. 2013). According to photocatalytic concerning, there are three phases of TiO_2 crystal especially anatase, rutile and brooklite phase. To be brooklite phase, TiO_2 crystals must be annealed in very high temperature to change their length; while anatase and rutile were possibly changed in room temperature. The best option for photocatalytic activity was anatase crystal which held high wavelength with UV light at around 400 nm as B and C types; while rutile phase was not high in this length in **Figure 8-20**. Therefore TiO_2 coating phase on solid fibre mop in this study was appropriate for photocatalytic process.

8.4 Discussions

Under the performance of fabric filter lamp, fan unit is an essential part for air movement. Even though the full speed fan lamp is the best solution to reduce PM2.5, reduced speed fan is sufficient to clean respiratory dust based on energy saving concern. So both full speed fan and reduced speed fan lamps are recommended to use in general rooms depending on the critical requirement of air cleaning level and energy efficiency.

8.4.1 Air cleaning efficiency

Table 8-3 The results of air PM2.5 cleaning efficiency comparing to regime A

Regime		Efficiency (%)	Ranking	
			BS EN	NAAQs
B	Buoyancy	41.54	M5	MERV 6
C	3 m/s	88.21	F7	MERV 15
D	2 m/s	67.80	M6	MERV 11
E	TiO_2	29.54	-	MERV 5
F	TiO_2+ 3 m/s	99.07	F9	MERV 16
G	TiO_2+ 2 m/s	94.17	F8	MERV 15

To estimate air purifying performance, the efficiency was calculated from the average indoor PM2.5 concentration comparing to those in existing concentration. In hot and humid condition, the highest of dust removal efficiency in this study was filter lamp regime F with 99.07% in **Table 8-3** within F9-BS EN and MERV16.

When filter lamps regime C and F were high enough efficiency for cleaning fine particle within F7 and F9 in BS EN and MERV15-16. In case of regime B and D, filter lamps were acceptable to purify middle fine particle within M5 and M6 in BS EN, but were not sufficient performance to clean fine dust.

In statistical 3-year data of PM2.5 concentrations in Thailand, it was possible that the highest PM2.5 concentration would reach 0.180 mg/m^3 and average concentration could get 0.040 mg/m^3 (Air Quality and Noise Management Bureau, P. C. D. 2004-2013). As the highest initial PM2.5 concentration was in regime G at 0.12 mg/m^3 that could be eliminated by filter lamp application to nearly 0 mg/m^3 in the first ten minutes period, so it is possible to apply this application in high risk of air pollutant source.

In case of PM10 mop cleaning, it is affirmed that low fan speed was better driven force for laboratory tests in Nottingham (Ma, Birnie & Riffat 2008, Riffat & Ma 2012). However, in this study, fan speed in system helped to increase air cleaning performance because this system needs high enough pressure to drive air pass through fabric filter with low air permeability. Then this flow speed in system relates to dust removal efficiency and the rapidity of dust reduction in system will be discussed in the next section.

Based on only one occupant in bedroom and lower activities during the monitoring period, PM2.5 concentration was sourced very low from temporary opening door. The results demonstrated nearby fixed generator of PM2.5 concentration. Therefore, further study may find out dust removal efficiency of application during high dust generating rate.

8.4.2 The rapidity of air cleaning performance

The rapidity of air cleaning performance was demonstrated in terms of slope in reductive trend. So the fluctuation in case of regime B and E could not be estimated for air cleaning rapidity even the average PM2.5 concentration was lower than those in existing regime. It can be seen that flow speed in lamp system can increase rapidity of dust removal performance of filter lamp.

There are three groups of rapidity obviously seen in **Table 8-4** especially fluctuations (A, B, E), moderate reductions (C, D) and rapid reductions (F, G). In case of regime C and D, indoor PM2.5 concentrations were reduced moderately with rapidity at 0.0006 mg/min and 0.0005 mg/min. The rapidity of dust removal in regime F was very high with rapid reduction at 0.012 mg/min in the first 10 minutes period. The average concentration in regime F and G were reduced dramatically to 0.00 mg/m^3 in fabric filter lamp integrated with TiO_2 coating mop and fan unit.

Table 8-4 The rapidity of air PM2.5 cleaning performance

Regime		Avg. PM2.5 concentration (mg/m^3)	Rapidity (mg/min)
A	Existing	0.06	-
B	Buoyancy	0.03	-
C	3 m/s	0.01	0.0006
D	2 m/s	0.02	0.0005
E	TiO_2	0.04	-
F	TiO_2+ 3 m/s	0.00	0.0120
G	TiO_2+ 2 m/s	0.00	0.0040

To be noted, ambient velocity in bedroom in every regime were nearly 0 m/s throughout the testing period following real time indoor air monitoring in Shanghai. However, several places of natural ventilation in hot and humid climate are normally forced to high velocity by fan unit to reduce skin temperature. That may affect dust removal efficiency in this study. So, for further research, it is possible to test the efficiency of filter lamp in high room velocity.

8.5 Conclusions

In conclusion, the filter lamp was developed based on the main concept of low cost, portable devices and high enough efficiency to clean respiratory particle in hot and humid climate. With two SES light bulbs, fabric filter was replaced lamp shade to cover the area of 0.29 m^2 on floor lamp. Then fan unit was installed to force system in different flow speed.

To extend experiment, solid fibre mop was coated TiO_2 on surface as a result of large amount of fibre surface area. This could promote photocatalytic process in lamp system. To assure TiO_2 coating on solid fibre mop, scanning electron microscope was used to identify TiO_2 crystal. Also fan unit was applied to increase efficiency of air cleaning performance.

Following all developments of filter lamp, seven regimes were test in 2.5x2.5x2.5 m^3 bedroom in particular (A) Existing, (B) Buoyancy, (C) Fan speed 3 m/s, (D)

Fan speed 2m/s, (E) TiO_2 coating mop, (F) TiO_2 coating mop with fan speed 3m/s and (G) TiO_2 coating mop with fan speed 2m/s. The best regime of air cleaning was regime F with air removal efficiency at 99.07% within F9-BS EN and MERV16. However, regime C and G could get adequate efficiency to clean fine dust at 88.21% and 94.17% respectively. Buoyancy system and only TiO_2 coating could slightly reduce indoor respiratory dust with low efficiency.

