Faculty of Engineering

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THERMAL PERFORMANCE OF TRADITIONAL AND CONTEMPORARY MOSQUE BUILDINGS IN THE SULTANATE OF OMAN

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ABSTRACT

The objectives of enhancing building energy efficiency and ensuring human thermal comfort are often challenging to achieve concurrently. Oman’s climate is hot and dry, and its buildings have high cooling demands. This research aims to investigate the thermal performance of buildings in Oman and improve it without compromising human thermal comfort. Mosque buildings are an interesting case for this research, as daily prayers are conducted intermittently throughout every day.

An enhancement in the energy efficiency of mosque buildings would contribute to environmental sustainability through the reduction of energy consumption. This research project aims to investigate two types of mosques: traditional mosque buildings that are 500 years old or older, and contemporary mosque buildings that have been built recently within the last 40 years. There are two primary research methodologies followed in this study: Computer Simulations, and Field Measurements. The computer simulation methodology utilises energy modelling using EDSL TAS computer simulation software. The field measurements methodology is conducted using thermal measurement instruments including temperature and humidity dataloggers. Findings from both the computer simulation and the field measurements were compared for analysis and discussion. The analysis compared between the traditional and contemporary mosque buildings. The objective was to identify solutions for improving building thermal performance and occupants’ thermal comfort.

The findings show that traditional buildings, which are naturally ventilated, perform better than contemporary buildings. During the winter, findings from both the field measurements and computer simulations concur that all mosques are within the thermal comfort zone as per the Muscat bioclimatic chart. During the summer, the case studies exceeded the maximum thermal comfort zone temperature despite their high energy consumption. This indicated room for improvement in both the energy efficiency and thermal comfort of the case studies.

After a thorough review of the academic literature, field measurements, and computer simulations, a total of fourteen suggested improvements were presented in Chapter 8 (Suggested Improvements Chapter). The initial set of nine improvements were made to enhance the building elements’ conductivity, glazing area, and material composition of walls and roof in the six mosques. The subsequent five improvements were suggested to improve the internal conditions of the buildings and to incorporate passive cooling techniques, such as adjusting the cooling thermostat setpoint, reducing infiltration rate, introducing higher efficiency lighting, introducing a Khalwah (an underground chamber), and increasing vegetation around the buildings. The proposed improvements aim to optimise thermal performance and create more comfortable environments within the mosque buildings.

These suggested improvements were carefully combined into three distinct combinations, each of which represented the most effective enhancements tailored to the specific needs of individual mosques targeting three key parameters: Resultant Temperature (RT), Cooling Load (CL), and Predicted Mean Vote (PMV).

The first combination was designed to enhance the Resultant Temperature (RT) parameter, leading to a 24% improvement compared to the baseline model. For the second combination, the most effective improvements were combined to address the Cooling Load (CL) parameter, yielding a 58% reduction in cooling load compared to the baseline model. Lastly, the third combination focused on optimising the Predicted Mean Vote (PMV) parameter, resulting in a reduction of up to 15% in annual discomfort hours. These suggested improvements have the potential to offer significant benefits for clients, architects, builders, and stakeholders in the region to provide a pathway to achieve both energy efficiency and thermal comfort in building designs.

بِسْمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيمِ

الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ

(1)

In the name of Allah, the Compassionate, the Merciful.

Praise be to Allah, Lord of the Worlds.

DEDICATION

To my dear mother, Alya, and father, Ahmed, you have nurtured and cared for me throughout my life, I owe a debt of gratitude that I will never be able to pay. Credit for my accomplishments, after Allah, belongs to you.

To my beloved wife, Kawthar, your constant support and belief have been the foundation of my PhD journey. I will be forever grateful.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	**Meaning**
AC	Air Conditioning
AMV	Actual Mean Vote
CS	Computer Simulation
DX System	Direct Expansion System
EDSL Tas	Thermal Analysis Software
EPW	EnergyPlus Weather File
FM	Field Measurement
IES VE	Integrated Environmental Solutions
N/A	Not Applicable
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
S	Summer
TMY	Typical Metrological Years
W	Winter
WS	Weather Station

LIST OF NOMENCLATURE

Nomenclature	**Meaning**	**Unit**
CL	Cooling Load	(Watts)
DBT	Dry Bulb Temperature	(°C)
MRT	Mean Radiant Temperature	(°C)
RH	Relative Humidity	(%)
RHi	Internal Relative Humidity	(%)
RHo	External Relative Humidity	(%)
RT	Resultant Temperature	(°C)
T	Temperature	(°C)
Ta	Air Temperature	(°C)
Tg	Globe Temperature	(°C)
Ti	Internal Dry Bulb Temperature	(°C)
OT	External Dry Bulb Temperature	(°C)
ST	Surface Temperature	(°C)
Tsi	Internal Surface Temperature	(°C)
Tso	External Surface Temperature	(°C)
V	Velocity	(m/s)
WBGT	Wet Bulb Globe Temperature	(°C)

LIST OF PUBLICATIONS

1. Al Rasbi, H. and Gadi, M. (2021) ‘Energy Modelling of Traditional and Contemporary Mosque Buildings in Oman’, Buildings, 11(7), p. 314. doi: 10.3390/buildings11070314.

2. Al Rasbi, H. and Gadi, M. (2021) ‘Energy Modelling of Traditional and Contemporary Mosque Buildings in Oman’ In: The Second International Conference on Comfort At The Extremes, CATE'21. College of Engineering, Sultan Qaboos University, Sultanate of Oman.

Chapter 1. INTRODUCTION

1.1 Background

The worldwide concern for sustainability and the efficient use of energy is escalating in response to the rise in pollution and energy consumption. The modern way of life is inconceivable without the use of electricity and air conditioning. Notably, air conditioning represents the primary consumption of energy within buildings in regions with warmer climates and this demand is on an upward trajectory annually (Chua *et al.*, 2013).

Although there seem to be an abundance of studies on the subject, there is still a gap in research on thermal building performance in hot and arid climates, and how to reduce cooling loads in such climates (Al-ajmi and Loveday, 2010). Oman features extremely hot climate with dry bulb temperatures recorded above the 50 °C mark. Relative humidity levels can reach the peak in 100% in coastal areas, while plummeting to below 10% in interior desert areas (NCSI Oman, 2018). According to The Authority of Electricity Regulation in Oman, the building sector consumes approximately 75% of total energy consumption in the country. (Krarti and Dubey, 2017; The Authority for Electricity Regulation, 2019).

The purpose of this research is to examine the thermal performance in buildings in Oman taking traditional and contemporary mosques as case studies. Mosque architecture is simple, but also unique which makes for an intriguing research. Mosque architecture is simple due to its shape and layout, which are typical of mosques in general, but it is unique due to its daily intermittent usage. The Sultanate of Oman has both newly constructed mosques and traditional 600-year-old mosques. There are an estimated 16,000 mosques in Oman (Times News Service, 2018). Contemporary mosques use on active cooling systems, while some traditional mosques still use passive cooling systems. The materials used are also different between contemporary and traditional mosques. However, the general layout and architecture of traditional and contemporary mosques has remained largely the same (Taylor *et al.*, 2009). Improving mosque energy efficiency could help to reduce energy use, which is desperately required. It may also help to improve the energy efficiency of other buildings because any approaches used in the traditional simple design of mosques can potentially be replicated in other buildings.

In 2017, Oman has put forward the 2040 vision. It outlined the 12 top priorities of the country to be achieved by 2040 which are called the “National Priorities”. Two of the National Priorities are the “Developments of Governorates and Sustainable Cities” and “Environment and Natural Resources”(*Oman Vision 2040*, 2020). This study intends to contribute to both of these National Priorities. Making a mosque more energy-efficient would be a significant step towards making cities and the environment more sustainable. This research is critical because, as of 2023, most buildings in Oman still receive subsidised power. However, beginning in 2021, these incentives will be gradually phased off until 2025, as announced on December 20, 2020 (*Oman Observer*, 2020). This highlights the significance of sustainable design and energy efficiency research in Oman for all types of buildings.

Another part of this research is the effect of vernacular architecture on thermal comfort and performance in buildings. Several research were done to understand how thermal comfort is attained in Oman's traditional buildings. There are features that improved the thermal comfort of historic buildings that may be applicable to new constructions. Compact settlement patterns and courtyards are two examples of Oman vernacular architecture that could promote building thermal comfort (Taylor *et al.*, 2009). Since Oman's mass modernisation in the 1970s, it has relied on active air conditioning systems, making subsequent buildings less efficient. Buildings constructed prior to this period were designed to achieve thermal comfort through passive means. The building's design, orientation, and construction materials were used to achieve passive thermal comfort (Al-Hinai, Batty and Probert, 1993).

This study focuses on the thermal performance of mosque buildings in Oman. A building is a thermal system with inputs and outputs of thermal energy. Heat inputs and outputs are influenced by the environment, the building, and the occupants (Szokolay, 2008). Oman's environment is characterised by a hot and arid climate. Solar gain and conduction through the building envelope are two of the most important building thermal performance factors when focusing on hot-arid climates (Silva and Ghisi, 2020).

Taking into account the surrounding environment, cutting-edge energy-efficiency research indicates that there are numerous techniques that could be used to significantly reduce cooling load (Cao, Dai and Liu, 2016). For example, building envelope insulation, building material, fenestration, and thermostat set point are thought to be potential areas for improvement in buildings in hot arid regions (Azmi and Ibrahim, 2020).

Fenestration is often cited as a building's weakest link. Controlling the window-to-wall ratio (or glazing ratio) is critical for improving building efficiency. According to a study conducted in Saudi mosques, the optimal glazing ratio is around 15% overall (Al-Homoud, 2009). To limit thermal transmittance into the building, it is also recommended that the thermal conductivity of the building envelope be reduced. Increasing the thermostat set point results in significant savings in cooling loads. According to a study conducted on mosques in Kuwait, increasing the thermostat temperature by 1°C resulted in a 10% savings in electricity consumption (Al-ajmi and Loveday, 2010). Another study on government buildings in Oman found that increasing the set point by 3°C resulted in annual energy savings of at least 13.23% (Al-Saadi *et al.*, 2017). This research should result in similar significant cooling load reductions, as well as improvements to the thermal comfort and performance of buildings in Oman.

1.2 Research Gap

Although there are numerous studies on sustainability and energy efficiency, there is a lack of research on reducing cooling loads in Oman's building sector, which accounts for approximately 75% of the country's total energy consumption (The Authority for Electricity Regulation, 2019). This research seeks to examine the thermal performance of modern as well as traditional mosques in Oman as case studies for improving the energy efficiency of mosque buildings, which could contribute to more sustainable cities and environments. The research will also investigate the effect of vernacular architecture on thermal comfort and performance, focusing on how old buildings achieved thermal comfort through techniques and whether these techniques can be replicated in modern buildings. The research will consider Oman's hot and arid climate, which poses significant challenges to the thermal performance of buildings due to factors such as solar gain and conduction through the building envelope. The research will assess the effectiveness of techniques to reduce cooling loads in mosque buildings, including fenestration, building envelope insulation, building material, and thermostat set point. The research holds significant value as it aligns with Oman's 2040 Vision National Priorities of “Developments of Governorates and Sustainable Cities”, and “Environment and Natural Resources” (*Oman Vision 2040*, 2020)

1.3 Research Aim

This research aims to investigate the thermal performance in buildings in Oman with a special focus on mosques as a case study. Oman’s unique climate conditions along with the mosques’ architectural features are taken into consideration. This research also aims to arrive to recommendations for improving the thermal performance of traditional and contemporary mosques in Oman.

1.4 Research Objectives

1. **To understand the different climate conditions of the Sultanate of Oman and its impact on mosques’ thermal performance.**

Understanding the climate conditions is necessary for identifying the specific factors that influence the thermal performance of mosque buildings and developing effective methods to improve energy efficiency and sustainability. Oman’s extreme climate is one of the most relevant factors.

2. **To understand building thermal performance in the Sultanate of Oman and its relation to vernacular architecture.**

Vernacular architecture is a significant component of Oman's cultural heritage and has the potential to significantly contribute to the development of sustainable building practises. Understanding the relationship between thermal building performance and vernacular architecture is essential for identifying strategies to improve the thermal performance of traditional and contemporary mosques.

3. **To assess the current indoor thermal comfort in mosque buildings in the Sultanate of Oman.**

It is essential to assess the indoor thermal comfort of mosques to identify the specific areas that require improvement. This assessment can assist in identifying factors that influence thermal comfort, such as dry bulb temperature, relative humidity, and air velocity.

4. **To compare traditional and contemporary mosque buildings’ thermal performance.**

Comparing the thermal performance of traditional and modern mosque buildings is essential for identifying the strengths and weaknesses of various building types and identifying strategies for enhancing energy efficiency and sustainability. This comparison can help identify traditional building techniques that can be applied to contemporary buildings to enhance their thermal performance.

5. **To recommend solutions to improve the thermal performance of mosque buildings in the Sultanate of Oman.**

   The main objective of this research is to recommend solutions for improving the thermal performance of buildings and mosques in Oman. This is essential for promoting energy efficiency and sustainability in the building sector, a major contributor to energy consumption and greenhouse gas emissions. The recommendations should also be applied to other building types in hot and arid climates, contributing to a more sustainable built environment.

1.5 Scope and Limitations

The scope of this research was limited to the thermal performance of mosque buildings in hot and arid climates, specifically in Oman. The research investigated the impact of vernacular architecture on thermal comfort and performance, as well as potential areas for reducing cooling loads, with a focus on traditional and contemporary mosque buildings. Other building types or architectural styles were excluded from this research.

Because of the research's complexity and time constraints, it was not possible to cover all aspects of mosque buildings' thermal comfort and thermal performance using field measurement and computer simulation methodologies. Field measurements were restricted to a set of parameters including dry bulb temperature, relative humidity, surface temperature, globe temperature, and air velocity. The analysed outcomes of the computer simulations were also limited to dry bulb temperature, relative humidity, heat gains, heat losses, and load breakdown.

Field measurements were carried out in six mosques in three locations in Oman, which are Muscat, Nizwa, and Al Wafi. Consequently, the applicability of the findings may be limited to these buildings and locations. Dhofar, a governate in the south of Oman, is not included in this research because its monsoon season makes it climatically distinct from the studied cities.

The outbreak of the COVID-19 pandemic, which began on 20 March 2020 had a significant impact on this research. The global health crisis imposed a set of constraints that altered both the methodology and data collection process. Due to strict health and safety regulations, access to mosques for on-site data collection was limited. Several quarantine periods, movement bans, social distancing, and lockdowns hindered the research timeline, delaying travel to various sites for data collection.

1.6 Thesis structure

This section presents an overview of the thesis chapters followed by the Thesis Structure Flowchart (Figure 1.1).

Chapter 1. Introduction

An introduction chapter outlines the aims and objectives. It also defines the scope and limitations of the research.

Chapter 2. Mosque Architecture

Chapters 2, 3, and 4 are the literature review chapters.

Chapter 2 reviews the literature of mosques’ architecture, design, construction, and environmental characteristics. It describes the difference between vernacular and contemporary mosques in Oman. This was chosen as the first chapter after the introduction as it describes the purpose and unique nature of the buildings studied. It attempts to answer the question: why and how the case studies have been built?

Chapter 3. Thermal Comfort, and Building Thermal Performance

This chapter explores the concepts of thermal comfort and thermal performance in buildings. It attempts to provide background knowledge to the question: what are the internal environment and conditions of the case studies?

Chapter 4. Oman’s Context

This chapter explores Oman’s context in light of what was discussed in the previous two chapters. It attempts to provide background knowledge to the question: what are the external environment and conditions of the case studies?

Chapter 5. Methodology

The methodology chapter explains how the research problems are solved. It describes the research methodologies utilised, the tools, the instruments, and the software.

Chapter 6. Field Measurement Results

The field measurement results are presented and discussed in Chapter 6, which is the first of the two result’ chapters. The main parameters discussed are Dry Bulb

Temperature (DBT), Relative Humidity (RH), Mean Tadiant Temperature (MRT), air velocity, Surface Temperature (ST), and thermal loads. The discussions are focused on winter and summer design days. The field measurement results for each case study are discussed and then comparisons between all the case studies are conducted.

Chapter 7. Computer Simulation Results

The computer simulation results chapter is the second of the two results' chapters. The computer simulations results are shown in comparison with the field measurement results for each case study for a separate discussion of each case study. The simulations offer a detailed view into various aspects including Dry Bulb Temperature (DBT), Mean Radiant Temperature (MRT), as well as a comprehensive analysis of heat gain, heat loss, and the breakdown of different loads.

Chapter 8. Suggested Improvements

Suggested improvements chapter applies the lessons acquired from the literature review and results chapters to improve the six mosques' thermal performance. The suggested improvements are presented in five categories: Walls, Roofs, Windows, , Internal Conditions, and Passive Cooling Techniques. There are fourteen different suggested improvement. Each suggested improvement is assessed from three perspectives: thermal performance, thermal comfort, and energy efficiency.

Chapter 9. Conclusions

This chapter presents the key findings and outcomes of the research, which sought to identify strategies for enhancing the thermal performance of buildings in Oman, focusing on both traditional and contemporary mosques as case studies. This chapter can be viewed as a reflection on the research questions and objectives, highlighting research limitations, recommendations, and potential future research.