The rapidity of air cleaning was high in case of applying fan unit in regime C, D, F and G. The highest reductive rapidity was show in regime F at 0.012 mg/min in the first ten minutes. From very high intensity of PM2.5 at 0.12 mg/m^3, regime G could drop rapidly to 0 mg/m^3 in the first 10 minutes. This can imply to use in high dust intensity areas such as industrial zone and traffic areas in hot and humid climate. For example, this application may be installed in small single unit of work space and resident room which dimensions are similar to experimental room at 2.5x2.5x2.5 m^3. In case of large area, quantity of lamp may be required for indoor air cleaning and the lamp should be located near occupant. For further study, the generating rate of dust may be investigated how it relates to dust cleaning efficiency of filter lamp.

According to experimental conditions, temperature and relative humidity were controlled as nearly same as climate in real time monitoring in Shanghai in Chapter 5. Even temperature in the hottest month in hot and humid climate can reach higher than in this experiment, but this is normally only one from twelve months. So the lamp application can be used effectively in almost full year.

The recommendations for further study are focused on maintenance process of fabric filter and TiO_2 coating. Fabric filter should be designed for easy take off for cleaning process and the period of maintenance depended on dust intensity and permeability of fabric material. Also TiO_2 crystal could be changed easily anatase to rutile phase in room temperature. So, in longer using period, it is important to permanently coat by manufacturing process or repeat self TiO_2 coating before real test.

Chapter 9: Conclusions and Recommendations

9.1 Summary

According to literature reviews of indoor air quality, pollutants can be basically categorized into five types in particular PM2.5, PM10, bioaerosol, gas and volatile organic compounds. Each type of air pollutants affects directly human respiratory systems and their dangerous levels are depended on air pollutants size and concentration. That's resulted from air pollutant sources, meteorological and environmental factors, for example, air temperature, relative humidity, precipitation, flow rate and other air contaminants. In case of hot and humid climate, temperature and relative humidity are top factors related to indoor air pollutants. So the main types of air pollutants in this study are particulate matter sized 2.5 micrometres and 10 micrometres (PM2.5 and PM10) and the studies of environmental factors are examined in terms of air temperature effects and relative humidity effects.

In developing countries, the data of air particulate matter has been mainly collected for research and study especially particulate matters diameter sized 2.5 micrometres and 10 micrometres (PM2.5 and PM10). From the importance of air pollutant extension in Southeast Asia, 3-year air particulate matters in several parts of Thailand have been exceeding WHO and national standards (Air Quality and Noise Management Bureau, P.C.D. 2004-2013). This can affect indoor air quality as a source of air pollutant, if building openings provide high leakage effects especially in natural ventilation buildings.

The existings solutions to clean indoor air quality in hot and humid climate are still expensive and normally working with dehumidifying concept. These solutions seem to go against energy efficiency concept and natural ventilation techniques in hot and humid climate. Also low cost families in industrial zone can only afford normally natural ventilation house; while the outdoor pollutant is higher than other areas.

The solutions of air cleaning techniques in this study have been focused on fabric filter, solid fibre mop and TiO_2 coating which are suitable for PM2.5 and PM10 cleaning in hot and humid climate. Fabric filter was normally used for PM2.5 cleaning in purifier; while solid fibre mop was used in PM10 cleaning system. The last technique of TiO_2 solvent was coated on building surface to clean bioaerosol and VOCs elimination. However this study involves integrating these three techniques for air cleaning and the results are concluded in the next section. Also the relationships between air cleaning techniques and environmental factors are identified in the next topic too.

9.2 All results conclusions

To develop a budget air purifier used in hot and humid climate, it was important to identify characters of indoor PM2.5 concentration in office and residence in Shanghai, China. In the same time, fabric filter and solid fibre mops were preliminary tested in a UK laboratory. Then fabric filter lamp with TiO_2 coating mop was developed for air PM2.5 cleaning. Additionally, the conclusion of relationships between filtration techniques and meteorological factors are examined.

9.2.1 Real time monitoring in Shanghai

To real time monitor PM2.5 in Shanghai, PM2.5 concentration in office related directly to outdoor concentration based on high opening leakage rate from multiple occupant behaviors. So, when outdoor dust concentration exceeded WHO standard at 0.025 mg/m^3 for 2 hours in early evening, indoor concentration was the same character to that in outdoor condition. In case of residence, opening leakage was very low as there was only one occupant and not much activity in bedroom. Indoor dust concentration was lower than that in outdoor condition by more than 10 times from 0.370 mg/m^3.

To focus on the relationship between indoor PM2.5 concentration and Meteorological factors, air temperature had a negative effect on indoor PM2.5 concentration; while relative humidity had positive effect on that the concentration in only low leakage air conditioned room. Outdoor dust concentration related directly to indoor concentration, if opening leakage was high. Thus, further real time experiment in this study would be focused on only indoor environmental conditions excepting.

Outdoor temperature and relative humidity ranged into 23.81-35.70 °C and 50.60-80.90% respectively which were in summer season of Shanghai climate. This weather condition was nearly similar to Bangkok, Thailand in the same month. Therefore, the temperature and relative humidity would be used in lamp real time monitoring.

To parallel real time PM2.5 monitoring in Shanghai, air purifier elements were evaluated air cleaning performance especially fabric filter and solid fibre mop. Then the conclusion of evaluated results will demonstrated in the next section.

9.2.2 Preliminary test of fabric filter and solid fibre mops

Fabric filter was estimated to have moderate arrestance to clean PM2.5 in preliminary test at 85% in case of high system velocity as well as F7 in BS EN and MERV16 in NAAQs; while lower air flow in system would decrease the arrestance to 50%. These two arrestance values still were moderate efficiency compared to general purifier at 99% of air cleaning arrestance. Also the efficiency of dust removal efficiency of fabric filter was evaluated statistically that related positively to dust concentration. To concern meteorological factors, temperature was analyzed to relate negatively to dust concentration; while relative humidity showed negative trend.

Turning to mop evaluation test, the performance of particle was extended to PM10 cleaning with 3 types of mop in particular mop A with solid fibre diameter 0.08-0.58 mm, mop B with solid fibre diameter 0.22 mm and mop C with solid fibre diameter 0.16 mm. The performance of particle cleaning was estimated in two terms especially the rapidity and efficiency of dust removal. For PM2.5, mop C in dry condition of test held the highest efficiency at 36%. But multiple mops B and C in wet condition offered the highest dust removal rapidity at 0.005 mg/sec in 350 seconds. Then, for cleaning PM10, mop B in wet condition provided the highest efficiency at 25%; while multiple mops C and A offered the highest dust removal rapidity at 0.021 mg/sec in 900 seconds. In meteorological factors, when increasing relative humidity to be wet condition, the efficiency of PM2.5 removal reduced while that of PM10 removal increased. So relative humidity seems to reduce effectively PM10 concentration; while it may have flexible effects on PM2.5 concentration.

Fabric filter and mop B were selected to integrate to filter lamp in order to clean indoor air PM2.5. Then with TiO_2 coating on mop would be optional technique in hot and humid climate.

9.2.3 Fabric filter lamp with TiO_2 coating mop

Fabric filter lamp with cylinder shape in bottom and top diameters at 0.24 m and 0.18 m respectively and height at 1.15 m was developed for air cleaning in a bedroom sized 2.5x2.5x2.5 m^3. Then, with TiO_2 coating on mop and UV light bulb, filter lamp was integrated photocatalytic process into system. Among all result regimes, the best option for air filtration in hot and humid condition was at 99.07% efficiency in regime F which consisted of fabric filter, TiO_2 coating mop and fan speed at 3 m/s. This regime was estimated into F9 in BS EN and MERV 16 in NAAQs. In the same regime, dust removal performance was the highest value in rapidity at 0.012 mg/m^3, while regime C with lower fan speed at 2 m/s provided second higher efficiency to clean air PM2.5 at 94.17% as in F8-BS EN and MERV15.

Fan speed affected air cleaning efficiency in both with and without TiO_2 coating mop; while fan speed can overcome buoyancy effect in system. Without fan speed, buoyancy effect in regime B offered higher middle fine dust cleaning efficiency than TiO_2 coating on mop case in regime E; but both regimes did not get adequate efficiency to clean fine particle.

To be noted in Shanghai study, opening leakage in office case is same as natural ventilation in low cost house in Thailand condition that always open windows and doors. So the highest outdoor PM2.5 from 3 years collection in Thailand at 0.180 mg/m^3 can lead to high indoor dust concentration. Very high dust concentration was found in regime G at 0.120 mg/m^3 and filter lamp with TiO_2 coating on mop could get rid of PM2.5 concentration to near 0 in the first ten minute. So it is possible to install this filter lamp in high dust concentration area.

9.2.4 The relationship between air filtrations and meteorological factors

For air quality in this study, temperature was proved to provide negative effect on indoor dust concentration; while relative humidity has flexible effect on PM2.5 concentration. In case of dust purifier, relative humidity can reduce PM2.5 removal efficiency, but increase PM10 removal efficiency in solid fibre mop.

Without high relative humidity, filter lamp was possible to clean air PM2.5 by only fabric filter. Fan speed can increase the efficiency of air cleaning from buoyancy case at 41.54% to normal fan speed case at 88.21%. With fan speed in regime C, air cleaning performance could hold F7 in BS EN and MERV 15 as the best performance of air filter lamp in dry climate.

9.3 Novelty & Limitations

In the era of industrial development, air pollutant has become more important issue due to affect directly global environment and human health. According to early review of air pollutants, higher concentration of other types of air pollutants can promote level of dust concentration. For example, an increase of gas and VOCs (Volatile organic compounds) possibly catalyse the chemical formation of particulate matter. Therefore, the holistic approach of indoor air purification has been developed in this study with integrating multi air cleaning techniques.

Based on sensitive area of air pollutant problems, Southeast Asia has been concerned as one of the main location in this study. As developing countries in Southeast Asia, most of local people lives within natural ventilation building. That allows air pollutant affecting directly people respiratory systems or even long term effects can be found in chronic symptoms and cancer. Then, with low income, they cannot afford to install air conditioners or air purifiers. Consequently, it is more beneficially for energy saving and low cost development, if air cleaning techniques can be integrated to household devices such as curtain, fan and lamp. Floor lamp is selectively developed in this study because the complex elements of lamp can be replaced by air purified materials and other users can self-adapt these techniques.

Due to low cost integrating concept, the combination of air purifications in this study is from 3 main techniques especially solid fibre mop, fabric filter, TiO_2 photocatalytic in order to clean air PM2.5 and PM10. The first purification is solid fibre mop that is suitably for pre-filtration of air filter lamp. With mop ability to clean PM10, solid fibre mop is integrated to floor lamp at the bottom part. When the inlet air flow with small fan unit is being driven through this mop, large particulate matter (PM10) can be trapped. The solid fibre suitably used in this study is 0.22 mm thickness fibre.

Another technique is fabric filter which is suitable for replacing lamp shade with appropriate transmittable light (as same as paper shade). This fabric filter can eliminate PM2.5 with sufficient flow rate from the same small fan unit. The large area of floor lamp shade at 0.27 m^2 is adequate for trapping PM2.5.

The third technique in this filter lamp is photocatalytic from UV light, air humidity and TiO_2 coating on solid fibre surface. For the purpose of improving photocatalytic technique, UV light bulb is installed instead of normal bulb. To set environment as same as hot and humid climate condition, boiler is periodically used to increase relative humidity and temperature in bedroom. Then relative humidity affects to increase the effect of photocatalytic technique. Based on reviews, photocatalytic was proved to clean all types of indoor air pollutants for instance bioaerosols, VOCs, gas and particulate matter depended on room function and purifiers' technique. This study aims to principally purify indoor air PM2.5, so smaller types of air pollutant are not monitored.

The result of above air cleaning techniques is demonstrated in terms of filter lamp integration with floor lamp, fan unit, fabric filter, solid fibre mop and TiO_2 coating. This device provides 99.07% efficiency of air cleaning in case of fan speed 3 m/s and TiO_2 coating on mop regime. This purifier shows high performance of air cleaning innovation with low cost materials and saving energy concept. Also all techniques can be principally used in natural ventilation buildings in industrial zone in hot and humid climate.