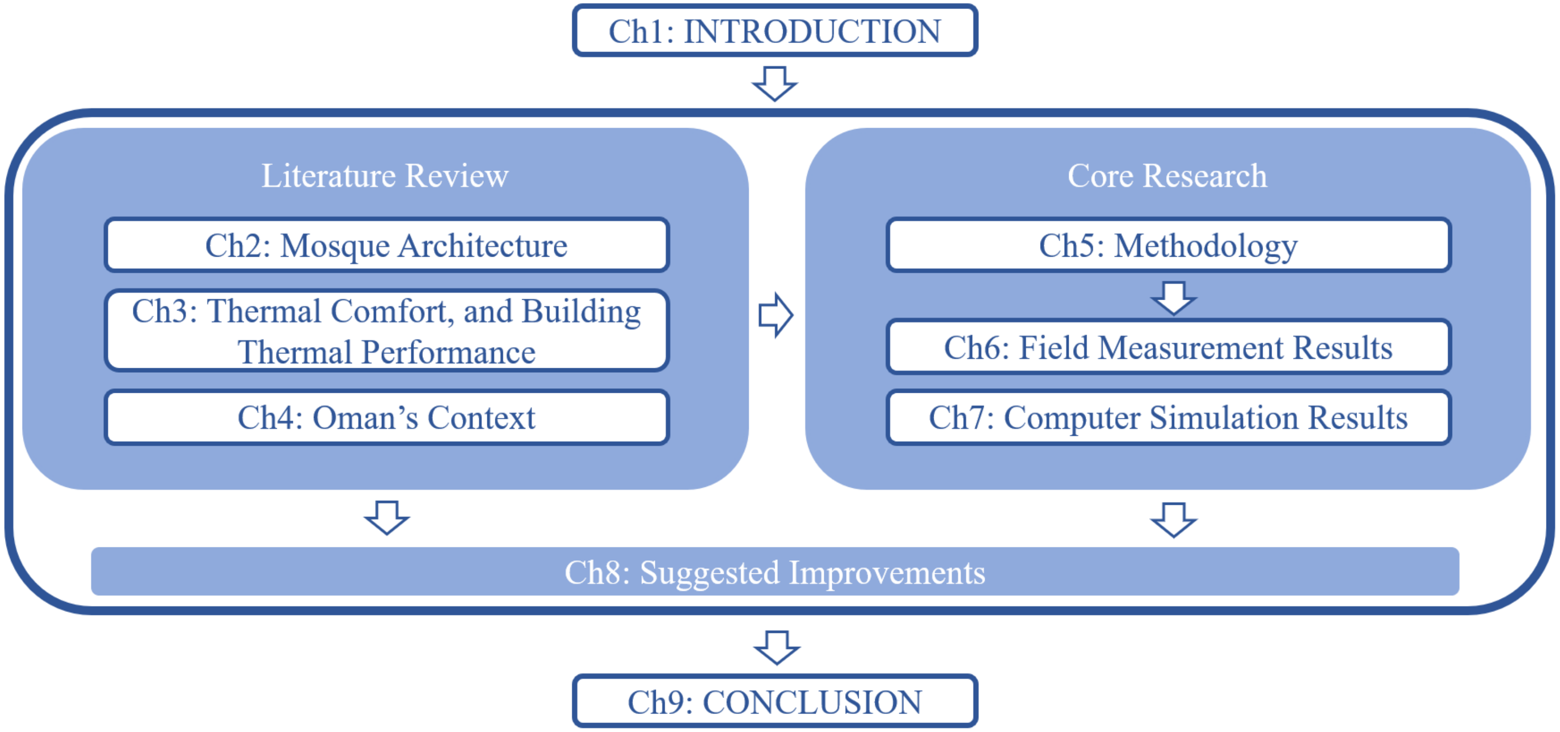


Figure 1.1: Thesis Structure Flowchart

Chapter 2. MOSQUE ARCHITECTURE

2.1 Introduction

This chapter explores the various aspects of mosque architecture. This was decided as the first literature review chapter, because it begs the question: “why build the building in the first place? What is its purpose?”. This foundational question guides to a deeper understanding of mosques, establishing a framework to realise the mosque’s thermal comfort objectives with the least energy resources possible. The chapter defines the word “Mosque” from theological and linguistic views to better understand why mosques are built. Architectural design of mosques and Islamic architecture are also explained. The construction techniques, and environmental characteristics were dissected taking case studies to showcase the different layouts of mosques.

By anchoring the discussion in the latest literature, it is aimed to encourage a rich understanding of the thermal comfort and energy demands of both traditional and contemporary mosque buildings, drawing from a range of studies that highlight the need for research in this area.

2.2 Mosque

Mosques are called “Masjid” in Arabic. The word “Masjid” comes from the word “Sujud” which is the act of prostration. Hence, a mosque or a masjid means a place for the ritual of prostration. This research focuses on the energy efficiency aspect of mosque architecture, prompting the essential question: what are the foundational reasons for constructing mosques? To address this, we turn to the Quran, which explains the motivations and purposes behind mosque building in the subsequent verses:

> اللَّهُ نُورُ السَّمَاوَاتِ وَالْأَرْضِ ۚ مَثَلُ نُورِهِ كَمِشْكَاةٍ فِيهَا مِصْبَاحٌ ۖ الْمِصْبَاحُ فِي زُجَاجَةٍ ۖ الزُّجَاجَةُ كَأَنَّهَا كَوْكَبٌ دُرِّيٌّ يُوقَدُ مِنْ شَجَرَةٍ مُبَارَكَةٍ زَيْتُونَةٍ لَا شَرْقِيَّةٍ وَلَا غَرْبِيَّةٍ يَكَادُ زَيْتُهَا يُضِيءُ وَلَوْ لَمْ تَمْسَسْهُ نَارٌ ۚ نُورٌ عَلَىٰ نُورٍ ۗ يَهْدِي اللَّهُ لِنُورِهِ مَنْ يَشَاءُ ۚ وَيَضْرِبُ اللَّهُ الْأَمْثَالَ لِلنَّاسِ ۗ وَاللَّهُ بِكُلِّ شَيْءٍ عَلِيم
>
> (Qur’an 24:35) (النور: 35)
>
> Allah is the Light of the heavens and the earth. The example of His light is like a niche within which is a lamp, the lamp is within glass, the glass as if it were a pearly [white] star lit from [the oil of] a blessed olive tree, neither of the east nor of the west, whose oil would almost glow even if untouched by fire. Light upon light. Allah guides to His light whom He wills. And Allah presents examples for the people, and Allah is Knowing of all things (Saheeh International, 2011)

In the first verse (Qur'an 24:35), we are presented with the *Ayat Al-Nur* (The Verse of Light) where Allah is described as the "Light of the heavens and the earth." The Divine Light represented in this verse is perceived as the guidance and the knowledge that Allah provides to the believers. This verse employs a rich imagery to describe the nature of divine guidance, portraying it as a pure, brilliant, and nurturing light that illuminates the darkness and guides individuals to the path of righteousness and wisdom (Nasr, 2015).

> فِي بُيُوتٍ أَذِنَ اللَّهُ أَنْ تُرْفَعَ وَيُذْكَرَ فِيهَا اسْمُهُ يُسَبِّحُ لَهُ فِيهَا بِالْغُدُوِّ وَالْآصَالِ
>
> (Qur’an 24:36)   (النور: 36)
>
> In houses (mosques), which Allah has ordered to be raised (to be cleaned, and to be honoured), in them His Name is glorified in the mornings and in the afternoons or the evenings, (Saheeh International, 2011).

> رِجَالٌ لَا تُلْهِيهِمْ تِجَارَةٌ وَلَا بَيْعٌ عَنْ ذِكْرِ اللَّهِ وَإِقَامِ الصَّلَاةِ وَإِيتَاءِ الزَّكَاةِ ۙ يَخَافُونَ يَوْمًا تَتَقَلَّبُ فِيهِ الْقُلُوبُ وَالْأَبْصَارُ
>
> (Qur’an 24:37) (النور: 37)
>
> Men whom neither trade nor sale diverts them from the Remembrance of Allah (with heart and tongue), nor from performing As-Salat (Iqamat-as-Salat), nor from giving the Zakat. They fear a Day when hearts and eyes will be overturned (from the horror of the torment of the Day of Resurrection) (Saheeh International, 2011).

> لِيَجْزِيَهُمُ اللَّهُ أَحْسَنَ مَا عَمِلُوا وَيَزِيدَهُمْ مِنْ فَضْلِهِ ۗ وَاللَّهُ يَرْزُقُ مَنْ يَشَاءُ بِغَيْرِ حِسَابٍ
>
> (Qur’an 24:38)(النور: 38)
>
> That Allah may reward them according to the best of their deeds, and add even more for them out of His Grace. And Allah provides without measure to whom He wills (Saheeh International, 2011).

In the verses (Qur'an 24:36-38), the sacredness and the high status of the houses of Allah (mosques) where His name is glorified are emphasised. It portrays mosques as houses of purity, spirituality, and divine remembrance, where individuals gather to remember Allah and seek His blessings through congregational prayers in the mornings and evenings. This verse, therefore, highlights the central role of mosques in promoting a spiritually enriched community based in the remembrance of Allah (Qurṭubī and Bewley, 2003).

> إِنَّ أَوَّلَ بَيْتٍ وُضِعَ لِلنَّاسِ لَلَّذِي بِبَكَّةَ مُبَارَكًا وَهُدًى لِلْعَالَمِينَ (آل عمران:96)
>
> (Qur’an 2:96)
>
> Indeed, the first House [of worship] established for mankind was that at Makkah - blessed and a guidance for the worlds (Saheeh International, 2011).

In the verse (Qur'an 2:96), it is referred to the Kaaba located in the city of Makkah, Saudi Arabia. According to Islamic tradition, the Kaaba was the first house of worship established for humanity, and its foundations were laid by Prophet Adam and later rebuilt by Prophet Ibrahim and his son Ismail (Ibn Kathir, 2000) Other narratives mention that the Kabba was the first ever building built on earth, which was built by the angels even before Adam was created (Abū Zahrah, 2001).

Mosques are centres for the community where daily prayers are performed. They also serve other purposes such as: a school, an institute, and an education centre. It can also be used as shelter and an emergency meeting point. It is also a place where weddings and funerals are held. Muslims observe and hold events in mosques throughout the year. Attendance tend to peak during Ramadan, Eid, and weekly Friday prayers. Mosques are places for worship, reading Quran, doing Dhikr, and devoting oneself to Allah. It is hence important to be thermal comfortable in such a place (Abdullah, Majid and Othman, 2016).

2.3 Architectural design of mosques

2.3.1 Islamic architecture

Architecture is the art of construction and building as per set rules. Islamic architecture started in the period of Prophet Mohamed (PUBH), and it refers to the architecture of any building whether it is a residential building or religious building or facility. The focus on function over form is one of Islamic architecture core features. Islamic architecture also focuses on delivering some environmental features. Islamic architecture has a reservation from sculptures and statues. However, it does utilise decoration using Islamic art and decoration. Islamic architecture also derives inspiration from the Holy Kaabah (Al Khouli, 2015).

Basic mosque plan was a prayer area against a qibla wall and a courtyard. Then it developed to have shade on the three sides of the courtyard to make it a roofed arcade. The prayer area was roofed by either palm trunks or re-used columns. Other options to support roofing are columns, piers, or domes. Later on other features of the mosques appeared and became standard such as the minbar, mihrab, ablution facilities, central pool or fountain, minaret (Petersen, 1996).

Islamic architecture is unique in nature that it supports sustainability at its very core. Mosques are by nature very simple in design and achieve its intended purpose in an efficient matter. This is done by constructing efficient buildings by "borrowing" from nature's materials such as water, clay, stone and timber to be used in construction. That construction would become complementary with nature and not cause any harm (Al-Qemaqchi, 2018)

Maximising the use of natural materials and nature in buildings can be done in many ways such as building with clay or brick, natural ventilation, natural lighting, and building underground. These are just examples of Islamic architecture features (Sirryeh, 2021)

This reflects the Islamic teachings as it described in many Quranic verses such as verses 6:141 and 7:31 about the prohibition of extravagance and waste.

> وَهُوَ الَّذِي أَنْشَأَ جَنَّاتٍ مَعْرُوشَاتٍ وَغَيْرَ مَعْرُوشَاتٍ وَالنَّخْلَ وَالزَّرْعَ مُخْتَلِفًا أُكُلُهُ وَالزَّيْتُونَ وَالرُّمَّانَ مُتَشَابِهًا وَغَيْرَ مُتَشَابِهٍ ۚ كُلُوا مِنْ ثَمَرِهِ إِذَا أَثْمَرَ وَآتُوا حَقَّهُ يَوْمَ حَصَادِهِ ۖ وَلَا تُسْرِفُوا ۚ إِنَّهُ لَا يُحِبُّ الْمُسْرِفِينَ (الأنعام:141)
>
> (Qur'an 6:141)
>
> And He it is who causes gardens to grow, [both] trellised and untrellised, and palm trees and crops of different [kinds of] food and olives and pomegranates, similar and dissimilar. Eat of [each of] its fruit when it yields and give its due [zakah] on the day of its harvest. And be not excessive. Indeed, He does not like those who commit excess (Saheeh International, 2011).
>
> يَا بَنِي آدَمَ خُذُوا زِينَتَكُمْ عِنْدَ كُلِّ مَسْجِدٍ وَكُلُوا وَاشْرَبُوا وَلَا تُسْرِفُوا ۚ إِنَّهُ لَا يُحِبُّ الْمُسْرِفِينَ (الأعراف:31)
>
> (Qur'an 7:31)

> O children of Adam, take your adornment at every masjid, and eat and drink, but be not excessive. Indeed, He likes not those who commit excess (Saheeh International, 2011).

In verses (Qur’an 6:141) and (Qur’an 7:31), believers are instructed to practice moderation and avoid excess and waste (Qurṭubī and Bewley, 2003).

2.3.2 Standard architectural features of mosques

A mosque has a number of standard features, but not all of which are necessarily found in all mosques (Abdou, 2003; Ching, Jarzombek and Prakash, 2017):

- Courtyard: It can be entered to the prayer hall through the courtyard. It can contain a fountain or a well for ablution.
- Mihrab: a niche in the middle of the Qiblah wall to indicate the direction of the Qiblah.
- Prayer hall: a large hall which can be one space or often split into two spaces. If it is split, usually the larger space would be the latter one that has the mihrab.
- Minbar: is a raised platform for the imam to deliver a sermon, Khutba, which happens every Friday.
- Minaret: a tall tower attached to the mosque from which it is called for the prayer before each prayer. Each mosque differs in terms of the location and quantity of minarets.
- Mosques’ Qubba (dome): a dome on top of the mosque, which is one of the most prominent features of a mosque.
- Mosques that have women’s prayer hall, it would be separated than the Men’s prayer hall.

Mosques are designed as a communal worship space for Muslims. The orientation of the mosque is always towards the Kaabah in Makkah. The direction from the mosque (or the place of prayer) to the Kaaba is called Qiblah (Kahera, 2009).

The typology, class identity, and interpretations of mosque buildings do differ over the decades There are generally two types of mosques: large mosques which are also called “Jami” are used for Friday communal prayers in addition to the daily prayers, and smaller local mosques which are used for the daily prayers (Kahera, Abdulmalik and Anz, 2009).

Mosques can also be classified as historical or modern. Historical mosques are built before the introduction of reinforced concrete. Modern mosques, which are built after the 19th century, tend to adapt the change in economic, social, and technical status. Reinforced concrete is one change. It made prayer halls beams span wider with a less requirement of columns. Another change is the introduction of air-conditioning. Prayer halls are most used within mosques, which means they require more focus when conducting technical research about mosques (Elkhateeb *et al.*, 2018).

Typical layout of mosques in the Arabian gulf region features the mihrab in the middle of the Qiblah wall. The minbar would be at the right side of the mihrab. This is in the main prayer hall, which is roofed. Mosques would also feature roofed arcade (Riwaq) before the main prayer hall, and a courtyard (Sahn) before the Riwaq. Mosques usually have three entrances from all three sides of the courtyard (Al-Kholaifi, 2006). Figure 2.1 is an example of a typical prayer hall.

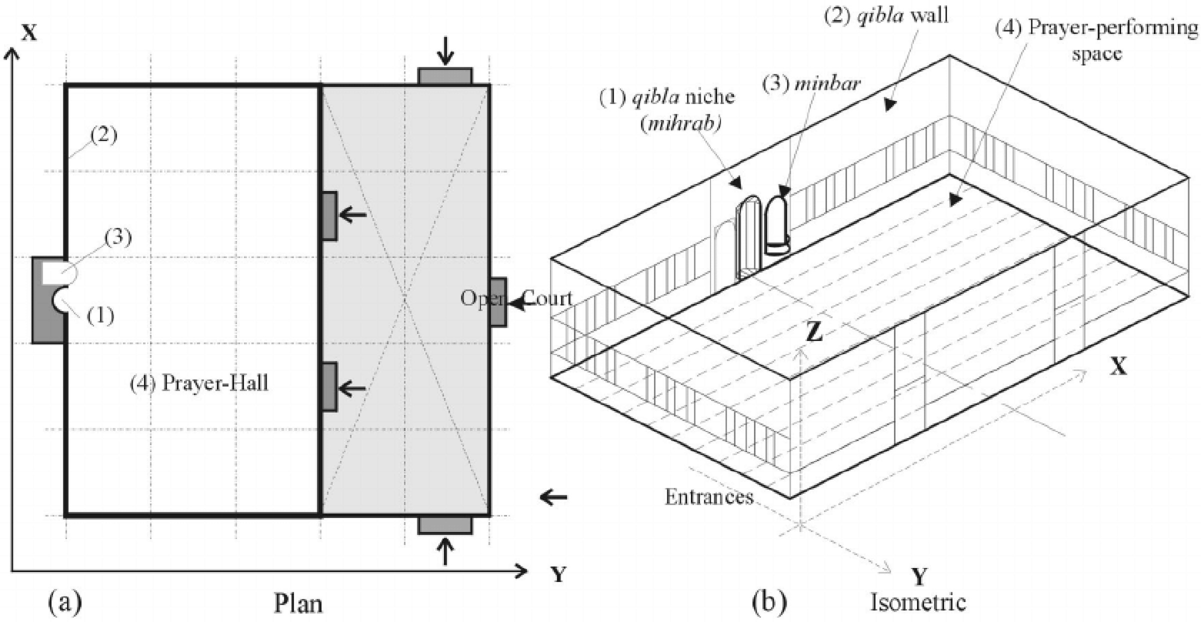


Figure 2.1: Simple mosque layout as followed by most modern mosques (*Mosque - Oxford Islamic Studies Online*, 2020)

2.4 Prayer times

There are five prayers performed every day in mosques. All prayer times are determined according to the sun's position. The first prayer is Fajr prayer and performed at the beginning of daybreak. The second prayer is Dhuhr (noon) prayer conducted soon after the solar noon. The third prayer is Asr (afternoon) prayer is given when shadows are double the size of their objects. The fourth prayer is Maghrib (sunset) prayer which is at sunset. The fifth prayer is Isha begins at nightfall. The prayer times differ each day and each location. Refer to Table 5.10 for the range of prayer times for the case studies of this research (Qurṭubī and Bewley, 2003). A relevant note here is that the Muslim day begins by *Maghrib* (sunset) and ends just before Maghrib the next day, so the Maghrib prayer is considered technically the first prayer of the day as per the Hijri (Islamic) calendar (*Lines of Faith - Prayer Times*, 2022).