For the limitation of climate, this purifier can be installed in dry climate with lower air cleaning performance at 88.21% dust removal efficiency. That results from lower relative humidity in photocatalytic process, so TiO_2 coating and UV light bulb may not support air purification in filter lamp system. Otherwise, if humidifier is integrated to filter lamp for increasing relative humidity, the performance will possibly reach 99.07% dust removal efficiency. While gloomy and cold climates will not affect air cleaning performance of filter lamp because of artificial UV light bulb.

Another limitation of experiment is meter equipment that can monitor air pollutants in terms of PM2.5 and PM10 only. Therefore, this filter lamp cannot be proved the ability to clean other types of air pollutants. However, as mentioning photocatalytic air cleaning performance, it is possible that filter lamp may clean poison gas, VOCs and bioaerosols. The recommendation of filer lamp development for cleaning other air pollutants will be demonstrated in the next part.

Lastly, the limitation of some experimental locations is showed in terms of lower temperature especially laboratory experiment and real-time monitoring in UK. According to the main study location in hot and humid climate, it is important to use artificial environment controls for example boiler and water spray bottle. These can increase relative humidity and air temperature for simulating hot and humid climate.

9.4 Recommendations

The recommendations in this chapter will be examined for three groups of user especially academic researchers, commercial developers and local people. For academic fields, the recommendation will focus on laboratory reliability, experimental control and expanding research boundary. The second concerning is commercial department that application development can be recommended for quality of production. Lastly, local users can produce air purifier themselves from the knowledge in this Thesis.

Based on academic research, further study can possibly review more air purifier techniques to increase air cleaning performance. These techniques might not be complicated but should be more effectively for cleaning indoor air in several climate and environmental conditions. In case of experiment, because of low generating of PM2.5 concentration and low velocity during the period of experiment, the results show nearby fixed rate of dust generation. Therefore, monitoring equipment should be selected meticulously for reading more decimal unit of data and should be calibrated before every experiment.

Moreover, in real-time test of filter lamp, fabric filter should be cleaned by reverse flow in system after test for maintaining filter lamp efficiency. Then, in the part of data analysis, the future test may investigate the relationship between dust generating rate and dust removal efficiency for peak hour of air pollutant emission. As another key of air cleaning process is system flow, every purifier system should be controlled air flow direction to pass through air cleaning techniques. Indoor velocity may also fluctuate with natural ventilation or fan unit, so further research may find out filter lamp efficiency within high velocity or fluctuated velocity.

Furthermore, weather and climate conditions may affect the efficiency of air cleaning as a limitation of in-used techniques in filter lamp. For example in dry climate, if average relative humidity is lower than 50%, TiO_2 coating on solid fibre mop may not be suitable and the fabric filter lamp can possibly work with fan unit only. That relates to lower efficiency as in regime C and D in chapter 8. Colder climate do possibly not affect filter lamp efficiency, if relative humidity is higher than 50% the same as United Kingdom in winter season.

The ability of TiO_2 coating surface can possibly cover gaseous, VOCs and aerosol eliminations, so further research may examine removal efficiency of other air pollutants. For coating mop in filter lamp, there are several grades of TiO_2 solvent from laboratory to manufacturing process. In this study, CrystalActiv^{TM} PCX-S2 is TiO_2 solvent with 2.0% concentration for laboratory grade. So it is possible to be washed off in high humidity condition.

Turning to commercial development, this innovative filter lamp is recommended for using in industrial zone in hot and humid climate. This filter lamp application is suitable for investment because it charges low cost for production with high demand of users in industrial areas. With the performance of 99.07% PM2.5 cleaning efficiency, this application can be used in natural ventilation buildings. For production development, fabric filter material may change for convenient developments and solid fibre material is flexible depended on local products. However, the thickness of fibre should be 0.2 mm same as solid fibre in this research. Additionally, the system of reverse flow should be installed in filter lamp process for self-cleaning system. Also, to maintain photocatalytic process, solid fibre mop should repeat TiO_2 coating process. For worldwide production, the application may be adjusted humidifier in case of dry climate countries.

Lastly, local self-developer may use three techniques of air purifications in this for easy clean indoor air. Fabric filter is possibly used in other element of household device such as window mesh screen and normal fan unit. This application can be simply installed fabric filter by DIY (Do-It-Yourself) and safe cost of indoor air cleaning process. More difficult installation is demonstrated in terms of TiO_2 coating and solid fibre mop production, but these elements can be produced or be brought in local market. To be awareness, the system of air purification is based on adequate air driven flow and system pressure. So each air purified technique should be controlled flow direction to assuredly pass through the process of air cleaning.

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APPENDICES

Appendix A Particle size

Particle	Particle Size *(microns)*
Spider web	2 - 3
Spores	3 - 40
Combustion-related - motor vehicles, wood burning, open burning, industrial processes	up to 2.5
Fly Ash	1 - 1000
Milled Flour, Milled Corn	1 - 100
Coal Dust	1 - 100
Iron Dust	4 - 20
Smoke from Synthetic Materials	1 - 50
Lead Dust	2
Face Powder	0.1 - 30
Talcum Dust	0.5 - 50
Asbestos	0.7 - 90
Calcium Zinc Dust	0.7 - 20
Paint Pigments	0.1 - 5
Auto and Car Emission	1 - 150
Metallurgical Dust	0.1 - 1000
Metallurgical Fumes	0.1 - 1000
Clay	0.1 - 50
Humidifier	0.9 - 3
Copier Toner	0.5 - 15
Liquid Droplets	0.5 - 5
Insecticide Dusts	0.5 - 10
Anthrax	1 - 5
Yeast Cells	1 - 50
Carbon Black Dust	0.2 - 10
Atmospheric Dust	0.001 - 40
Smoldering or Flaming Cooking Oil	0.03 - 0.9
Corn Starch	0.1 - 0.8
Sea Salt	0.035 - 0.5
Bacteria	0.3 - 60
Bromine	0.1 - 0.7
Lead	0.1 - 0.7
Radioactive Fallout	0.1 - 10

Particle	Particle Size *(microns)*
Rosin Smoke	0.01 - 1
Combustion	0.01 - 0.1
Smoke from Natural Materials	0.01 - 0.1
Burning Wood	0.2 - 3
Coal Flue Gas	0.08 - 0.2
Oil Smoke	0.03 - 1
Tobacco Smoke	0.01 - 4
Viruses	0.005 - 0.3
Typical Atmospheric Dust	0.001 to 30
Sugars	0.0008 - 0.005
Pesticides & Herbicides	0.001
Carbon Dioxide	0.00065
Oxygen	0.0005

Appendix B Dust meters

B.1 DPM-4000

B.1.1 DPM-4000 Specifications

Display: Alpha-numeric LCD-4line, 20 character mg/m^3 concentration reading

Operations: Four key splash proof membrane switch – menu driven

Calibration: NIOSH gravimetric reference NIST traceable – SAE fine test dust

Accuracy: +/- 10% to filter gravimetric SAE fine test dust

Particulate Size Range: <1 to 10 μm

Precision: +/- 2 μg/m^3

Sample Flow Rate: 1.0 – 3.3 liters/minute (recommend flow 1.7 LPM)

Filter Cassette: 37mm disposable

Analog Output: 0-2 vdc

Alarm Output: 90db at 3ft

Recording Time: 1 second to 21 weeks

Sampling Rate: 1 second, 1 minute, and 10 minute intervals

Concentration Range: 1-20,000 μg/m^3

Data Storage: 21,500 data points

Security Code: 4 digit combinations

Memory & Time Storage: ≥5 years

Real-time Clock and Data Display: Hours, minute, second, day, month, & year

Data Display: Concentration in μg/m^3 & TWA, MAX, MIN, STEL, date, & time

Digital Output: RS-232

Operating Temperature: 0 to 50º C

DustComm Pro Software: Windows™ Driven

Power: NiMH Rechargeable Battery

Operating Time: ≥8 hours

Charging Time: 10-12 hours

Humidity: 95% non-condensing

Dimensions (case): 5.5″x3.25″x2.75″

Sensor Dimensions: 1.75″ x 1.5″

Weight: 2 lbs

B.1.2 DPM-4000 Applications

- Diesel Engine Surveys
- Combustion Efficiency
- Mining
- Transportation (i.e. Bus Depots, Trucking, & Freight)
- Valuable Survey Tool for MSHA& NIOSH Compliance Program – Reviews or any air monitoring applications involving lung damaging diesel particulate matter

B.1.3 DPM-4000 Features

- Direct Read Out in $\mu g/m^3$
- Comfortable Light Weight
- Miniaturized Sensor Design
- Adjustable Alarm Signal
- Enhanced Accuracy
- Splash-Proof
- On Screen Display of Statistics
- Data Logging
- RFI/EMI Protection

B.2 DustTrak™ DRX Aerosol Monitor 8533

B.2.1 Features and Benefits

- Simultaneously measure size-segregated mass fraction concentrations corresponding to PM_1 , $PM_{2.5}$, Respirable, PM_{10} and Total PM size fractions
- STEL alarm setpoint
- Automatic zeroing (with optional zero module) minimizes the effect of zero drift
- Perform in-line gravimetric analysis for custom reference calibrations
- Manual and programmable data logging functions
- Aerosol concentration range 0.001 to 150 mg/m^3
- Environmental protected and tamper-proof with Environmental Enclosure
- Cloud Data Management System for efficient remote monitoring
- Heated Inlet Sample Conditioner to reduce humidity effects
- Desktop unit

B.2.2 DRX 8533 Applications

- Industrial/occupational hygiene surveys
- Indoor air quality investigations
- Outdoor environmental monitoring
- Baseline trending and screening
- Engineering control evaluations
- Remote monitoring
- Process monitoring
- Emissions monitoring
- Aerosol research studies

B.2.3 Included Items

- Analog alarm outputs
- Rechargeable 6600 mAH Li-Ion battery
- Switching power supply with universal line cords
- Zero filter
- USB (device and host) computer cables
- Analog/alarm output connector
- Inlet cap (x2)
- 37-mm cassette with mesh filter

- Calibration impactor kit (with PM2.5 impactor, impactor plates (x2) and impactor oil)
- Sample extension tube (3-ft/1-m)
- Sheath air HEPA filters (x4)
- Filter removal tool
- Operation service manual
- Calibration certificate

Appendix C Multiple regression result relating to dust concentration in chapter 4

C.1 Table of multiple regression result

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.81061
R Square	0.657089
Adjusted R Square	0.654749
Standard Error	0.067299
Observations	296

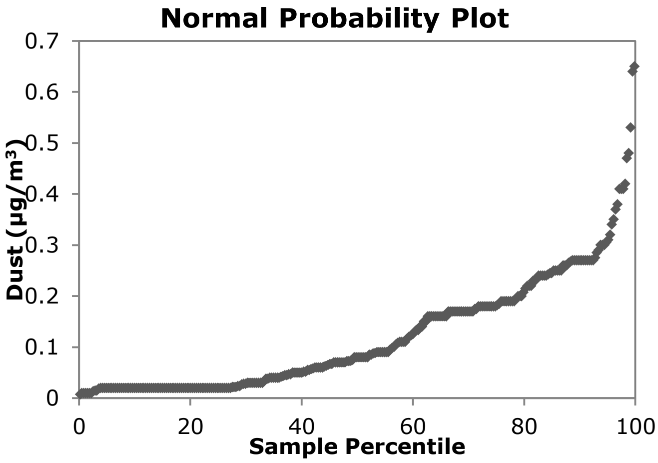
ANOVA

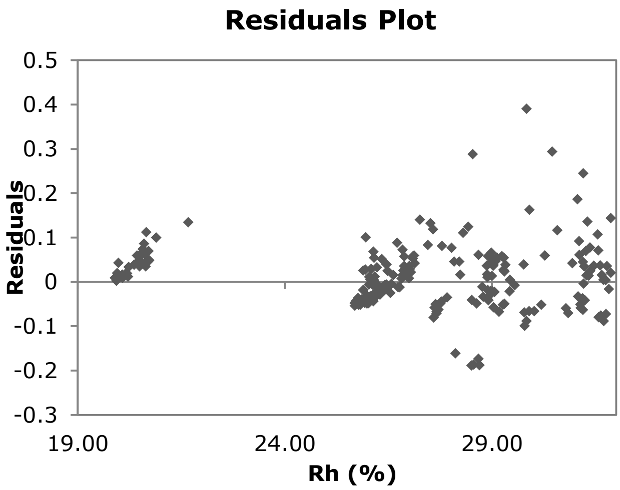
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	2.542887	1.271444	280.7249	8.02E-69
Residual	293	1.327039	0.004529		
Total	295	3.869926			