2.5 Examples of mosque buildings

The Prophet Mohamed (Peace be upon him) classed the three mosques as the three holy mosques and have a special status. Al-Masjid Al-Haram (which means The Sacred Mosque) is where the Kaaba is located. Al Aqsa Mosque is the first Qiblah for Muslims. Al-Masjid al-Nabawi means the Prophet's Mosque. This research focuses on the smaller mosques, so it would be interesting to see how the first version of Al-Masjid Al-Nabawi was built. It was built by Prophet Muhammad (peace be upon him) in Medina in 622 AD. Its size was about 35 by 30 metres (Triayudha *et al.*, 2019). The mosque design and construction were simple. Mudbrick was used for the walls, palm tree trunks for the columns, and palm tree branches for the roof. The roof was partially open (Tahir, 1987). Prayers are performed in parallel rows behind the imam. According to the Islamic law, the front rows are favour over the back rows (Kahera, Abdulmalik and Anz, 2009). That is why the qiblah wall is usually longer than the side walls (Elkhateeb *et al.*, 2018).

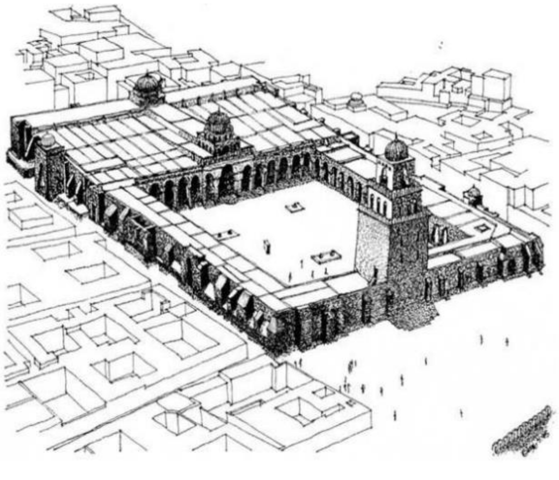


Figure 2.2: Drawing of the Mosque of Uqbah at Kairouan, Tunisia (Kahera, 2009)

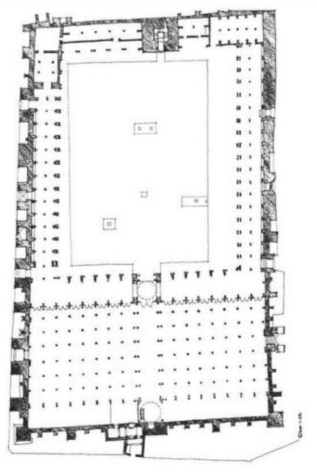


Figure 2.3: Floor plan of the Mosque of Uqbah at Kairouan, Tunisia (Kahera, 2009)

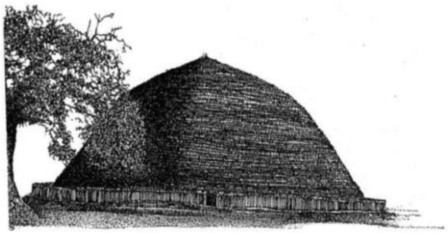


Figure 2.4: Drawing of the mosque at Dingueraye, Guinea, West Africa (Kahera, 2009)

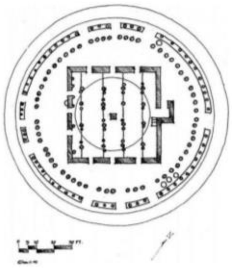


Figure 2.5: Floor plan of the mosque at Dingueraye, Guinea, West Africa (Kahera, 2009)

Another example of a mosque would be the Grand Mosque of Kairouan, also known as the Mosque of Uqba. The town of Kairouan was founded in 670 AD. After which, the Great Mosque of Uqba was built (Binous, Baklouti and Zouari, 2014). The mosque of Uqba is shown in Figure 2.2 and 2.3. Most mosques in the modern era follow the same design layout as Mosque of Uqba in Kairouan in terms of featuring a main prayer hall with a mihrab and a Qubba. Some mosques feature a roofed arcade (Riwaq), and a courtyard (Sahan) (Kahera, Abdulmalik and Anz, 2009). Another example is the mosque of Dinguerave Guinea, which appears as a non-typical mosque shape, which is shown in Figures Figure 2.4 and 2.5. It has a square shaped interior wall that are fully covered by a spherical roof. This mosque is a great example of how local materials are utilised to build a mosque. This is an example of integration between the basic layout of mosques and the local construction knowledge and expertise.

In a study conducted by Elkhateeb *et al.* (2018), mosques were classified according to their shape and layout. Refer to Figure 2.6 for examples of the mosque’s layouts included in the survey, and to Figure 2.7 for the classification. It was concluded that most mosques out of the surveyed mosques have a basic closed symmetric traditional layout.

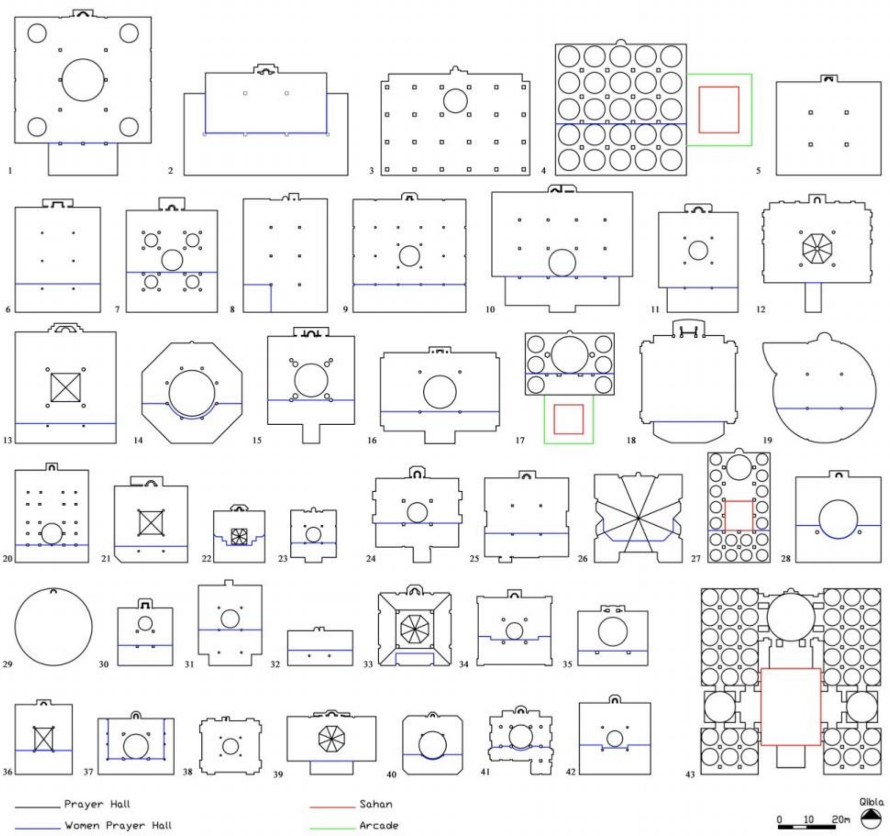


Figure 2.6: Plans of surveyed sample of mosques by (Elkhateeb et al., 2018)

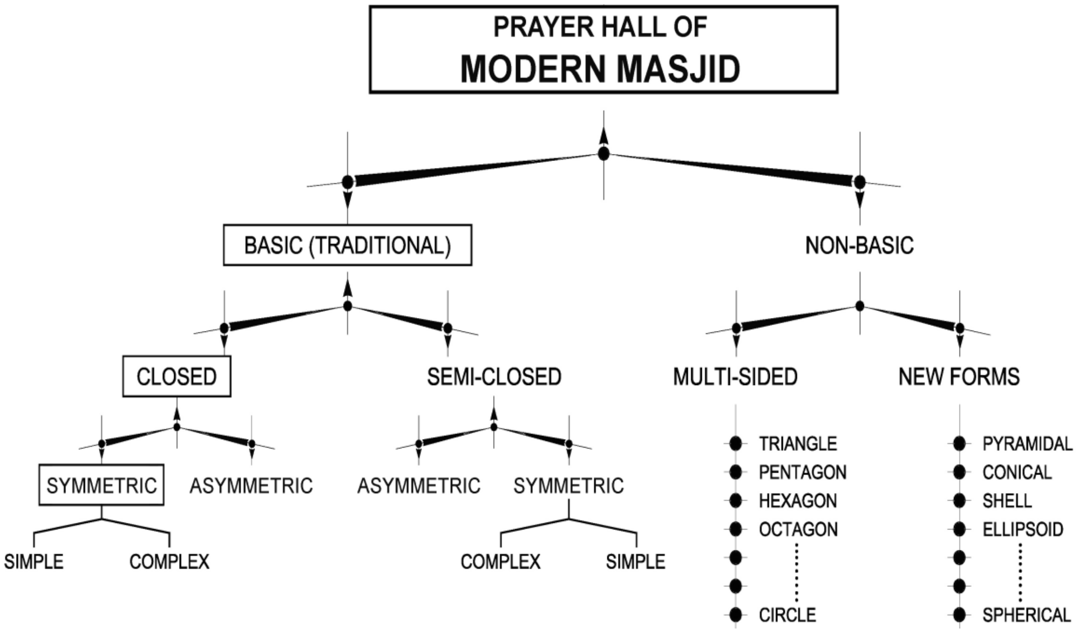


Figure 2.7: Classification of prayer halls design layout in modern mosques (Elkhateeb et al., 2018).

2.6 Mosque’s construction

2.6.1 Vernacular mosque construction

The two main building elements of vernacular buildings construction in the Arabian Gulf were walls and roofs. One the main historical building materials for walls is limestone. It was used frequently in most types of buildings. The limestone is brought from mountains and laid to form a wall. Walls are covered with mud plaster and/or gypsum. Mud was also used to plaster and protect the walls, but it can be less effective with rain. Gypsum had widely replaced mud as a stronger plaster material that protects the walls from different weather conditions and makes the building more aesthetically pleasing. Another material used for walls is coral rock (Al-Kholaifi, 2006).

Roofs were mainly made from different types of wood. Roof is first laid with a Danshal tree trunk. And then it is laid with Murabaa wood stems diagonally in both ways such as Figure 2.8. Next, tree stems called bamboo are laid on top. And then mangroves are laid on top of the bamboo to close any gaps. Last step is to cover it with mud paste mixed with hay straws to increase its cohesiveness. Other types of timber can be used in the construction of roofs such as palm tree trunks, palm tree branches, basgel, and teak wood (Al-Kholaifi, 2006).

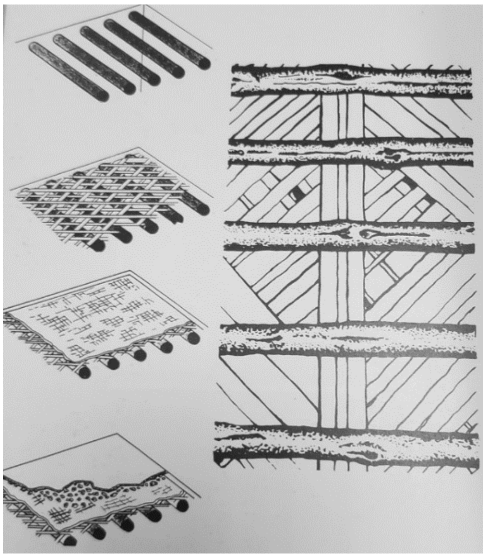


Figure 2.8: Illustration of vernacular roof construction process (Al-Kholaifi, 2006).

2.6.2 Contemporary mosque construction

The construction of contemporary mosques in the Arabian Gulf region is usually built using steel and concrete. Refer to section 5.11.1 for an example of construction elements of a modern mosque building.

2.7 Mosque’s environmental characteristics

Mosques have had many techniques to achieve thermal comfort ever since they were first built. One of their oldest features is the courtyard. Courtyards in mosques usually are fully tiled, features vegetation and trees for shading, and water features. All of this could help with the thermal comfort of the worshipers (Yousef and Yousef, 2001). Another example is domed roof which is proved to have cooler temperatures when cooling winds increases their speed over the curved surface (Fathy, 1986).

Khalwah, which is an underground prayer room, is another way to regulate temperature in winter and summer seasons in hot regions. Examples of it can be found in old mosques in Saudi Arabia. Figure 2.9 shows cross section of Al Husaini Mosque in Shaqra in Saudi Arabia (Saudi Commission for Tourism & National Heritage, 2018).

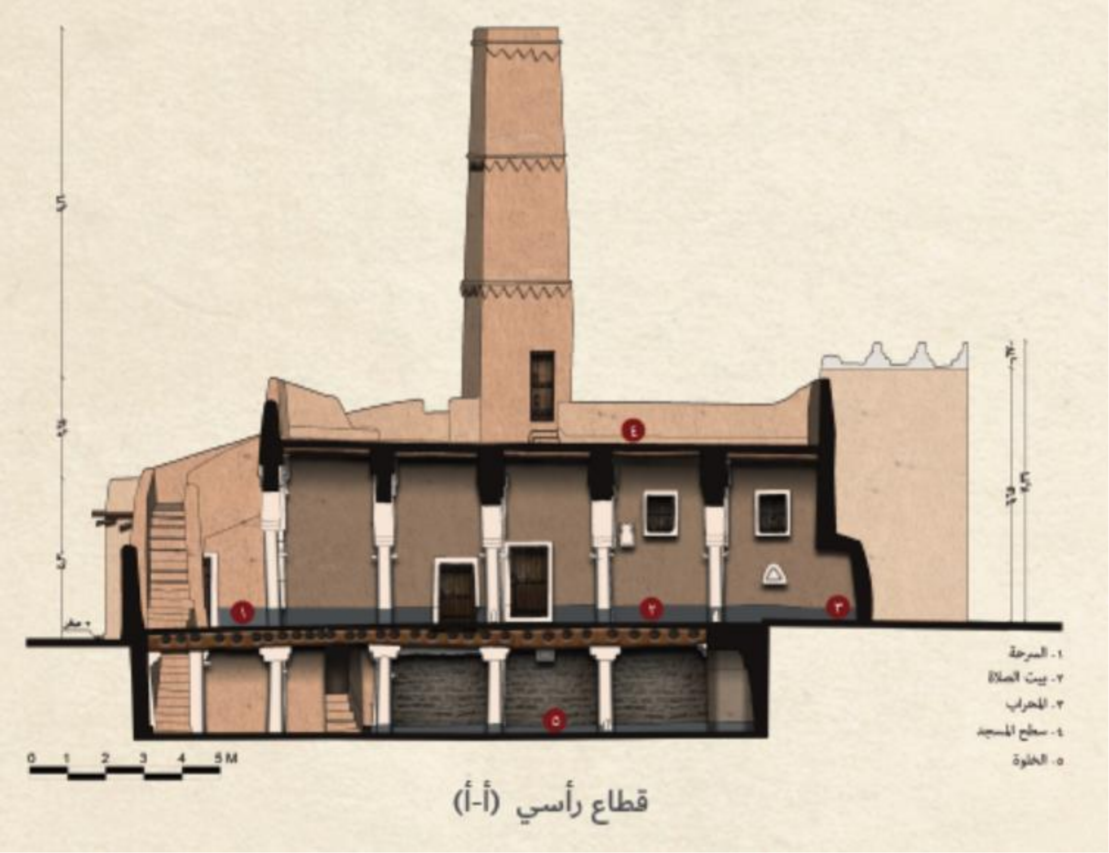


Figure 2.9: Cross section of Al Husaini Mosque in Shaqra in Saudi Arabia showing the Khalwah (underground prayer hall) (Saudi Commission for Tourism & National Heritage, 2018).

By the end of twentieth century, buildings shifted to active cooling system instead of passive cooling techniques. This made the Mosque buildings case unique because of the intermittent usage of the mosque throughout the day since there are five prayers a day performed in congregation. This makes mosque buildings an interesting case and a challenge to provide acceptable indoor environment for worshippers while ensuring low energy consumption (Alabdullatief and Omer, 2017). Mosques in Oman usually have DX split units which is also common in residential buildings and most other buildings. Some modern mosques built during the twenty-first century use DX roof packaged units, which is becoming more common in Oman (Krarti and Dubey, 2017).

2.8 Suggested Improvements and future research for mosques in hot climates

There were a number of recent studies on mosques buildings in hot climates that offered valuable insights for enhancing thermal comfort and thermal performance such as Shohan (2015) who compared computer simulations with field measurement, highlighting issues like solar radiation and inadequate materials, Alabdullatief (2020) focused on sustainable solutions like insulation and shading, and Al-ajmi (2010) examined indoor climate in Kuwait.

Shohan (2015) conducted research on mosque buildings energy performance in Abha city in Saudi Arabia. The research compared the computer simulation and field measurement results to determine the thermal comfort and thermal performance of the mosque buildings. The questionnaires revealed that some occupants experienced thermal discomfort because of the direct solar radiation from openings and internal gains. The findings reveal that excessive heat gains and losses were caused by the inadequate quality of mosque buildings’ building envelope materials. Indoor dry bulb temperatures were rarely within the acceptable thermal comfort limits especially during summer. The results also show that, especially during the winter, the indoor relative humidity was mostly above the upper limit of RH comfort (65%). Furthermore, significant differences were found between PMV in controlled mode and free-running mode in all mosque buildings studied. Both field measurement and computer simulations found that different climates, locations, and orientations of design mosque buildings result in different outcomes. The research concludes that passive cooling/heating and sustainable operation systems are essential based on environmental study results. Accordingly, different materials, designs, sustainable techniques, and systems should be explored further in the next studies. This is to determine if the proposed changes enhance sustainability and CO2 pollution in these buildings.

Alabdullatief, (2020) explored sustainable technologies for mosque buildings in hot climate regions. The research focused on passive techniques such as building insulation, shading, and green roofs. Several mosques from various regions, periods, and climates have been examined to determine the most pertinent sustainable features. The connection between the characteristics and climate zones was analysed. Sustainable technologies such as insulated roofs, green roofs, white chipped stone finishing, and the application of a movable shading layer on top of the roof can reduce the cooling burden for the selected hot, arid climate, according to the research. The most encouraging of these techniques is the use of a green insulated roof. The research concluded with recommendations that architects and designers should consider sustainable and passive techniques. Insulated roofs with green surfaces, movable shading layers, and green roofing are some of the techniques recommended for reducing the cooling load and providing improved indoor environments for building occupants while achieving sustainable building design. It is necessary to establish design correlations and guidelines for architects and mosque building designers to promote the development of sustainable mosque building designs.