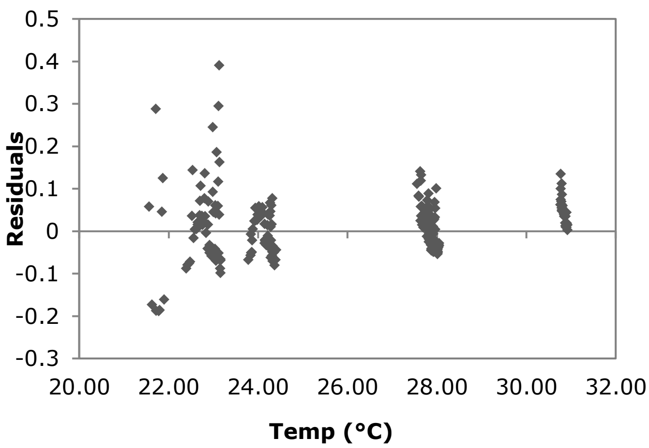
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	2.287711	0.190867	11.98588	3.32E-27	1.912067	2.663356	1.912067	2.663356
Rh (%)	-0.02344	0.003444	-6.80519	5.69E-11	-0.03021	-0.01666	-0.03021	-0.01666
Temp (°C)	-0.05788	0.003843	-15.0639	2.28E-38	-0.06545	-0.05032	-0.06545	-0.05032

C.2 Multiple regression plot

The statistic plot of multi-regression test in dust concentration related to meteorological factors (more details in Appendix C.1)







Appendix D Regression analysis responding to indoor PM2.5 in chapter 5

D.1 Table of multiple regression analysis in office

SUMMARY OUTPUT in office

R Square	0.988378
Adjusted R Square	0.987037
Standard Error	0.000915
Observations	59

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	6	0.003705	0.000617	737.0534	1.84E-48
Residual	52	4.36E-05	8.38E-07		
Total	58	0.003748			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.032088	0.008984	3.571795	0.000774	0.014061	0.050115	0.014061	0.050115
Rh in	6.21E-05	4.43E-05	1.402572	0.166687	-2.7E-05	0.000151	-2.7E-05	0.000151
Temp in	-0.00119	0.000449	-2.65178	0.010589	-0.00209	-0.00029	-0.00209	-0.00029
PM2.5 out	0.897811	0.02634	34.08584	3.01E-37	0.844957	0.950666	0.844957	0.950666
V out	-0.00075	0.000571	-1.31449	0.194449	-0.0019	0.000395	-0.0019	0.000395
Rh out	-1E-05	5.93E-05	-0.17427	0.862333	-0.00013	0.000109	-0.00013	0.000109
Temp out	-6.7E-05	0.000117	-0.57214	0.569695	-0.0003	0.000168	-0.0003	0.000168

D.2 Table of second multiple regression analysis in office

SUMMARY OUTPUT in office

R Square	0.984568
Adjusted R Square	0.984017
Standard Error	0.001016
Observations	59

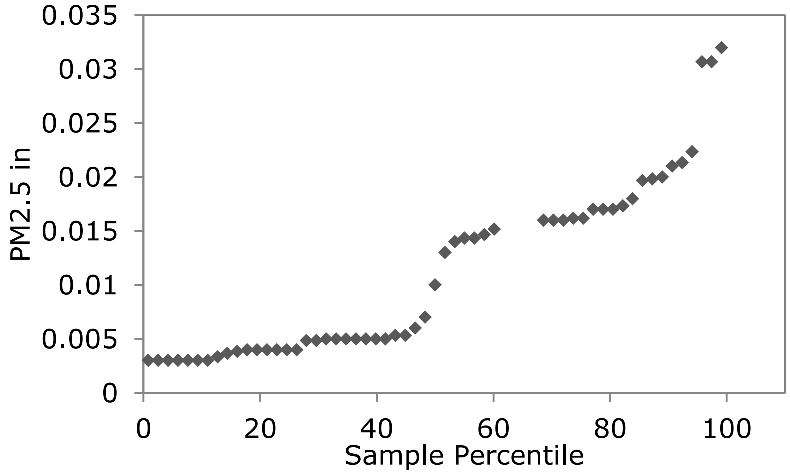
ANOVA

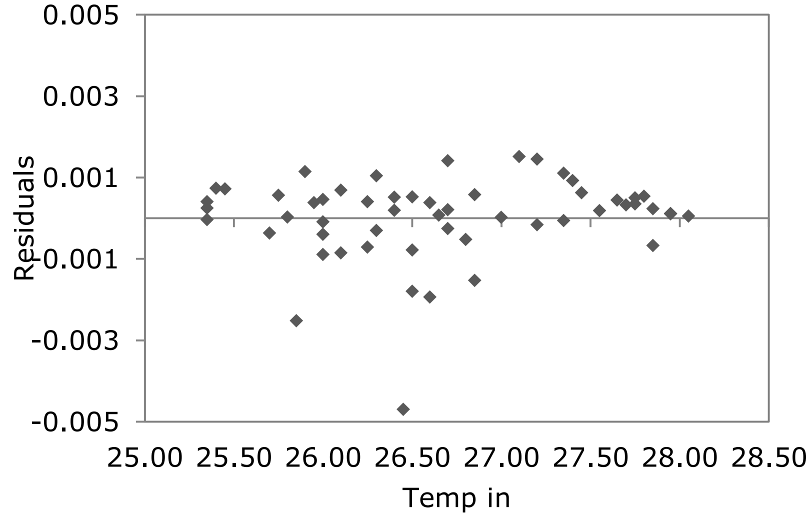
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.00369	0.001845	1786.408	1.89E-51
Residual	56	5.78E-05	1.03E-06		
Total	58	0.003748			

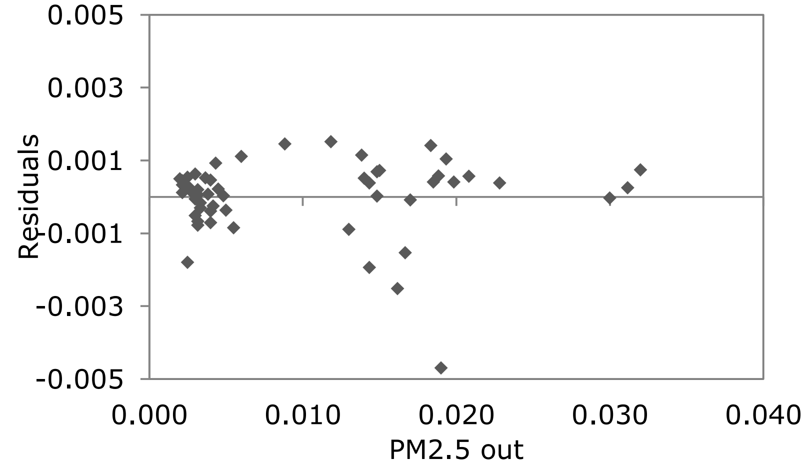
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.016461	0.00572	2.877998	0.005656	0.005003	0.027918	0.005003	0.027918
Temp in	-0.00057	0.00021	-2.71692	0.00875	-0.00099	-0.00015	-0.00099	-0.00015
PM2.5 out	0.92112	0.01928	47.7756	4.47E-47	0.882497	0.959742	0.882497	0.959742

D.3 Multiple regression plot in office

The statistic plot of multi-regression test in indoor dust concentration related to meteorological factors in office (more details in Appendix D.2)







D.4 Table of multiple regression analysis in residence

SUMMARY OUTPUT in residence

Regression Statistics	
Multiple R	0.821713
R Square	0.675212
Adjusted R Square	0.637002
Standard Error	0.003479
Observations	58

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	6	0.001284	0.000214	17.67092	6.05E-11
Residual	51	0.000617	1.21E-05		
Total	57	0.001901			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.09612	0.032202	-2.98501	0.004346	-0.16077	-0.03147	-0.16077	-0.03147
Temp in	-0.00117	0.000463	-2.52994	0.014539	-0.0021	-0.00024	-0.0021	-0.00024
Rh in	0.001289	0.000196	6.558773	2.71E-08	0.000894	0.001683	0.000894	0.001683
Rh out	0.000972	0.000344	2.823109	0.006766	0.000281	0.001664	0.000281	0.001664
PM2.5 out	-0.01362	0.017743	-0.76766	0.446226	-0.04924	0.021999	-0.04924	0.021999
V out	0.002318	0.012585	0.184164	0.854615	-0.02295	0.027582	-0.02295	0.027582
Temp out	-0.00026	0.000577	-0.45761	0.649173	-0.00142	0.000895	-0.00142	0.000895

D.5 Table of second multiple regression analysis in residence

SUMMARY OUTPUT in residence

Regression Statistics	
Multiple R	0.818692
R Square	0.670256
Adjusted R Square	0.651937
Standard Error	0.003407
Observations	58