Al-ajmi (2010) conducted a field study in six air-conditioned mosque buildings during the summers of 2007 to investigate indoor climate and prayer thermal comfort sensations in Kuwait. During the summer of 2007, 140 occupants of six air-conditioned mosque buildings in Kuwait's dry desert climate were surveyed. Environmental parameters and human thermal comfort responses were recorded during the survey, and the results were analysed using linear regression analysis. The research found that the mean indoor dry bulb air temperature was 23°C with a mean relative humidity of 44.19% and a mean air movement of 0.23 m/s. The neutral operative temperature for prayers was 26.1°C, and the AMV and PMV were within the range of -2.67 to +2.33 and -0.005 to +1.43, respectively. The widely accepted criterion for thermal acceptability was an operative temperature range of 22.3°C to 29.8°C. The findings are that adjustments to the indoor/outdoor design temperatures in the energy code of the Ministry of Electricity and Water in Kuwait could have a significant effect on national energy consumption. However, further research is needed before such a recommendation can be made. Further research is needed to confirm whether the PMV model underestimates the actual sensation in a dry desert climate due to possible adaptive effects. This knowledge can be used to help Kuwait develop future energy-related design codes.

2.9 Conclusion

Mosques are built as houses of worship where the five daily prayers and the Friday weekly prayers are performed. It is also considered a centre for the community, a school, an institute, and an education centre. Islamic architecture is unique in that its very essence promotes sustainability. Mosques are by nature very basic in design and serve their intended function effectively. This is accomplished by "borrowing" materials from nature, such as water, earth, stone, and wood, to construct energy-efficient buildings. This construction would become harmonious with nature and cause no damage (Al-Qemaqchi, 2018). Mosques have had many techniques to achieve thermal comfort ever since they were first built such as courtyards (Yousef and Yousef, 2001), domed roof (Fathy, 1986), and underground chambers “Khalwah”

(Saudi Commission for Tourism & National Heritage, 2018).

The Sultanate of Oman features a good number of both traditional and contemporary mosques. Contemporary mosques rely on active cooling systems, while traditional mosques still feature some passive cooling systems. The materials used in the construction of contemporary and traditional mosques are not the same. This research aims to implement the different principles and methodologies discussed into both traditional and contemporary mosque buildings in Oman.

Numerous recent studies concur that research is required in the areas of building thermal performance of mosques (Shohan, 2015; Alabdullatief, 2020), passive and sustainable cooling techniques (Azmi, Arıcı and Baharun, 2021), and the development of energy-related design codes (Al-ajmi, 2010).

Chapter 3. THERMAL COMFORT, AND BUILDING THERMAL PERFORMANCE

3.1 Introduction

In the field of building design and architecture, thermal comfort and building thermal performance are central topics that significantly influence the energy efficiency of buildings. This chapter offers a detailed exploration of these critical concepts, providing definitions, examining the various factors that determine them, and discussing the methods used to measure them through field measurement studies and computer simulations.

Initially, the definition of thermal comfort is explained, based on the relavant standards. This is followed by an examination of the elements that affect thermal comfort, including dry bulb temperature and relative humidity. The discussion then moves to the topic of thermal sensation, exploring the physiological and psychological aspects that influence how people perceive different thermal environments. In this section, predictive models like the PMV model are introduced, showing the scientific efforts made to understand thermal comfort in depth.

Following this, the chapter transitions to building thermal performance, discussing the fundamental principles of heat transfer in buildings, a critical aspect that dictates the thermal dynamics in constructed spaces. Here, vital performance factors such as thermal transmittance and capacity, solar heat gain, and the characteristics of glazing materials are detailed, offering insights into how they can enhance the thermal performance of buildings.

The methods used in the field monitoring and surveying of thermal comfort are described, highlighting the important considerations for physical measurements. This leads to a discussion on building energy modelling and computer simulation, which are the two main research methodologies employed in this study.

3.2 Thermal comfort definition

Thermal comfort can be defined as the condition of mind which expresses satisfaction with the thermal environment (ASHRAE, 2020).

Thermal comfort is subjective and can differ due to individual differences resulting in thermal dissatisfaction. Thermal discomfort or dissatisfaction should be minimised as part of the design criteria as much as possible. Other environmental comfort factors include visual, acoustic, and air quality factors, which are not covered by this chapter (Butcher, 2006).

3.3 Factors determining thermal comfort

According to ASHRAE Standard 55-2017, Thermal Environmental Conditions for Human Occupancy, the six factors to be considered for thermal comfort are the following: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity. The first two factors, Metabolic rate and clothing insulation, relate to the occupant, while the other four factors relate to the environment (ASHRAE, 2020).

Factors related to the thermal comfort are not limited to the above, there are other factors which are referred to by local thermal discomfort factors (ASHRAE, 2009):

- Radiant temperature asymmetry: caused by having different radiant temperatures in the body.
- Draft: air movement that causes unwanted cooling of the body.
- Vertical air temperature difference: A vertical difference in the temperature of the body. For example, a temperature of the head is different than the arm’s temperature.
- Floor surface temperature: A surface that is too hot or too cold will be uncomfortable to touch or walk on.
- Temperature variations with time: A fluctuating air temperature or mean radiant temperature.
- Cyclic variations: A fluctuating operative temperature within a short time frame (not greater than 15 minutes).
- Drifts: passive temperature change
- Ramps: active temperature change

It can be noticed that the local thermal discomfort factors mainly deal with temperature difference or sudden change in time. A sudden change of more than 5 °C can cause thermal discomfort (Du *et al.*, 2014).

3.3.1 Air temperature

Air temperature can be defined as the temperature of the air surrounding the human body (Parsons, 2002). Human’s body core temperature is normally about 37 °C, while skin temperature can vary between 31 °C and 34 °C. It produces heat at a different rate depending on the human's metabolic rate and activity (Szokolay, 2008). The human body tries to maintain its core temperature, otherwise any deviation can have a negative effect on the human its comfort and/or health condition (Parsons, 2002).

Dry-bulb temperature is one of the most crucial parameters in thermal comfort and thermal performance research as it directly correlates to human thermal comfort. Dry-bulb temperature is the air temperature inside a room measured by a dry-bulb thermometer. The dry-bulb thermometer needs to be protected from radiation and suspended in the middle of the space during measurement (McMullan and Seeley, 2007).

3.3.2 Mean Radiant Temperature (MRT)

There is a unique radiation point at any given point in a space. As a person moves around, energy is continuously exchanging between different bodies via different methods, one of which is radiation. In studies concerning human thermal environment in buildings, mean radiant temperature is one of the main parameters considered (Parsons, 2002). McIntyre (1980) defines it as "the temperature of a uniform enclosure with which a small black sphere at the test point would have the same radiation exchange as it does with the real environment."

Thermal radiation is complex as radiation comes from different sources at the same time and in different directions. Mean Radiant Temperature is the mean of a radiant temperature at a point from all directions (Nicol, Humphreys and Roaf, 2012).

The mean radiant temperature (T_{MRT}) is calculated from T_g, T_a and the air velocity v for a globe of diameter d as can be seen in Equation 1 (Nicol, Humphreys and Roaf, 2012).

$$T_{MRT} = \left[\left(T_g + 273\right)^4 + (1.2 \times 10^8 d^{-0.4}) v^{0.6} \left(T_g - T_a\right)\right]^{0.25} - 273 \qquad (1)$$

T_{MRT} = Mean radiant temperature (°C)

T_g = Globe temperature (°C)

d = Diameter of the globe (metre)

v = Air velocity (metre per second)

T_a = Dry-bulb temperature (°C)

Globe temperature is measured using a globe thermometer. It is a black sphere (usually 40mm in diameter) to measure globe temperature. The Globe thermometer reacts to the surrounding environment similar to a human body (Nicol, Humphreys and Roaf, 2012).

3.3.3 Operative temperature:

Operative temperature combines both air temperature and MRT. This value could be useful to analyse the effects of both air temperature and MRT in a single value. Equation 2 can be used to calculate operative temperature indoor where air speed is below 0.1 m/s (Nicol, Humphreys and Roaf, 2012).

$$T_{op} \approx \frac{1}{2}\, T_a + \frac{1}{2} T_{MRT} \tag{2}$$

3.3.4 Relative Humidity

Air carries different amounts of water vapour at any given temperature and air pressure. Relative humidity can be defined as “the prevailing partial pressure of water vapour to the saturated water vapour pressure” (Parsons, 2002). A relative humidity between 30% to 65% is normal and does not have high effect on human thermal comfort. A relative humidity higher than 65% can restrict evaporation from the skin while a relative humidity lower than 30% can cause a drying out effect on human, hence causing thermal discomfort (Szokolay, 2008). Hence, the water vapour pressure (or humidity) is an important factor in hot conditions. It can be measured using a hygrometer (Nicol, Humphreys and Roaf, 2012).

3.3.5 Air Velocity

Heat flow between a human body and the surrounding environment can be affected by air movement and velocity (Parsons, 2002). Air flow can be described by air velocity (m/s), mass flow rate (kg/s), and volume flow rate (m^3/s). Air flows naturally from a high-pressure zone to a low pressure zone. Pressure different can be described by two effects: stack effect or wind effect. Stack effect happens when there is a vertical difference of temperature provided there is a high outlet and a low inlet. This will allow warm air to exit the space through the high outlet, which is replaced by cooler air entering from the low inlet. Wind effects are stronger than stack effect and happen when there is a difference in pressure between one side of a building to another, in which case wind can travel from the high pressure zone to a low pressure zone across the space (Szokolay, 2008).

Air movement could be minimal in an enclosed space but could be measured initially using a smoke puffer to recognise any droughts or air movements. Any air movement below 0.1 m/s is insignificant (Nicol, Humphreys and Roaf, 2012).

3.3.6 Metabolic rate

Heat production is an important part of humans. Metabolic rate is the heat generated by human body. Metabolic rate is a crucial part of the human thermal comfort research and it can be easily overlooked (Luo *et al.*, 2018). Table 3.1 presents typical heat output of an adult male for each activity type (McMullan and Seeley, 2007).

Table 3.1: Typical heat output of the human body for each activity type (McMullan and Seeley, 2007)

Activity	Example	Typical heat output of adult male (W)
Immobile	Sleeping	70
Seated	Watching television	115
Light work	Office	140
Medium work	Factory work	265
Heavy work	Lifting	440

3.3.7 Clothing insulation

Clothing provides thermal resistance between the human body and the surrounding environment. It helps keep the human body closer or within the comfort zone (Parsons, 2002). Thermal insulation of clothing can be measured in units of clo. The higher the value of clo means higher insulation level. Clo value is affected by the thickness of the clothing material, but it is also affected by the type of the clothing material and its fit (Butcher, 2006). For the purposes of this research, which conducted on mosque buildings in the Sultanate of Oman, both the clothing and the activity levels are similar between worshippers. Loose clothing is common since it is hot and humid climate. The worshippers usually go through Wudu, which is the washing of their hands, face, arms, and feet. Next, they usually immediately enter the mosque. The act of wudu might have an impact on their perception of thermal environment (Irmak, 2014).

3.3.8 Age

Studies conducted by (Griffiths and McIntyre, 1973) have found that age does not have a significant impact on the thermal comfort and thermal sensation between younger adults and older adults.

However, in a study conducted by Schaudienst and Vogdt (2017) shows that older adults have a higher PPD (Predicted Percentage Dissatisfied) than younger adults. The study shows female adults older than 75 years have a PPD of as much as 24% younger female adults between 18 and 20 years old would have around 6.2%.

It is argued a lower metabolic heat production can be balanced by evaporative loss of heat, which makes older adults temperature preference similar to younger adults (Collins and Hoinville, 1980).

3.3.9 Gender

There is no significant difference between the temperature preference of male and female according to Fanger’s model (Schaudienst and Vogdt, 2017). When different thermal comfort responses occur between male and female subjects, it can be because of their different clothing. However, in a study conducted by Schaudienst and Vogdt (2017) shows that male subjects have different temperature preference than female subjects given the same environmental conditions and considering their clothing conditions.

3.3.10 Adaptation

Adaptation is a dynamic process. Small changes to a person’s clothing or changing of movement could affect the thermal comfort of a person (Nicol, Humphreys and Roaf, 2012). Thermal comfort can also be influenced by past thermal experiences, and thermal expectations. Hence, thermal adaptation can be grouped in three categories: behavioural, physiological and psychological (Brager and De Dear, 1998).

Behavioural adaptation are human behavioural responses to adapt to an environment such as change of clothing or change of movement (Indraganti, Ooka and Rijal, 2015)

Physiological thermal sensation is the thermal environment felt. A study conducted by Yu *et al.* (2012) confirm that people do acclimatise to different climates. However, their thermal adaptability can be different due to several factors. One of which is whether they are accustomed to living in a naturally ventilated or air-conditioned building.

Psychological thermal sensation is the thermal environment perceived as opposed to the thermal environment felt (Zabetian and Kheyroddin, 2019). As an example, there is a distinction between the thermal expectation of air-conditioned and naturally ventilated buildings. Occupants tend to have a more relaxed expectation of naturally ventilated building; hence their thermal preference is more flexible. On the other hand, occupants of air-conditioned buildings have less flexible thermal preference (Brager and De Dear, 1998).

3.4 Thermal sensation

3.4.1 Thermal balance and comfort

Human's body core temperature is normally about 37 °C, while skin temperature can vary between 31 °C and 34 °C. It produces heat at a different rate depending on the human's metabolic rate and activity (Szokolay, 2008).

According to Szokolay (2008), body's thermal balance can be expressed as shown in Equation 3.

$$M \pm R_d \pm C_y \pm C_d \pm E_y = \Delta S \tag{3}$$

M = metabolic heat production

R_d = net radiation exchange

C_y = convection (incl. respiration)

C_d= conduction

E_y = evaporation (incl. in respiration)

ΔS = change in stored heat

If a person's body reaches the equilibrium, it can be assumed that that person is within the thermal comfort zone, but that is not always the case. The human body is also subject to psychological factors beyond the physical and environmental factors. This makes thermal comfort subjective and different for each person (Szokolay, 2008). If a person's body is warm, but has cold feet (in literal terms), the thermal balance equation will show that he or she has reached equilibrium, but that is not necessarily the case (Nicol, Humphreys and Roaf, 2012).

Thermal comfort is not only about external factors such as temperature and humidity, but also about how the human body adapts to hot climates. Despite the difficulties posed by extreme heat, the human body possesses remarkable adaptability to maintain homeostasis. Nevertheless, the harsh conditions of hot climates can affect thermoregulation, fluid and electrolyte balance, and metabolism. In such climates, staying hydrated is essential because dehydration is a common and serious health risk. To maintain proper fluid balance, it is necessary to provide the body with enough fluids to compensate for sweating and fluid loss. Adequate hydration prevents adverse effects such as fatigue, weakness, headaches, vertigo, nausea, and even heat exhaustion and heat stroke (Adolph, 1969).

3.4.2 Prediction of thermal comfort using the PMV model

PMV (Predicted mean vote) is “an index that predicts the mean value of votes of a large group of persons on the 7-point thermal sensation scale”. There are many heat balance models and thermal comfort scales, but the PMV model, which was introduced by Fanger (1970) is the basis for most thermal comfort standards (Nicol, Humphreys and Roaf, 2012). It is used by the ISO 7730:2005 (Ergonomics of the thermal environment) standard. The seven point thermal sensation scale is in Table 3.2 (*BS EN ISO 7730:2005*, 2005).

Table 3.2: Thermal sensation scale according to ISO 7730 (*BS EN ISO 7730:2005*, 2005)

Scale	Condition
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Fanger (1970) states four conditions for a human to achieve thermal comfort: a) the body is in heat balance, b) sweat rate balance, c) mean skin temperature are within the comfort limits, and d) the human body is free from local discomfort factors. PPD (Predict Percentage Dissatisfied) is “an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people who feel too cool or too warm.” For the purposes of the ISO 7730 standard, people who vote hot, warm, cool, or cold on the 7 point thermal sensation scale are considered dissatisfied (BS EN ISO 7730:2005, 2005)

There are some limitations to the heat balance approach, and more specifically to the PPD approach. Thermal sensation scales are continuously improved to bridge the gap between actual thermal data and sensation votes. For example, ASHRAE developed an adaptive thermal model to account for warmer climates as an improvement over other thermal comfort models such as PMV, which was criticized to overestimate temperature values in warmer climates (Lee *et al.*, 2010).

It is believed that it does not account for real life situation with a dynamic activity level and different clothing (Humphreys and Fergus Nicol, 2002). Another source of error could be the consideration of loose clothing compared to fit clothing, and the wetting of clothing due to sweat (Nicol, Humphreys and Roaf, 2012).

3.4.3 Psychometric chart

The psychrometric chart is “a tool for understanding the relationships between the various parameters of supply air and the relative humidity” (Dyro and Iadanza, 2004).

The psychrometric chart has five sets of skeleton lines as are shown on Figure 3.2 and are explained below (Yaciuk, 1981):

1. Dry bulb temperature–is “the air temperature measured by a thermometer” (represented by vertical line on Figure 3.2).
2. Wet bulb temperature–is “air temperature measured by a thermometer whose glass bulb is covered by a wet cloth” (represented by sloped lines at small angle).
3. Dewpoint temperature–is “the temperature at which moisture condensation at surface occurs” (represented by horizontal line with figures read from left side)
4. Relative humidity–is “the ratio of actual partial pressure of the water vapour to the saturation partial pressure at the same temperature” (represented by lines sweeping upward from left side of chart).
5. Specific volume–is “the volume occupied by a unit weight of dry air” (represented by steep angled lines).

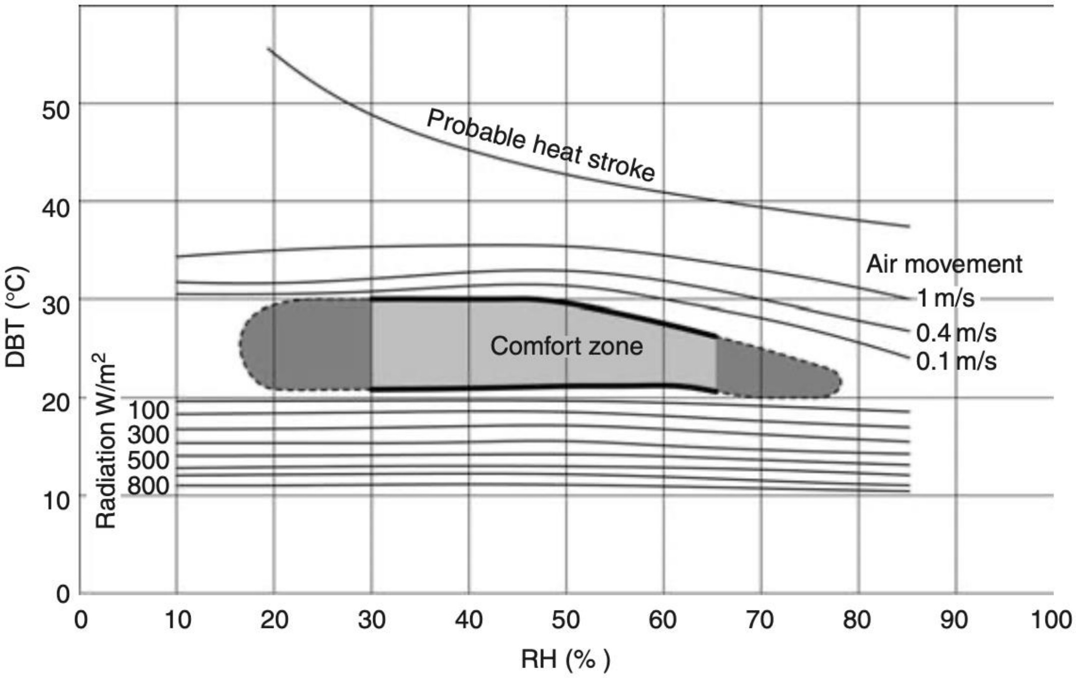


Figure 3.1: Olgyay's bioclimatic chart (Olgyay, 1963).

Figure 3.1 shows a bioclimatic chart which was introduced by Olgyay (1963). It shows the comfort zone, which is confined by the relative humidity and dry bulb temperature factors. Between 10 and 20 °C, thermal comfort can be achieved if offset with sufficient radiation as noted between 100 and 800 W/m^2. Above the comfort zone in Figure 3.2, thermal comfort can still be achieved if offset with sufficient air movement between 0.1 and 1 m/s, as shown.

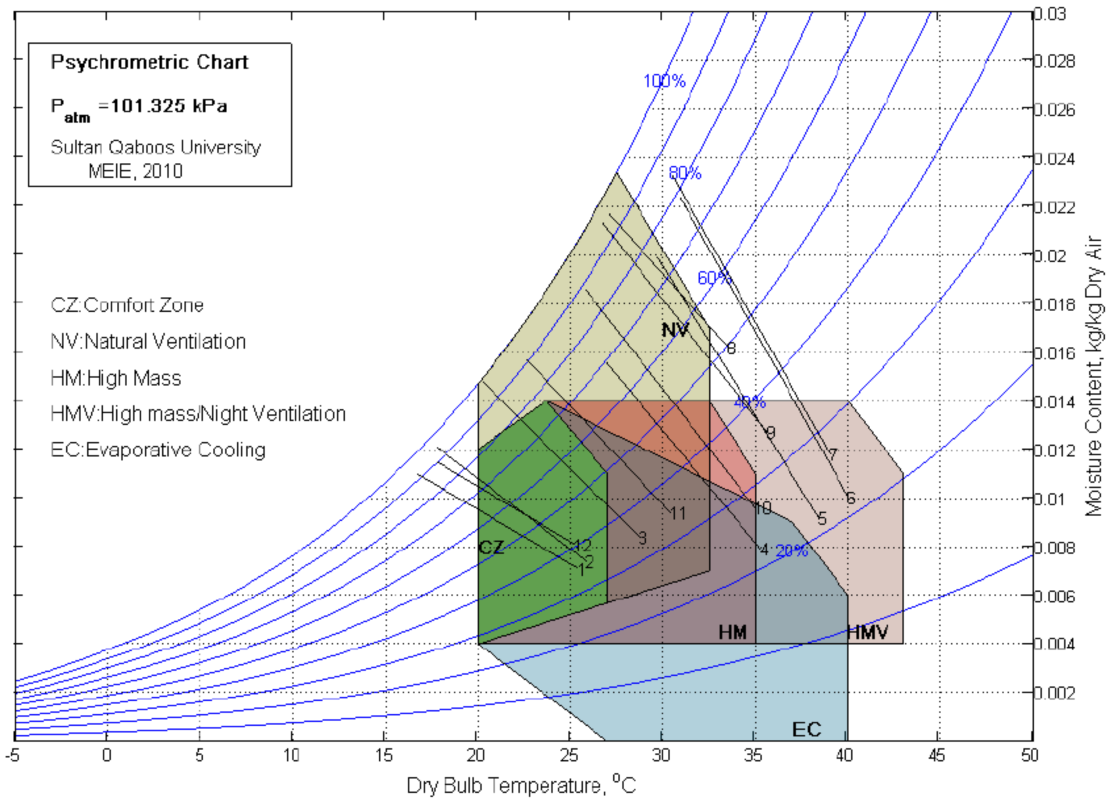


Figure 3.2 Bioclimatic chart from Muscat (Givoni,, 1992) (Al-Azri, 2016).

As an example of a bioclimatic chart laid on a psychrometric chart as per (Givoni, 1992), Figure 3.2 shows the Givoni's bioclimatic chart for the city of Muscat in the Sultanate of Oman. The green area is the comfort zone (CZ). The chart also shows the five other thermal comfort zones that use one of the five passive cooling techniques: natural ventilation (NV), high mass, high mass/night ventilation (HMV), and evaporative cooling (EC) areas (Al-Azri, 2016). Similar to the Olgyay chart, the NV area above CZ is considered a thermal comfort zone only if there is natural ventilation (air movement) that helps reduce relative humidity to thermal comfort levels. The EC area below CZ is a relatively dry area (below 20% RH) and can be considered as thermally comfortable within the EC area if provided with sufficient evaporate cooling which helps increase relative humidity to thermal comfort levels. The High Mass (HM) is considered thermally comfortable beyond CZ up to 35° C if the building has a relatively high mass envelope to absorb and release heat overnight. The High Mass/ Night Ventilation area is considered thermally comfortable beyond CZ up to 43° C if the building has a relatively high mass envelope to absorb and release heat overnight in addition to a night purge system. The average daily maximum temperature is match with the average minimum daily absolute humidity to form a point (T_{max}, w_{min}). The average daily minimum temperature is match with the average maximum daily absolute humidity to form a point (T_{min}, w_{max}). These two points are linked for each month to represent twelve different lines representing the twelve months of 2010 in Muscat as shown in Figure 3.3. This shows that achieving thermal comfort can be done using passive cooling techniques throughout most of the year (Al-Azri, Zurigat and Al-Rawahi, 2012).

3.5 Thermal comfort field monitoring and surveying

The comfort zone is as an area within defined climatic condition in which thermal comfort is mostly achieved (ASHRAE, 2020). In order to measure thermal comfort, thermal comfort factors can be measured which can be in a form of post-occupancy buildings survey, physical measurement survey or an energy audit. For a buildings survey, there can be three levels of complexity (Nicol, Humphreys and Roaf, 2012)**:**

- Level 1: simple measurements with no subjective responses. For example, air temperature measured only for a set period.
- Level 2: measurement of the core set of factors (air temperature, radiant temperature, relative humidity, and air velocity)
- Level 3: Measurement of all factors needed to calculate heat exchange between occupants and the environment as accurate as possible. It includes subjective responses from the occupants.

It is important when measuring physical measurements to make sure to have an idea of the measurements of on several different points inside the room and different points in time. It is also essential to have an idea of the thermal pathway and air patterns. When conducting the physical thermal measurements in a building, it is imperative to define which type of “temperature” is measured exactly, and why (Nicol, Humphreys and Roaf, 2012). It could be argued in some cases that the difference between the air temperature and the mean radiant temperature is negligent. In a study conducted by Walikewitz *et al.* (2015) that air temperature and mean radiant temperature could have a negligible difference indoors in warm outdoor conditions with intense solar radiation.

3.5.1 Considerations for physical measurements

There are several considerations that should be taken when taking physical measurement using thermal instruments. Temperature probes respond to both heat through convection and radiation. The effect of heat radiation on the temperature probe needs to be minimized to give a more accurate air temperature. When measuring air temperature, it is also important to consider its vertical layering. Air temperature could be different near the floor from near the ceiling, which means it is recommended to take the measurement on a point at half the height of a seating or standing person depending on the research conditions. For example, half the height of a seating person on a chair would be approximately 0.6 metres (Nicol, Humphreys and Roaf, 2012).

Using a datalogger makes physical measurements easier and non-intrusive, and more accurate. Taking manual measurements could be intrusive, less accurate, and time consuming. A thermometer should be placed not less than half a metre away from any wall. If measured inside the room, it is better to measure the air temperature on more than on point. One point of which should be at least should the centre of the room. Settling time is different between instruments and should be taken under consideration. Humidity does not vary greatly from point to point inside a room, which means taking one measurement should be sufficient. (Nicol, Humphreys and Roaf, 2012).

3.6 Building Energy Performance

Building performance is a term usually means how well a building performs in terms of its energy efficiency, indoor environmental quality, and thermal comfort (de Wilde, 2019). Achieving high building energy performance and efficiency is vital to reduce energy consumption and cut carbon dioxide emissions. One of the ways to tackle this issue is through policies, regulations, and standards, which can be either national or international. Policymakers prioritise targeting the heating and cooling consumption in buildings within their energy efficiency policies. In order to improve building energy performance, policies tend to focus on improving building thermal insulation, shading, usage of ventilation, and adopting of new solutions (Asdrubali and Desideri, 2018).

Another way to help achieve high building energy performance is through building green building certification programme. There are several green building certification programmes that encourage energy efficiency in buildings such as Leadership in Energy and Environmental Design (LEED), BRE Assessment Method (BREEAM), Green Building Challenge (GBTool). The systems differ in their criteria, but all of which have a focus on energy efficiency (Juan, Gao and Wang, 2010).

3.7 Heat Transfer in Buildings

Buildings help people stay inside thermally comfortable and away from the solar impact. This is true if the building envelope has the required properties to keep people thermally comfortable. The building envelope consist of walls, fenestration, roofs, and floors. Walls are the predominant part of the building, while fenestration are believed to be the weak point in buildings as it may allow infiltration. Reconsidering roofs in buildings is vital as it most affected by solar radiation and other environmental conditions. Choosing the right material and the properly insulated component for each building envelope component helps towards a more energy efficient building (Sadineni, Madala and Boehm, 2011).

Heat can be transferred inside buildings via three forms: conduction, convection, radiation. Conduction occurs within a body or when two bodies contact each other by molecule movement. It depends on the conductivity of a material, which is the heat flow density of a material in one-meter-thick body in one degree temperature difference. A material is deemed to be more insulating if it has low conductivity. U-value is a more common measurement to indicate the insulation of a material. U-value is a heat flow density with one degree temperature difference between the inside and outside of a material. Convection is heat flow via moving fluid from one surface to another. It depends on the area of contact, difference in temperature, and the convection coefficient (h_c). Radiation happens from a warmer surface to a cooler one, and has a 700nm to 10,000nm wavelength band of electromagnetic radiation. The emitting body’s temperature determines the wavelength (Szokolay, 2008).

3.8 Building Performance Factors

There are several building performance factors which can affect a building performance at any given time. They can be split into six categories: architectural, building service equipment, occupant behaviour, climate, technology, and building codes and regulations (Adjei, 2016).

Identifying gaps in building performance factors can help improve a building performance. If building design is inadequate and technical guidance is lacking to achieve required building performance, it could lead to low building thermal performance. The required building performance though can be argued to be unrealistic if, for example, the U-values are unrealistically low for local building elements set out by regulations. Another area of improvement is the usage of international standards with subjective adjustment instead of specialized local standards (Adjei, 2016).

Technical guidance and building standards for thermal comfort is often in complex terms of temperature, humidity, and clothing which is not easy to work with for designers, and contractors in the construction industry. Hence, this can be viewed as another gap to bridge between policy makers, researchers, and practitioners (Nicol, Humphreys and Roaf, 2012).

In a study conducted by (Silva and Ghisi, 2020), 21 design variables were identified which are the most influent input variables in a building performance. The 21 design variables are:

1. Thermal transmittance of the external walls
2. Thermal transmittance of the internal walls
3. Thermal transmittance of the roof
4. Thermal transmittance of the floor
5. Thermal capacity of the external walls
6. Thermal capacity of the internal walls
7. Thermal capacity of the roof
8. Thermal capacity of the floor
9. Solar absorptance of the external walls
10. Solar absorptance of the roof
11. Longwave emissivity of the inside-face roof
12. Fraction of the opening area by the floor area
13. Fraction of the ventilation area by the opening area
14. Air Infiltration Rates of the windows
15. Air Infiltration Rates of the external doors
16. Air Infiltration Rates of the internal doors
17. Solar transmittance of the venetian blinds
18. Solar Heat Gain Coefficient of the windows
19. Thermal transmittance of the glass
20. Azimuth of the main facade of the building
21. Fraction of the shading by the window height

Out of the 21 design variables the variables with the highest effect on air temperature for cooling are found to be: solar absorptance of the roof, thermal transmittance of the roof and the fraction of the ventilation area. The variables with the highest effect on cooling energy consumptions are found to be solar absorptance of the roof, thermal capacity of the roof, and solar absorptance of the walls (Silva and Ghisi, 2020). In the next sub-section (Section 3.8.1), the 21 variables are categorised and discussed in more detail.

If mosque buildings in hot regions are taken as an example (since these are the building types selected for this research), the top envelope thermal design considerations are the design, materials, and shading of the roof, walls, and windows in addition to the ventilation and infiltration of the building (Azmi and Ibrahim, 2020). IT was investigated how to create environmentally sustainable, energy-efficient, and thermally comfortable mosques by focusing on the factors that affect the thermal performance and energy efficiency of mosques. The findings indicate that there are significant design factors that contribute to the thermal comfort and sustainability of mosques. In hot climates, heat gain through the walls, roof, and windows contributes the most to the cooling burdens of mosques. The energy consumption of mosques is primarily determined by the end-users' behaviour as well as the operational profiles and energy management protocol. Mosques are predominantly skin-load buildings; consequently, the majority of heating or cooling load is caused by external climatic conditions. To reduce energy consumption in mosques, it was suggested to optimise building design, increase thermal insulation, install appropriate thermal control systems, and employ suitable operation strategies. In addition, the report suggested training end-users and management of mosques to promote awareness, investigating the concept of smart mosques, and establishing regulations and policies on mosque energy usage. To reduce carbon footprint, incorporating renewable and pure energy sources was also suggested. Research on mosque architecture is still in its infancy, and the literature available varies widely in terms of scope, methodology, objectives, and findings. Numerous research gaps should be addressed to improve the thermal performance of mosque buildings (Azmi and Kandar, 2019), Azmi and Ibrahim (2020), Azmi, Arıcı and Baharun, (2021).

When making the design decisions, it is important to consider the implications of such decisions on other areas of the building. For example, decreasing the window area of a building in a hot climate will result in less heat gain, but will allow for less daylight. Table 3.3 gives examples of how design options are linked with various aspects of buildings’ design.

Table 3.3: Effect of design decisions of various aspects of the building (McMullan and Seeley, 2007).

Design decision	Heating	Ventilation	Lighting	Sound
Sheltered site	Less heat gain	-	Less daylight	Less noise
Deep building shape	Less heat gain	Reduced natural ventilation	Less daylight	-
Narrow building shape	More heat gain	More natural ventilation	More daylight	More noise
Heavy building materials	Slower heating and cooling	-	-	Less noise
Increased window area	More heat gain	-	More daylight	More noise
Smaller and sealed windows	Less heat gain	Reduced natural ventilation	Less daylight	Less noise

3.8.1 Thermal Transmittance

The first set of the 21 design factors that affect building thermal performance is thermal transmittance. Thermal Transmittance (or the U-value) is defined as the coefficient of heat transmission through a building component as per the 2012 International Energy Conservation Code (International Code Council, 2012). The thermal transmittance is considered as one of the most important parameters in building thermal performance and energy efficiency research as low U-value building envelope materials mean the building is able to minimise external heat gain, lowering the cooling load demand (ASHRAE, 2017).

Construction layers can be complicated because each layer has unique thermal characteristics. Different layers conduct heat at various rates. Radiation and convection have different effects on internal and external surfaces. The U-value is important because it is regarded as a single measurement for the air-to-air behaviour of a specific construction section. Hence, the U-value is one of the most frequently used thermal insulation targets and limits in building regulations and codes. There is still much room for improvement in both the UK and other parts of the world's building codes. To increase the insulation in existing buildings, strategies like cavity fill, double glazing, and exterior wall cladding can be used (McMullan and Seeley, 2007).

Thermal insulation is especially important in climates with large difference between the external dry bulb temperature (DBT) and the comfort zone. It should be the main passive heat flow control mechanism, so regulatory bodies should set a minimum U-value for all building envelope component (Szokolay, 2004).

Insulation is a method to limit the heat flow between external and internal space for a more energy efficient building. There are three types of insulation: reflective, resistive and capacitive (Szokolay, 2008).

- **Resistive insulation** is an insulation against heat transfer through conduction (Szokolay, 2008).
- **Reflective insulation** is an insulation that reflects heat. Foil insulation is an example (Szokolay, 2008).
- **Capacitive insulation – thermal mass -** is an insulation that slow down heat flow (Szokolay, 2008). Thermal mass helps stabilises the temperature inside a space (Nicol, Humphreys and Roaf, 2012). A steady state thermal condition means the indoor and outdoor conditions are steady and non-changing. In a non-steady state, the thermal mass of material takes time to for the heat to flow through a material (Szokolay, 2008).

3.8.2 Thermal Capacity

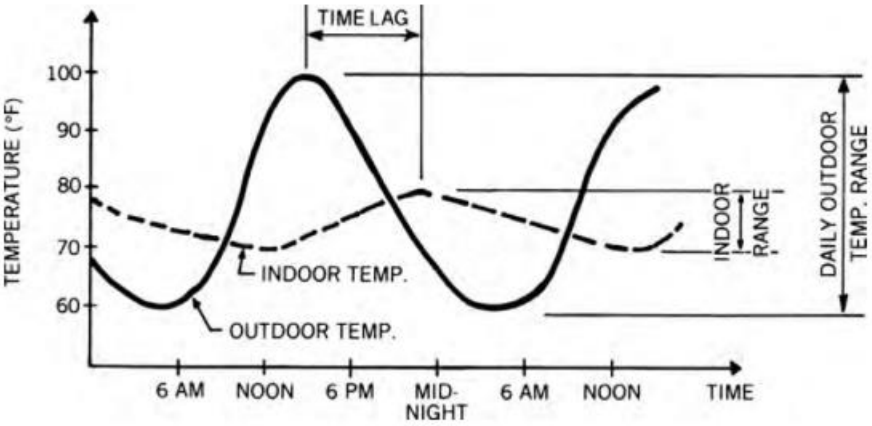


Figure 3.3: The difference between internal DBT and external DBT to reach their peaks is defined as time lag (Lechner, 2015).