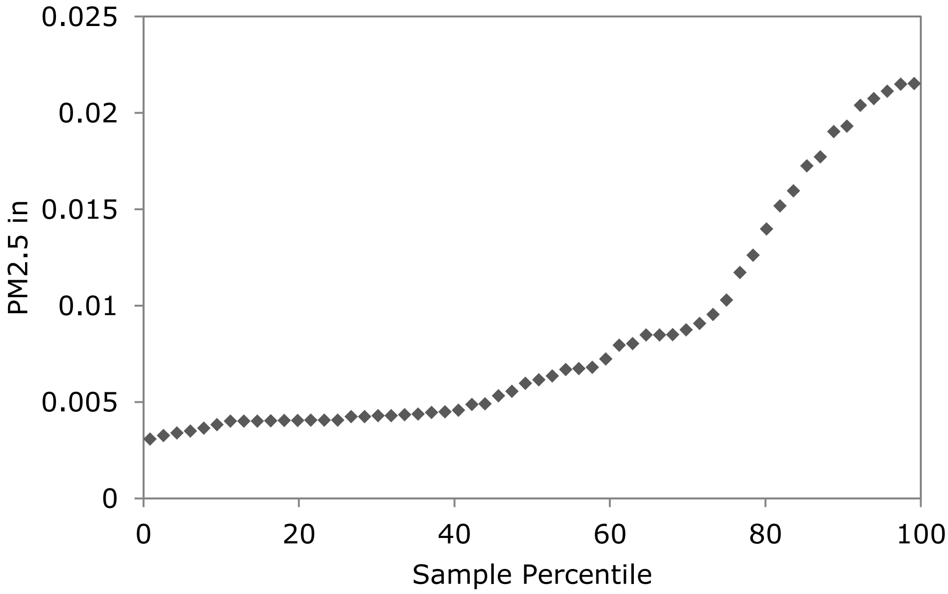
ANOVA

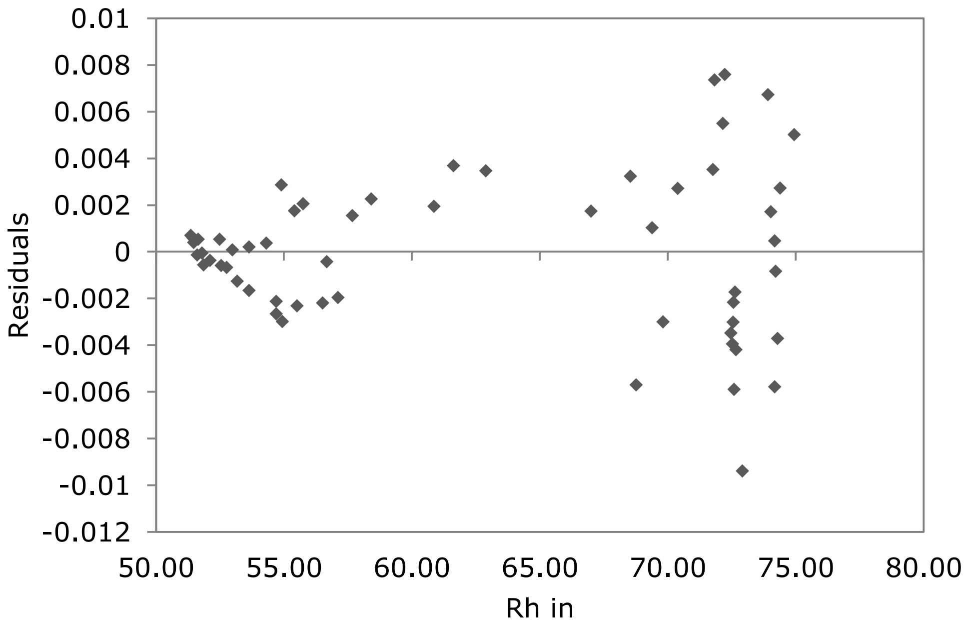
	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.001274	0.000425	36.58785	4.81E-13
Residual	54	0.000627	1.16E-05		
Total	57	0.001901			

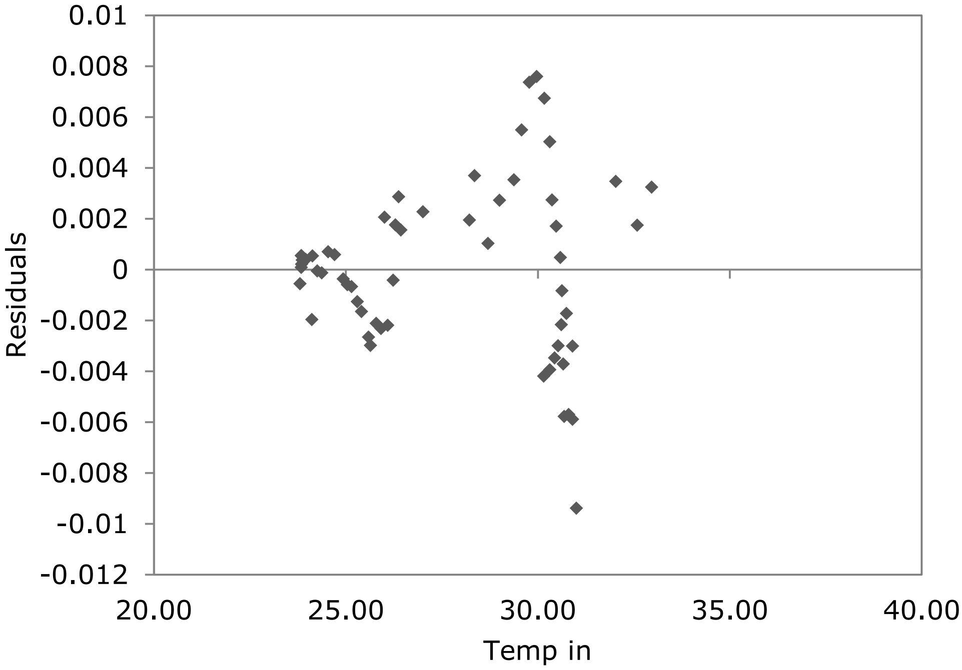
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.10137	0.02143	-4.73017	1.65E-05	-0.14433	-0.0584	-0.14433	-0.0584
Temp in	-0.00106	0.000409	-2.58603	0.012439	-0.00188	-0.00024	-0.00188	-0.00024
Rh in	0.001298	0.000174	7.439001	7.98E-10	0.000948	0.001647	0.000948	0.001647
Rh out	0.00084	0.000189	4.456165	4.25E-05	0.000462	0.001218	0.000462	0.001218

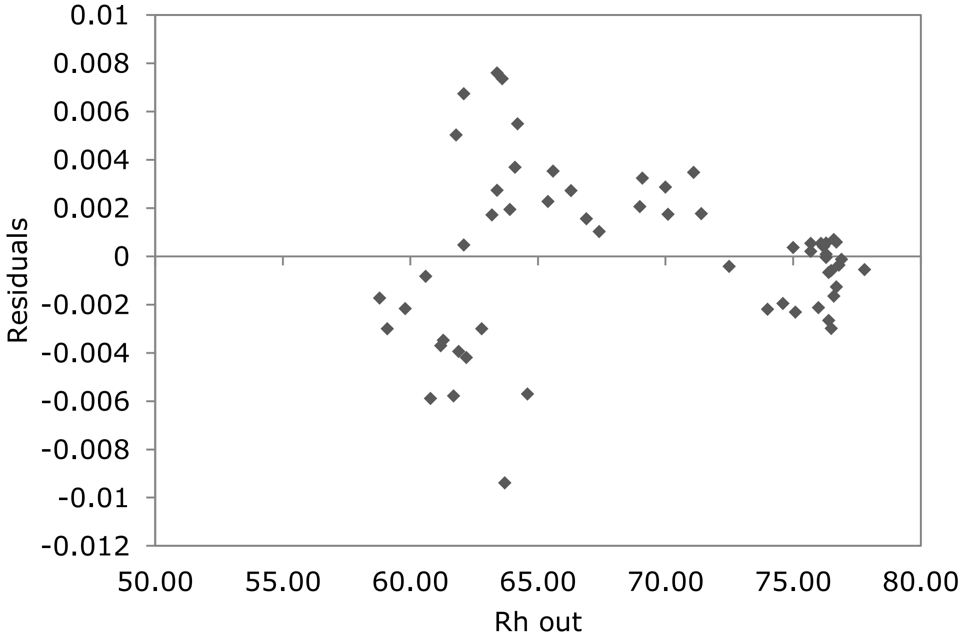
D.6 Multiple regression plot in residence

The statistic plot of multi-regression test in indoor dust concentration related to meteorological factors in office (more details in Appendix D.5)






0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
Residuals
20.00
25.00
30.00
35.00
40.00
Temp in


0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
Residuals
50.00
55.00
60.00
65.00
70.00
75.00
80.00
Rh out