The second set of the 21 design factors that affect building thermal performance is thermal capacity/mass. Thermal mass is the building elements which absorb or release heat from the interior space. It is usually a dense material such as concrete, brick, or stone. Thermal mass is important to minimise temperature swings and have a stable temperature throughout the day. Large buildings can have the advantage of the delay of the gain (or loss) of heat for days or even weeks thanks to their relatively high time constant. This can be noticed in old historic buildings. The disadvantage here is that these buildings can have a long cooling (or heating) if unoccupied for a long time (Baker and Steemers, 2003).

Figure 3.4 shows the stark difference in Dry Bulb Temperature (DBT) ranges between indoor and outdoor areas, which is primarily attributed to the building envelope’s high time lag. The thermal capacity of the building materials used in the construction has a significant impact on this time lag; materials with a higher thermal capacity can enable a more pronounced time lag, which has a significant impact on the indoor DBT. Designing buildings that are both energy-efficient and comfortable for the occupants can be greatly aided by understanding the role of high thermal capacity materials in controlling indoor temperatures. Additionally, it emphasises how important it is to choose the right materials for a building's construction in order to promote a sustainable and comfortable indoor environment, which is a key topic in modern architectural and environmental research (Lechner, 2015).

Two walls can have the same U-value but absorb or dissipate heat at different rates due to a different response time or time constant. Structures that are heavier and have more thermal mass react more slowly than lighter and have less thermal mass. This is because heavier structures have better heat-storage capabilities and experience slower temperature changes (McMullan and Seeley, 2007).

Materials with a high thermal capacity are categorised as capacitive insulation. They leverage their substantial thermal mass to moderate the transfer of heat, thereby facilitating a gradual absorption and release of heat energy. On the other hand, resistive insulation, which is more commonly utilised for the purpose of building thermal insulation nowadays, characterised by low thermal conductivity, including but not limited to polystyrene and polyurethane insulation boards, serving as effective barriers to heat flow (Szokolay, 2004).

Ventilation is buildings can be used in order to supply fresh air, or remove internal heat from the building or the human body skin (Szokolay, 2008). Ventilation is most known to be direct by opening the windows, but also can be integrated into the air conditioning systems improve indoor air quality and reduce the cooling load (Zhang *et al.*, 2020).

In a building that is continuously occupied (like a residential building or a hospital), a heavy mass construction would enable intermittent cooling while maintaining a constant temperature. Lightweight resistive insulation may be preferable in buildings that are only occasionally occupied, like offices or schools, as it will have a shorter cooling-up period in the morning and as heat lost will be gained overnight (Szokolay, 2004).

When the daily average exceeds the thermal comfort limit, night ventilation or night purging may be essential to help a high thermal mass structure dissipate heat overnight. Evaporative cooling is another passive cooling technique that can be provided by a pool or a pond. Evaporation lowers the DBT but raises the humidity, which must be taken into account when calculating the cooling load demand. (Szokolay, 2004).

3.8.3 Solar Heat Gain, Absorptance, and Emissivity

The third set of the 21 design factors that affect building thermal performance relate to solar heat gain, absorptance, and emissivity. Solar gains refer to the thermal energy accrued from solar radiation that is absorbed by a building's surface and subsequently transmitted to its interior through the building fabric. It can greatly impact how comfortable the building is temperature-wise and how much energy is needed for heating or cooling. In the United Kingdom, empirical data indicate that surface temperatures during the summer can reach approximately 35°C for light-coloured surfaces and escalate to as high as 45°C for dark-coloured surfaces (Baker and Steemers, 2003).

Building envelopes are affected by solar radiation through three main processes which are reflectance, absorptance, and emittance. Reflectance indicates the amount of incident radiation is reflected by the surface. Absorptance is the amount of radiant energy a body absorbs in comparison to a black body. Emissivity is the amount of energy radiated by a body in comparison to a black body at a given temperature is known. Colour of the material influences the heat absorbed but has less effect on the heat emitted (Szokolay, 2004; McMullan and Seeley, 2007).

The amount of solar heat gain is affected by several variables, including the site's latitude, the building's orientation, the time of year, the presence or absence of clouds, the characteristics of the window glass, and the type of building envelope. Throughout the day and the year, the solar heat gain varies. Solar heat gain can be regarded as negligible if the building envelope has high thermal capacity walls that delay the heat gain until the external conditions change in the evening. A building can be designed with a solar control to reduce solar heat gain. It might be an introduction of a special glass, an internal control, or an external control. A special glass can be multiple glazed window, or a low-e glass. An internal control can be a type of shading that is located externally such as an external shutter or a shade. External shades are the most effective solar control as they minimise radiant heat before reaching the building envelope. An internal control is located inside the room such as blinds, which are effective against direct radiation, but absorb and emit solar heat into the room (McMullan and Seeley, 2007).

Solar radiation is estimated to contribute to approximately 40% to 70% of the cooling load in buildings, which highlights its potential in reducing energy consumption in buildings (KiranKumar, Saboor and Ashok Babu, 2017). To best explain the interaction between buildings' surface and the solar radiation, it is best to refer to the surface thermal transfer balance equation in Equation 4 (Shi and Zhang, 2011).

$$q_S + q_R + q_B + q_g = q_0 + q_{ca} + q_{ra} \tag{4}$$

q_S = Solar energy absorbed by the external surface

q_R = Ground reflecting solar energy absorbed by the external surface

q_B = Sky longwave radiation energy absorbed by the external surface

q_g = Ground longwave radiation energy absorbed by the external surface

q_0 = Net heat gain/loss of the wall

q_{ca} = Convection heat transfer between the wall and the surrounding environment

q_{ra} = Radiation heat transfer between the wall and the surrounding environment

Equation 4 is useful for quantifying the thermal interactions occurring at a building's external envelope. By presenting each component of thermal energy transfer, the equation facilitates an understanding of the building's energy dynamics, thereby enabling more accurate computational models for energy consumption and thermal comfort. The equation shows that the energy absorbed by the external surface equals to the net heat gain/loss, convection heat transfer, and radiation heat transfer between the wall and the environment (Shi and Zhang, 2011).

3.8.4 Glazing, Solar and Thermal Properties

The fourth set of the 21 design factors that affect building thermal performance relate to glazing, solar, and thermal properties. Glazing is a critical part in a building envelope when considering energy efficiency as it is most prone to infiltration and heat gain. It is important to consider glazing area and building orientation when designing the windows for a building (Kontoleon and Zenginis, 2017). Glazing can be insulated, tinted, or coated with reflective coatings in order to add insulated properties to it (Szokolay, 2008). Window frames should also be reconsidered to minimise thermal bridging and infiltration (Sadineni, Madala and Boehm, 2011).

In a hot climate, a window should offer a view, let in light, allow for adjustable ventilation, and allow for minimum solar heat gain. In any building envelope, the weakest thermal point is the glazing, so it is imperative for glazing to allow for the minimum solar heat gain. This can be done by considering various factors including solar transmittance, glazing ratio, and the U-value (Szokolay, 2004; LETI, 2017).

Solar transmittance is the proportion of solar incident radiation transmitted through the glass. Some of the radiation will be reflected and some will be absorbed by the glass itself (Szokolay, 2004). When solar radiant energy enters the room and is absorbed by internal objects and surfaces, it can retransmit into the room, trapping it. This is referred to as the "greenhouse effect" (LETI, 2017).

The glazing ratio refers to the proportion of glazing relative to the opaque surface in a wall. While decreasing the glazing ratio can reduce solar heat gain, it also reduces the amount of natural light entering the space and the likelihood of natural ventilation, so a careful balance is required to achieve the best possible levels of thermal comfort and lighting. Adding more glass layers, expanding the space between them, exchanging the air in the space for argon, and coating the inner pane of glass with a low emissivity layer are other techniques for enhancing the thermal performance of glazing (Nicholls, 2002).

3.8.5 Air Infiltration Rate

The sixth set of the 21 design factors that affect building thermal performance to air infiltration rate. Air infiltration or ventilation is necessary to bring fresh air into the building. Fresh Air removes carbon dioxide from the air and helps with oxygen for breathing. Infiltration, however, also allows hot air to enter the building in hot climates (Nicholls, 2002). Air infiltration can be either intentional as a requirement for comfort and safety. Or it might be unintentional through openings, gaps, or cracks through the building envelope (McMullan and Seeley, 2007). It can also happen through porous building materials (Nicholls, 2002).

3.8.6 Shading

The seventh set of the 21 design factors that affect building thermal performance relate to shading. Solar radiation is believed to be the most significant energy input in any building. Solar control devices such as shading devices can help reduce solar radiation (Szokolay, 2008). In a study conducted by (Alabdullatief *et al.*, 2016) it is believed that mosques have benefited from shading the roof to achieve a U-value similar to an insulated roof. In a study conducted by (Park *et al.*, 2020) it is believed that Phase Change Material shading system has resulted in a 44% cooling energy saving in a hot and humid climate.

3.9 Building Energy Modelling and Computer Simulation

A diverse collection of software, including EDSL Tas, IES VE, Ecotect, EnergyPlus, and Design Builder, is available for specialists to conduct Dynamic Simulation Modelling (DSM), each offering unique features to facilitate comprehensive thermal analyses and simulations. The software of choice used in this research is EDSL's Tas Engineering software. It is one of four approved software assessment providers by CIBSE Certfication, a subsidiary of the Chartered Institution of Building Services Engineers (CIBSE). The other three software approved are Bentley, DesignBuilder, and IES VE (CIBSE Certification Ltd, 2023). Out of the software mentioned, EDSL Tas, IES VE, and Design Builder are widely used in research. Table 3.4 offers a comparison of these software options.

Table 3.4: Computer simulation software comparison (EDSL, 2021; CIBSE Certification Ltd, 2023; *DesignBuilder Software Ltd*, 2024; *Integrated Environmental Solutions | IES*, 2024)

Software	**EDSL TAS**	**IES VE**	**Design Builder**
Approved by CIBSE as an energy modelling software	Yes	Yes	Yes
DBT and RH output	Yes	Yes	Yes
Heat gain and heat loss analysis	Yes	Yes	Yes
HVAC sizing	Yes	Yes	Yes
Repetitive simulations	Yes	Yes	Yes
Technical Support	Excellent	Good	Good

As shown in Table 3.4, all three software are capable according to the criteria chosen for the computer simulation and that is why all three software options are widely used in academic and industrial applications. In terms of limitations, computer simulation software do not represent real-world data, and it is up to the researcher to validate and calibrate the model to an acceptable degree (Renken and Nunez, 2013).

All three software options were tested, and it was decided to move forward with EDSL TAS software for this research. The TAS EDSL technical support team was exceptional and answered most queries within 24 hours.

The following is more information about the TAS EDSL software and how it relates to the concepts discussed in this chapter. Tas Engineering is a complex software that leverages dynamic simulation to analyse the thermal performance of buildings throughout a whole year, aiding in tasks such as predicting energy consumption, sizing plant equipment, and setting energy targets. It offers a detailed understanding of a building's operation, considering the intricate interactions of various thermal processes occurring at different locations and times within the structure (EDSL, 2020).

Utilising the ASHRAE response factor method, the software can analyse buildings with up to 12 different layers of materials, supported by an extensive database of materials and structures. It considers heat transfer methods including conduction, convection, and long-wave radiation exchange. Tas Engineering groups internal conditions such as heat from lighting, equipment, and occupants, as well as plant operations and infiltration rates into profiles that can be applied to different zones in the building. It also accounts for the effects of heating and cooling systems, representing them through their capacities and set points. The software helps to perform a detailed analysis by developing equations for energy balances in different zones, considering both radiant and convective gains, and factors like moisture transfer and the operation of humidification and dehumidification systems. This approach, repeated hourly in the simulation, ensures a thorough thermal performance analysis, which lead to optimised building design and assessment (EDSL, 2020).

3.10 Conclusion

Human thermal comfort is a complex subject, and it is affected by many factors. Factors that affect a human thermal comfort can related to the surrounding environment, the built environment, or the human body itself. Taking this into consideration, there are several variables that can be measured to study a thermal environment in given a time and a location. This can be done using field measurement physical instruments. This is an integral part of this research as it will be employed in this research.

In addition to the field measurement methodology, a computer simulation can be conducted to study a building’s energy performance. Some of the top energy building performance factors are related to the thermal control aspects such as insulation, fenestration, shading devices, and ventilation. This is important in this research as the computer simulation methodology is employed as part of this study to investigate the building performance factors and their effects.

Chapter 4. OMAN’S CLIMATE, SOCIOECONOMIC CONTEXT, AND VERNACULAR ARCHITECTURE

4.1 Introduction

In this chapter, Oman's distinct geographical, geological, and climatic characteristics are explored along with Oman's vernacular architecture as the case studies selected are situated in Oman.

The discussion highlights how Oman's diverse landscapes, which include mountains, deserts, and coastal areas, have adopted a sustainable architectural approach that matches with the environment. It is noted that the region's geological features have supplied a rich array of building materials, promoting constructions that naturally blend with their surroundings.

Oman's hot climate has historically influenced building designs to facilitate cool interiors, offering refuge from the harsh external conditions. The chapter highlights the value of revisiting Oman's vernacular architecture, not only to appreciate its historical depth but also to gather insights for future sustainable architectural solutions.

4.2 Background of Oman

The Sultanate of Oman is located at the South- Eastern corner of the Arabian Peninsula, which is between latitudes of 16° 40’ and 26° 20’ North and longitudes 51° 50’ and 59° 40 East. Its coastal line is about 3165 km in length and borders Republic of Yemen, the Kingdom Saudi Arabia, and the United Arab Emirates. The total area of the Sultanate of Oman is 309,500 sq. km. The total population of Oman as of 2017 is about 4.6 million, 1.46 million of which are residing in Muscat governorate where the capital, Muscat, is located (NCSI, 2021).

Oman is the third-largest country in the Arabian Peninsula after Saudi Arabia (2,149,690 km^2) and Yemen (555,000 km^2). This places Oman in the group of medium-sized countries, with an area close to that of Italy, the Philippines, and Poland. Oman has a group of about 293 islands, most of which are rocky outcrops in the sea. The largest of these islands in terms of area is Masirah Island in the Arabian Sea, which is inhabited and has an area of 640 km^2 and a length of 60 km (Al-Hatrushi, 2014).

4.3 Oman’s Geology

Oman is known for its three main topography types: mountains, plains, and deserts. This variety have created unique climates for each area. Deserts are hot and dry, mountains are moderate, and plains have semi desert climate. As can be seen in Figures 4.1 and 4.2, most of the population is in coastal or mountain areas. Given Oman’s location, it is affected by exceptional tropical weather such as storms and hurricanes (Al-Hatrushi, 2014).

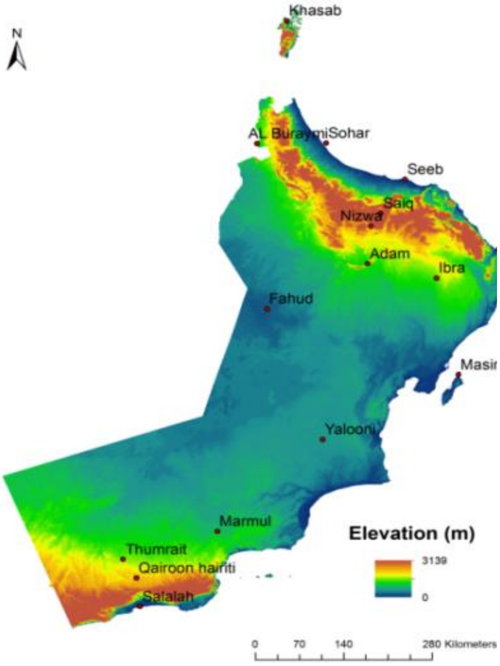


Figure 4.1: Topography of Oman (Al-Hatrushi, Al-Buloshi and Charabi, 2014)

Figure 4.2: Population spread areas in Oman as of 2007 Oman (Al-Hatrushi, Al-Buloshi and Charabi, 2014).

The Sultanate of Oman is characterised by diverse topographical features, with mountain ranges occupying about 15% of the country. These ranges are primarily divided into the Hajar mountain range in the north and the Dhofar range in the south, each bearing distinct geological characteristics and histories (Al-Hatrushi, 2014; Searle, 2019).

In addition to this, the mountains of Oman contain the largest continuous exposure of ophiolites, which are oceanic crustal rocks over the continental mass, in the Middle East. Ophiolites are a group of igneous rocks formed as part of the oceanic crust and then later pushed and thrown to overlap over the continental mass of southeastern Arabian Peninsula. These rocks are of great significance to geologists as they represent an unusual phenomenon. When continental and oceanic masses collide, the oceanic mass is typically pushed beneath the continental mass due to its higher density. In Oman, however, the Semail Ophiolite defied this norm by being pushed upwards and overlapping across the continental mass. This has endowed Oman with a distinctive geological feature, attracting many geologists to study it in hopes of understanding a significant part of Oman's geological history and learning more about the tectonic plate movements that pushed the fiery ophiolite rocks and sedimentary rocks over the Arabian continental shelf, and their role in shaping the Earth's surface over different geological eras (Robertson, Searle and Ries, 1990; Kusky and Cullen, 2010; Al-Hatrushi, 2014).

Plains are depressions in the land formed by valleys descending from the Western Hajar mountains to the Gulf of Oman and from the Dhofar mountains to the Arabian Sea. These plains were formed during the rainy climatic periods that occurred in the southern region of the Arabian Peninsula in the Pleistocene period. In the far west and southwest of the Sultanate of Oman extends the Empty Quarter desert, one of the largest sand seas in the world, covering an area of about 560,000 square kilometres (Al-Hatrushi, 2014).

For this research, four different locations were selected that feature three different climates. Muscat, Nizwa, Al Wafi, and Jalaan Bani Bu Ali are the locations selected which are shown in Figure 4.3. The capital, Muscat, was selected as being the biggest city in Oman. It is a coastal city that is near Al Hajar Mountains. Nizwa is one of Oman’s main cities and located in a mountainous area. Al Wafi and Jaalan Bani Bu Ali are villages located in agricultural area famous for Palm trees that are close to Al Hajar Mountains and Al Sharqiyah Sands. Al Wafi and Jalaan Bani Bu Ali are about 62 km and 40 km from the eastern coast, respectively. By selecting all four cities for the research, it covered a diverse selection sample that covers most of Omani climate. Dhofar, the Southernmost region of Oman, features a monsoon season between July and September of every year which makes have lower average temperatures and higher precipitations than the North of Oman. Dhofar region is not covered by this research.

Figure 4.3 Map of Oman showing the locations of Muscat, Nizwa, Al Wafi and Jalaan Bani Buali

4.4 Oman's Climate

Sultanate of Oman is situated in the southeastern corner of the Arabian Peninsula. This astronomic location places the Sultanate in the heart of the tropical region characterised by distinct climatic features. Besides the astronomic location, the climate in the Sultanate, as everywhere, is influenced by several factors, primarily the elevation above sea level and the proximity to the sea. These factors have created a diversity in the local climate of the Sultanate, ranging from the dry desert climate with extreme temperatures in the Empty Quarter to the moderate winter climate in the Hajar Mountains, and the semi-desert climate in the coastal plains and the plains adjacent to the mountains. The Sultanate is also affected by exceptional climatic conditions, especially tropical cyclones. In recent times, it has been affected by the occurrence of two tropical cyclones, which are Cyclone Gonu in 2007 and Cyclone Phet in 2009 (Al-Hatrushi, 2014). The most recent cyclone is called Shaheen, which hit Al Batinah region in October 2021 (Masters, 2021).

4.4.1 Climatic Diversity

The thermal distribution in the Sultanate of Oman endures seasonal variations, with the lowest temperature averages recorded during the winter months (December-February) and the highest temperature averages recorded during the summer months (June-September). The annual temperature averages range between 10 degrees Celsius in the elevated northwestern regions of the Sultanate to 30 degrees Celsius in the southwestern desert regions. However, this general distribution shows thermal exceptions, especially along the southern coastal regions of the Sultanate of Oman, which are under the influence of the southwestern monsoon winds, where temperatures drop in these coastal areas in June and July. This is clear in Salalah, where the temperature averages are 8 degrees Celsius lower than most other regions of the Sultanate during this period. Temperatures also drop on the Hajar Mountain range by averages ranging between 8 to 10 degrees compared to the inland areas, influenced by the temperature decrease with elevation, estimated at 0.65 degrees Celsius per 100 meters elevation in humid air. The Empty Quarter records the highest annual temperature averages overall, influenced by the distance from the sea coast, and thermal concentrations in the summer season. During the winter season, the minimum temperatures drop to their lowest annual levels, becoming negative on the peaks of the western Hajar Mountains and moderate along the Omani coasts (Al-Hatrushi, 2014; NCSI Oman, 2018; Directorate General of Meterorology, 2021).

4.4.2 Climate classification

According to Al-Hatrushi (2014), Oman features four different climates: dry desert, coastal, tropical monsoon, and mountainous climates. The details of these climates are provided in this section. It is noteworthy that Oman experiences some of the most extreme temperatures globally, with arid conditions in desert regions and high humidity levels in the coastal areas.

4.4.2.1 Dry Desert Climate

The central region of Oman extending to the south and west from the northern mountains of Oman to the Dhofar highlands in the south, including the internal alluvial plains, in addition to the sandy deserts. This region belongs to the driest regions in the world, including the Empty Quarter desert, Eastern sands, and the central alluvial plains extending between the Hajar Mountains and Dhofar mountains, where temperature averages range between 27-31 degrees Celsius, the annual rainfall does not exceed 20 millimetres, and the relative humidity plummeting to below 10% (Al-Hatrushi, 2014; NCSI Oman, 2018)

4.4.2.2 Coastal Climate

The coastal plains such as the coastal plain of Al Batinah features a coastal climate.. The region is affected by the movement of local winds (land and sea breezes). The annual temperature averages range between 25-28 degrees Celsius. Humidity rates increase in this region, especially in the summer season, reaching up to 90%, as is the case on the Al Batinah coast (Al-Hatrushi, 2014).

4.4.2.3 Tropical Monsoon Climate

The highlands of Dhofar in the southern parts of Oman, where rainfall occurs in this region in the summer months, especially in July and August features tropical monsoon climate. The source of this rainfall is the southwestern monsoon winds blowing from the Arabian Sea and the Indian Ocean. The amount of rainfall on the Dhofar highlands ranges between 200-240 millimetres per year, 70% of which falls in the summer season. This is accompanied by a drop in DBT and an increase in RH, leading to the formation of fog and dew that condenses on plants and trees, especially at night and early morning hours. This often becomes a vital source of water for plants, animals, and humans (Al-Hatrushi, 2014).

4.4.2.4 Mountainous Climate

The higher parts of the western Hajar mountain range that exceeds 3000 meters above sea level, such as Jebel Shams and Al Jabal Al Akhdar, has an annual temperature average around 16-17 degrees Celsius, and the annual average rainfall is approximately 300 mm (Al-Hatrushi, 2014).

4.4.3 Climate Conditions of Muscat, Nizwa and Al Kamil

The four selected cities for this research, Muscat, Al Wafi, Jaalan and Nizwa, are classified as hot and dry according to the Köppen–Geiger climate classification (Grieser *et al.*, 2006). Muscat is a hot coastal climate city which is located by the coastline of Gulf of Oman. It features long summers and short warm winters (Peel, Finlayson and Mcmahon, 2007). Al Wafi village and Jalaan village are 25 km apart and both are located near Bidyah desert and around 250 kilometres away from Muscat. Nizwa features a mountainous climate, and it is located 150 km away from Muscat. For the purposes of this research, Muscat weather data was input into the simulations of both mosques’ buildings.

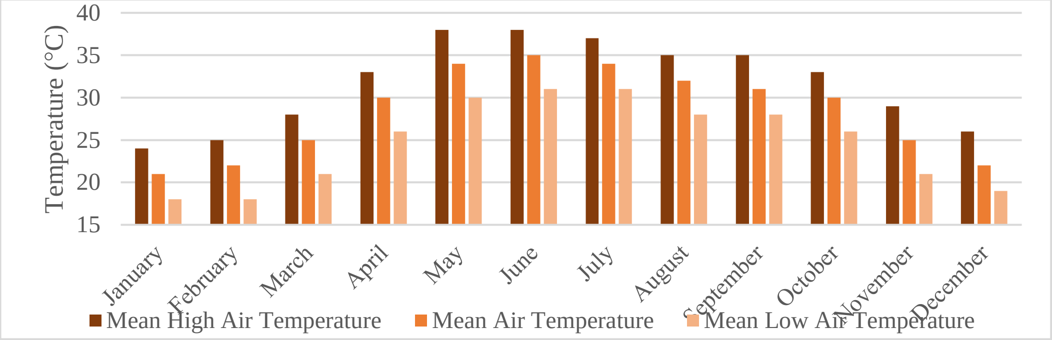


Figure 4.4: Mean ambient air temperature in a typical year in Muscat, Oman.

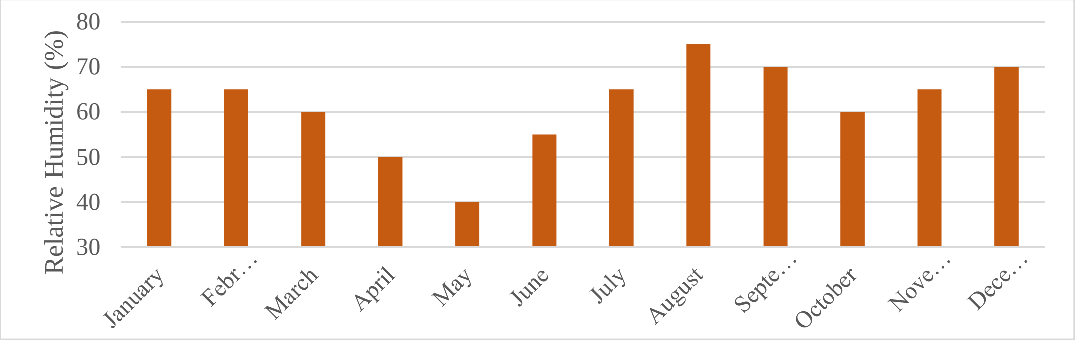


Figure 4.5: Mean relative humidity in a typical year in Muscat, Oman (Al Rasbi and Gadi, 2021).

Figure 4.4 shows the mean temperatures and humidity throughout a typical year in Muscat. As per the bioclimatic chart shown in Figure 3.3, most months have ambient air temperature above 30 °C. The green area is the comfort zone area under air conditioning, which makes 20 °C to 24 °C thermostat set point reasonably within the comfort zone if humidity is between 30% and 80% (Al Rasbi and Gadi, 2021).

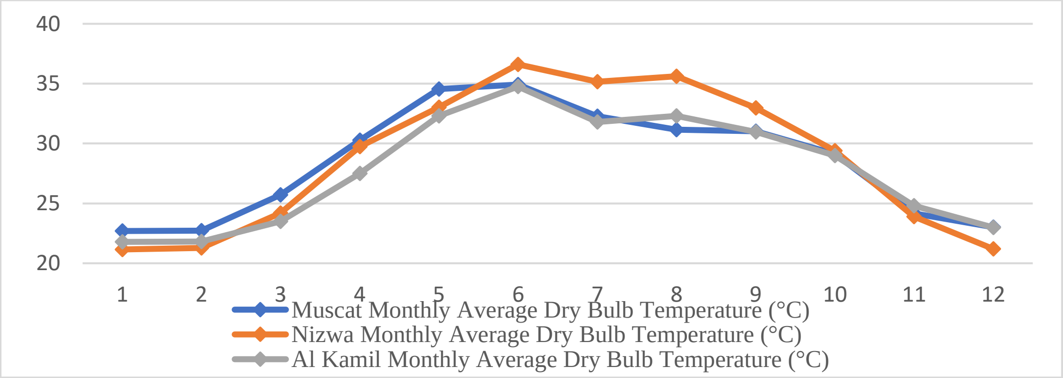


Figure 4.6 Mean DBT in a typical year in Muscat, Nizwa, and Al Kamil (Directorate General of Meterorology, 2021).

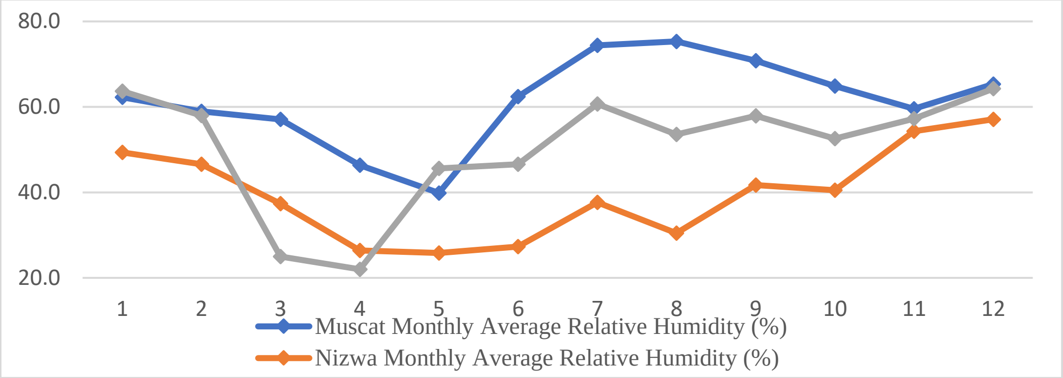


Figure 4.7 Mean RH in a typical year in Muscat, Nizwa, and Al Kamil (Directorate General of Meterorology, 2021).

Figures 4.6 and 4.7 show the mean monthly DBT and RH throughout a typical year in three locations: Muscat, Nizwa, and Al Kamil. Al Kamil is located about 6 kilometres away from Al Wafi and about 30 kilometres away from Jaalan Bani Buali. Nizwa is a mountainous area, so it features higher DBT than Muscat and Al Kamil during summer months, while it is about the same for all three locations during the rest of the year as seen in Figure 4.12. Figure 4.13 shows that there is a noticeable difference in RH between all three locations. Muscat is a coastal city which features the highest RH average especially during summer, while Nizwa has the lowest RH out of the three locations during summer months.

4.5 Socioeconomic Context and its relation to Omani Buildings

In September 1973, Allan Cain, Farroukh Afshar, and John Norton went to Oman to conduct research on the "The problems and potentials of the indigenous built environment in a developing country, Oman". They were recommended by the infamous architect Hassan Fathy. The researchers evaluated traditional buildings in various towns and villages in Oman, analysing their construction techniques and how they related to the locals' requirements.

The research project conducted fieldwork, where the researchers visited and stayed in approximately twenty towns and villages. They used a questionnaire to collect information from local craftsmen and builders, as well as residents of the dwellings under study. The researchers aimed to understand the physical, economic, and social factors that influenced the settlements and house types in each region, as well as to create a climatic profile for each region they visited.

The research found that traditional building and planning methods were still used and modified by families and craftsmen in Oman, and that these methods were closely related to the requirements of the locals, the structure of the family, and the local environment. It was also discovered that locals are increasingly opting for concrete buildings over clay buildings, which are more expensive, inefficient, and considered less suitable. It was understood that the majority intend to transfer to concrete due to "reputation" or "prestige". The research also identified the physical, economic, and social factors influencing the settlements and dwelling types in each region, as well as the evolution of these factors.

Figure 4.8: Eleven year old Salim’s drawing of his house as he perceived it back in the 1970s (Cain, Afshar and Norton, 1975).

Figure 4.9: A photo of Salim's house (Cain, Afshar and Norton, 1975).

During their visit to Nizwa, they asked a schoolboy to draw his house. As can be seen in Figure 4.8, he drew a European style house with a pitched roof. The clothing also does not represent his own clothing. This shows how much western influence a young boy had, back in the 1970s. Omanis were shifting from mud and clay buildings to concrete and steel building, which were perceived as more “prestigious.” One key takeaway from their research is that housing “should be sufficiently economical to ensure that the greatest number can afford it” (Cain, Afshar and Norton, 1975). This is a still a problem today (Heim *et al.*, 2018).

The rapid development of Oman in the 1970s has resulted in energy inefficient that require mechanical air conditioning, leading to a substantial increase in the demand for electricity (Al-Hinai ,1992). It is suggested that Oman's traditional building and planning practises be preserved and incorporated into new construction projects. Future research should focus on how traditional building and planning methods in Oman can be adapted to satisfy the changing needs of the population and the local environment, according to this research. In addition, the research suggests that research be conducted on how these methods could be implemented in other parts of the world with similar issues (Cain, Afshar and Norton, 1975).

Fathy (1986) presented a design philosophy that emphasises sustainability, cultural sensitivity, and integration with the natural environment in his Natural Energy and Vernacular Architecture book. Fathy demonstrated through his work in hot, arid climates that it is possible to design environmentally and socially responsible buildings that are also functional and aesthetically pleasing. Considering climate change and the demand for more sustainable design practises, his principles continue to influence architects and designers today. This research is very influenced by his work.

In his book, Fathy (1986) recommended several principles. The first is utilising local resources. Fathy believed that the use of locally sourced materials, such as clay, stone, and wood, was essential for the development of environmentally friendly and culturally appropriate structures. These materials are abundant in the local ecosystem, inexpensive, and have a low carbon footprint. The second principle advocated by Fathy is the use of passive cooling techniques. Fathy achieved comfortable interior temperatures in hot climates by incorporating elements that promote natural ventilation and shading, including courtyards, wind turbines, and mashrabiya screens.

The third principle recommended by Fathy (1986) is the integration with the surrounding environment. Fathy believed that buildings should be designed to function in harmony with their natural surroundings as opposed to in opposition to them. This requires design considerations for orientation, landscape, and topography. Fathy frequently incorporated water channels and gardens into his designs, which not only provided practical benefits such as shade and cooling, but also created a sense of harmony between the built environment and the natural world.

Hassan Fathy noted in his book "Architecture for the Poor" that any building material such as steel, concrete, and timber should be regarded with suspicion for Egyptian peasants (and the case in many developing countries). Building materials should be free or cheap for peasants to buy, and easily accessible (Fathy, 2000). For the case in Oman, it is confirmed by a number of studies that housing design and materials are inadequate and require improvement to become more sustainable (Alnasiri, 2016; Hegazy, 2021; Scholz, 2021).

There were several major nationwide or city specific urban strategies conducted for Oman since the 1970s. The good news is that there are set rules that can enable Oman to become more sustainable and ahead of other regions such as the building height limit restrictions, which is set to twelve floors as of 2022 (AlShueili, 2015).

Ibn-az-Zubair (2013) explained this that Oman is one of the countries that deliberately chose to preserve its ancient traditions but in a modern form. This includes the architectural aspect and the lifestyle that many people still maintain, which is characterised in some of its aspects by simplicity. One of the most important characteristics of Omani culture is the focus on the public interest, which is reflected in architecture in the human-centric buildings that meet practical needs and activities more than it is reflected in high-rise buildings intended for showing off or competition. Oman provides wonderful practical examples of modern architecture that is both innovative and strongly rooted in traditions. In the severe climate, where travelling by foot or via camel and donkey posed considerable hardship, individuals leveraged readily available materials to construct their built environment. A pivotal impact of this traditional architectural ethos on contemporary Omani buildings is the restriction of building heights to a maximum of twelve stories. This guideline aids in preserving the nation's historic essence within its urban centres, promoting a harmonious blend of the old and the new in Omani cities.

Bridging Oman's rich architectural heritage with its ambitious Vision 2040, this research navigates the intersection of tradition and modernity. While Oman's architectural ethos emphasises human-centric, practical designs, the Vision 2040 policy framework highlights the urgency of sustainable and energy-efficient designs, aligning closely with the nation's National Priorities. Oman 2040 Vision was introduced by the Government of the Sultanate of Oman in 2017. It outlined the country's top 12 priorities, which are referred to as "National Priorities" that are planned to be achieved by 2040. "Developments of Governorates and Sustainable Cities" and "Environment and Natural Resources" are two of the National Priorities (*Oman Vision 2040*, 2020). This research also aims to contribute to both these National Priorities. Creating more energy-efficient buildings would be a big step toward making cities and the environment more sustainable. This research is especially important because, as of 2023, most buildings in Oman still get subsidised electricity. However, starting from 2021, these subsidies were gradually removed until 2025, as announced on 20 December 2020 (*Oman Observer*, 2020). This is emphasising the importance of sustainable design and energy efficiency research for all types of buildings in Oman.

4.6 Vernacular architecture in Oman

The Arabian Peninsula has a harsh land and a disturbing climate. As a result, there arose a significant interest for the role of nature in life, the economical use of natural resources, and a profound understanding of all environmental factors. The experience of thousands of years has led to the honing of a traditional ability among the Arabs in dealing with nature. They possess a high competence that can indeed assist in addressing their problems, due to the insight it entails, ultimately enabling the understanding of anticipated environmental issues (Costa, 2000; Ibn-az-Zubair, 2013).

Oman was modernised late in the 1970s and 1980s. This means that traditional architecture lasted better in Oman in comparison with other Gulf countries. The main traditional building materials in Oman were mud brick, baked brick, stone, mangrove poles, palm trees, and lime (Petersen, 1996). Most of the vernacular settlements and buildings have not survived the test of time unfortunately. Mosques are an exception as they were and are continuously used and renovated (Damluji, 1998).

Mosques are built using either mud brick or rough-hewn stones. The roofs usually made of palm fronds. Minarets were rare in Oman, although it is one of the main mosques features today. Baked brick was mostly used in Sohar, and some icon buildings outside Sohar such the Great Mosque of Bahla (Petersen, 1996).

Omanis used to have winter and summer houses. The winter house had flat roofs while the summer houses had pitched roofs. Omani architecture was known for its fortified structures. Fortified structures would be either as a sur (fence) which comes in a square shape that houses a village or town, or it would be a complex structure such as a fort or castle. Mud brick was one of the most commonly used building material in Oman (Petersen, 1996).

There are several advantages for mud walls and mud roofs such as (Al Abri, 2015):

- Longevity and Self-Repair: Mud walls have a long lifespan, being able to withstand the test of time and environmental factors. They have a unique self-repairing feature where cracks that appear post-construction can heal automatically with rain, a characteristic not found in other building materials.
- Thermal Regulation: Mud walls offer thermal regulation, adapting to different weather conditions. During summer, the interior remains cool, facilitated by air circulation and numerous openings, while in winter, it

retains warmth, due to the thick walls absorbing heat, making the interior warmer than the external environment.

- Availability and Cost-Effectiveness: In the Omani environment, the materials for constructing mud houses are abundantly available, making the construction process cheaper compared to cement houses. Moreover, the mud used in previous constructions can be reused, either in new constructions or in agriculture, as it retains its quality and enriches the soil with nutrients.
- Easy Construction: Mud houses do not require foundations or pillars, making the construction process simpler and lighter compared to cement houses. The construction process is further facilitated by the availability of mud in most construction sites, reducing transportation costs and energy consumption during both the construction and usage phases.
- Environmental and Safety Benefits: Mud walls offer sound insulation and are fire-resistant, providing privacy and safety to the inhabitants. Moreover, they can be easily recycled, avoiding the accumulation of construction and demolition waste, thereby promoting environmental sustainability.

However, mud walls do also have several disadvantages such as (Al Abri, 2015):

- Water Resistance: Mud walls have a significant drawback in resisting the effects of water from rain, floods, or rising damp from the ground through capillary action. This water absorption can lead to rapid deterioration and even collapse, especially affecting the roof.
- Load-Bearing Capacity: Mud walls have a relatively low load-bearing capacity, making them unsuitable for supporting heavy roofs. This limitation restricts the architectural designs and structures that can be achieved with mud walls.
- Erosion and Maintenance: Mud walls are highly susceptible to erosion due to various environmental factors such as rain, wind carrying sand, and usage wear and tear, necessitating continuous repair and maintenance to maintain their durability. This ongoing requirement can potentially increase the long-term costs associated with mud buildings.

In addition to the building envelope, windows in Oman were carefully designed to to allow breezes from the sea to cool the interior space. The windows were shaded and had gypsum lattice screens to allow for breezes to come in while minimising solar heat gain. The evaporative cooling system was another passive cooling method used in Muscat. In the window openings that air entering the room would pass over, porous water jars were positioned. The water on the surface began to evaporate as the air passed over it, absorbing heat energy in the process. This cooled the air and produced a supply of cool water in the jar itself for drinking. It can lower the internal temperature by up to 10 °C, according to tests (Damluji, 1998).

4.6.1 Thermal Comfort in Oman

Thermal comfort in modern Oman is reliant on air conditioning systems, a shift that contrasts with the country's rich history of vernacular architecture designed for passive cooling. In a survey, it was found that the majority of residents preferred a thermostat setting between 20 and 22 °C (Majid *et al.*, 2014), while the temperature inside government buildings is set at about 22 °C (Al-Saadi *et al.*, 2017). On the other hand, a pilot measurement study in Oman found that 24 °C is thought to be the ideal thermostat set point to achieve thermal comfort (Al-Saadi and Shaaban, 2019).

There were several studies conducted to investigate how thermal comfort is achieved in vernacular buildings in Oman. There are features that improved the thermal comfort of old buildings but could apply to new buildings. Oman having had mass modernisation in 1970 it began to depend on active air conditioning systems, which made buildings built afterwards less efficient. Buildings built before this period were built to be passively thermally comfortable. Passive thermal comfort was achieved by building’s design, orientation and construction materials (Al-Hinai, Batty and Probert, 1993). Compact patterns of settlement and courtyards are two examples from the vernacular architecture in Oman that could improve thermal comfort in buildings. On the other hand, rapid modernisation in Oman in the 1970s led to the usage of mechanically insufficient air conditioning systems in concrete buildings (Taylor *et al.*, 2009).

4.7 Conclusion

The geographical, geological, and climatic details of Oman have historically dictated a vernacular architectural style that is both sustainable and harmonious with the environment. The exploration of Oman's diverse landscapes, from the series of mountains to the expansive deserts and coastal areas, highlights the rich variety of influences that have shaped Oman’s built environments.

Coping with the urgent need to reduce energy consumption and carbon emissions, the lessons derived from Oman's traditional architectural practices present a viable pathway. Oman’s hot climate, which ranks among the most extreme globally, further stresses the pressing necessity to adopt passive strategies to limit electricity usage. This research has a pivotal role in this context, aiming to reintroduce vernacular architecture methods with a keen focus on thermal performance and sustainability. It predicts putting vernacular architectural features to the test in contemporary buildings, encouraging buildings that are in tune with the environment while being energy efficient. The utilisation of locally available materials and the adoption of construction techniques optimised for thermal comfort stand as a testament to the wisdom embedded in Oman's architectural heritage. Moreover, the emphasis on passive cooling strategies, as highlighted in the works of renowned scholars such as Hassan Fathy, offers a blueprint for contemporary architects to encourage buildings that resonate deeply with the cultural and historical context of Oman while championing energy efficiency.

By encouraging a deep understanding of the vernacular architecture in Oman, the initiative aspires to lead a movement towards a more sustainable and environmentally conscious architectural landscape. It indicates a future where the architectural endeavours are not just a reflection of Oman's storied past but an inspiration of innovation, uniting tradition with modernity to carve out a sustainable path forward, where the buildings of tomorrow harmonise with the natural surroundings, offering thermal comfort while reducing energy consumption and celebrating Oman's rich architectural heritage.

Chapter 5. METHODOLOGY

5.1 Introduction

This chapter outlines the detailed process undertaken to address the research questions. The spotlight is on the two main research methodologies that have been utilised: field measurement and computer simulation. The research is anchored in the analysis of six mosque buildings in Oman, carefully chosen to represent a variety of characteristics. The study spans both the winter and summer seasons, aiming to the two extreme climatic conditions. The methodologies are explained, offering insights into the various stages involved, from the selection of case studies to the processes of data collection and analysis. This approach ensures a structured and systematic exploration, leading to results that are both reliable and grounded in empirical evidence.

5.2 Research methodology

The research methodology employed in this research consists of two main parts: Computer Simulation (CS) and Field Measurement (FM). This research is categorised both as simulation research and as correlational research. It involves using EDSL Tas software to create energy models of six mosques of varying sizes It could also be considered a correlational research as it attempts to study the relationships between the different energy models (computer simulation) and the real world data (field measurement) (Groat and Wang, 2013).

In this research, six different case studies are discussed thoroughly. Multiple case studies from the same building type (in this case six mosque buildings of different characteristics) decreases the chance of errors, validates the results, and creates a more robust research. A multi-method approach on these multiple case studies further validates the data and it is believed to provide “appropriate checks against the weak points in each, while simultaneously enabling the benefits to complement each other” (Groat and Wang, 2013).

5.3 Research workflow

Figure 5.1 shows a chart showing the general stages of the research process.

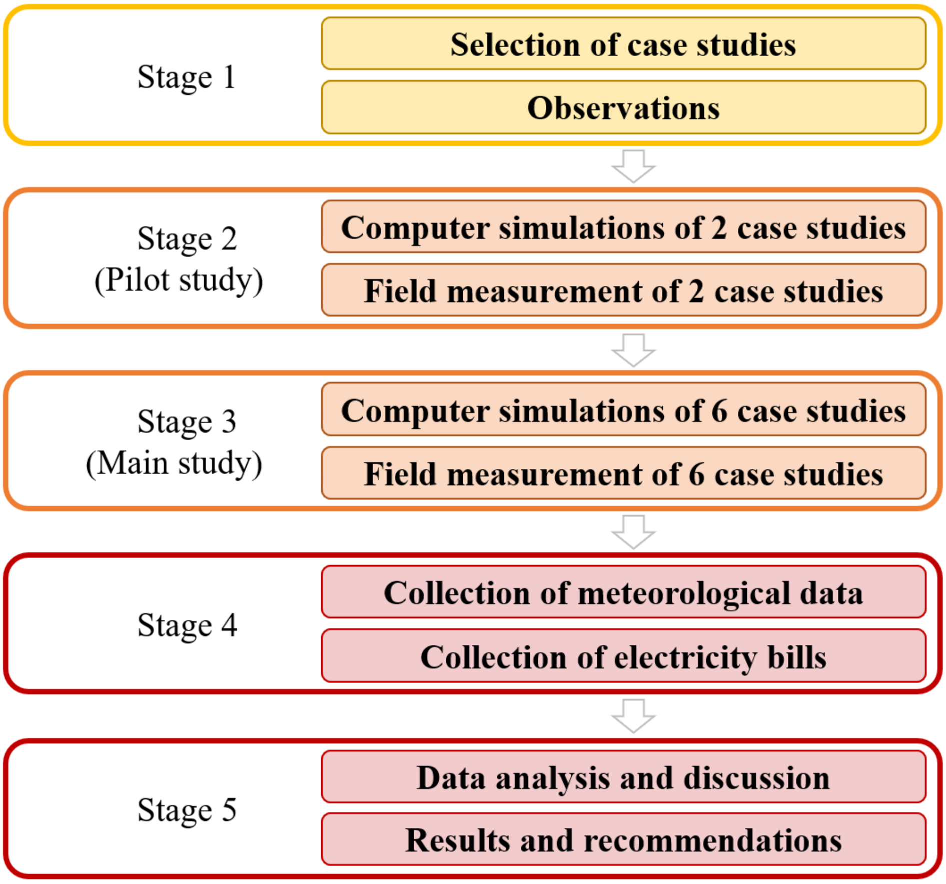


Figure 5.1: Research process

5.3.1 Stage 1: Selection of case studies and observations

The first stage of the research methodology includes the selection of the case studies and observations. Since the research focuses on mosques, the research would take six mosques as case studies. Three mosques are recently built, while the other three are 500 years old or more mosques, which are outlined in Table 6.1. The assessment of the two sets of mosques from two different eras could create new knowledge in the field of building energy efficiency in Oman. Energy modelling all six mosques could lead to possibilities of using old traditional methods in new buildings to improve the architectural construction and design and arrive to recommendations implementable in different types of buildings not restricted to mosques. There are more than 16,000 mosques in Oman (Times News Service, 2018). Increasing their energy efficiency would greatly contribute to much needed reduction of energy consumption in mosque buildings, and potentially other buildings.

During Stage 1, observations form an integral component of the research methodology. Each case study mosque is not merely visited but subjected to a comprehensive examination. Photographic documentation is conducted to capture all relevant building elements, providing a visual record that complements other forms of data collection. To gain an authentic understanding of the user experience, extended periods are spent within each mosque, engaging in prayer, as an occupant would. This immersive approach facilitates meaningful interactions with both the occupants and the management of the mosques. Through these engagements, valuable insights are gathered about the buildings' characteristics and the challenges they may be encountering. This observational strategy improves the depth and breadth of the study, ensuring a deep understanding of each case.

5.3.2 Stage 2: Pilot Study

The second stage of the research methodology is the pilot study stage, which was conducted in September 2020. Computer simulations were conducted for Al Wafi and Hudhayfah mosques. Field measurements were also conducted for both mosques for a period of 72 hours each. The field measurement comprised of humidity, outdoor and indoor dry bulb temperature measurements.

During the pilot study, it was learned more about the tools used and how to properly make the field measurements. It was also a way to see how stakeholders react to the research being done. The worshippers and the management of the mosques were accommodating and helped throughout the process.

5.3.3 Stage 3: Main Study

The third stage is the main study stage of the research. Integrating the lessons learned from the pilot study and literature review, the researcher can conduct the main study for all six mosques using both computer simulations and field measurements. For more information about the Field Measurement, refer to Section 5.6 and Chapter 6. For more information about the Computer Simulation refer to Section 5.7 and Chapter 7.

5.3.4 Stage 4: Collection of meteorological data and electricity bills

The fourth stage comprises of electricity bills and meteorological data collection. Electricity bills can be used to validate the computer simulation and field measurement results. Meteorological data such as DBT and RH are essential in the data analysis, which come in the fifth stage followed by results, recommendations, and conclusions.

5.3.5 Stage 5: Data analysis, Discussion, Results, and Recommendations

The fifth and final stage of this research includes data analysis, discussion, results, and recommendations. The results are shown of each mosque from winter and summer. The results are discussed and compared between winter and summer and between each mosque. Then comparisons are made between the two main research methodologies of computer simulation and field measurement. This gave a good foundation to make improvements to the case studies.

5.4 Case studies selection

In order to analyse the thermal performance and thermal comfort of contemporary and traditional mosques in Oman, it is necessary to select both contemporary and traditional mosques as case studies. The following criteria were established for the case selection process:

- Proximity to Muscat and Al Wafi: It was essential to choose mosques that are close to the researcher's hometown, Muscat, or his relatives in Al Wafi. This will reduce transportation costs, as frequent visits will be required throughout the research for observations and field measurements.
- Contemporary and traditional mosque types: Both contemporary and traditional mosque types need to be included. Contemporary mosques refer to those built with brick and concrete in the last forty years, while traditional mosques refer to those constructed with clay and have a history of at least five hundred years.
- Size: Selecting mosques of varying sizes for each type would provide a more representative sample of the overall mosque population.
- Access: Ease and approval of access is crucial, especially outside prayer hours.

Based on the case studies selection criteria, a total of six mosque buildings were selected as case studies. The selected six mosques are outlined in Table 5.1. The first three mosques are all contemporary recently built mosques located about 2 kilometres from each other in the same city, Muscat. The fourth mosque, Sa’al Mosque, is a historical mosque built in 1252 AD in Nizwa, which is a historic city known of its traditional buildings. The fifth mosque is Al Wafi mosque built about 400 years ago in

Al Wafi village, which is located about 250 kilometres away from Muscat. The sixth mosque is Aal Hamoodah Mosque also built about 400 years ago in Jaalan Bani Bu Ali, which is about 275 kilometres away from Muscat, and about 25 kilometres away from Al Wafi. Al Wafi and Aal Hamoodah Mosques were renovated several times ever since they were built. A major restoration was conducted for both mosques in 1990 (Biancifiori, 1994). Refer to Figure 5.3 for the location of Muscat, Nizwa, Al Wafi, and Jaalan Bani Bu Ali. The first three mosques (M1, M2, and M3) are all contemporary mosques recently built between 1990 and 2015. They feature the current main method of construction employed in the Oman using concrete and steel. The other three mosques (M4, M5. M6) were all built more than 400 years ago. Their construction method was primitive and used clay, mud, and stones as the main construction materials.

Table 5.1: A list of selected mosques for the case study

No.		**Mosque's picture**	**Mosque's name**	**Location**	**Year Built**	**Area (m^2)**	**Number of worshippers**
M1	Contemporary mosques		Hudhayfah Bin Alyaman Mosque	Muscat, Oman	2015	1120	1100
M2			Abu Hamza Al Shari Mosque	Muscat, Oman	1994	727	730
M3			Othman bin Afan mosque	Muscat, Oman	1990	466	470
M4	Traditional mosques		Sa'al Mosque	Nizwa, Oman (150 km from Muscat)	1252 AD	256.3	324
M5			Al Wafi mosque	Al Kamil Wal Wafi, Oman (250 km from Muscat)	1600s	470	462
M6			Aal Hamoodah Mosque	Jaalan (250 km from Muscat)	1600s	735	730

5.5 Field measurement

The field measurement methodology employed is using thermal instruments to measure the thermal properties of mosque buildings to investigate the thermal performance in buildings in Oman. Three traditional and three contemporary mosques of varied sizes are studied and compared thoroughly from a thermal performance point of view.

To thoroughly analyse the six mosques, the following parameters are measured, air temperature, humidity, globe temperature, surface temperature, and air velocity are measured (Nicol, Humphreys and Roaf, 2012) (ASHRAE, 2020).

A pilot field measurement was conducted for two mosques (a traditional and a contemporary mosque) in September 2021. The main winter field measurement for all six mosques was conducted in December 2020 and January 2021, while the main summer field measurement for all six mosques was conducted in May 2021. A second winter field measurement was conducted in December 2021 and January 2022 to make spot measurements as these were not taken during the first winter field measurements.

5.5.1 Selection of instruments

There are several considerations that should be taken when taking physical measurement using thermal instruments. Using a datalogger makes physical measurements easier and non-intrusive, and more accurate. Taking manual measurements could be intrusive, less accurate, and time consuming. A thermometer should be placed not less than half a metre away from any wall. If measured inside the room, it is better to measure the air temperature on more than on point. One point of which should be at least should the centre of the room. Settling time is different between instruments and should be taken under consideration. Humidity does not vary greatly from point to point inside a room, which means taking one measurement should be sufficient (Nicol, Humphreys and Roaf, 2012).

- **Air temperature and humidity**

Temperature probes respond to both heat through convection and radiation. The effect of heat radiation on the temperature probe needs to be minimized to give a more accurate air temperature. When measuring air temperature, it is also important to consider its vertical layering. Air temperature could be different near the floor from near the ceiling, which means it is recommended to take the measurement at a point at half the height of a seating or standing person depending on the research conditions. For example, half the height of a seating person on a chair would be approximately 0.6 metres (Nicol, Humphreys and Roaf, 2012).

- **Globe temperature**

Globe thermometers use a black sphere (usually 40mm in diameter) to measure globe temperature. Globe thermometers react to the surrounding environment similar to a human body (Nicol, Humphreys and Roaf, 2012).

- **Surface temperature**

Surface temperature can be measured using an infrared thermometer. This is useful in this research to measure the inside and outside surface temperatures of the walls and ceilings (Slávik and Čekon, 2016).

- **Air velocity**

Air movement could be minimal in an enclosed space but could be measured initially using a smoke puffer to recognise any droughts or air movements. Any air movement below 0.1 m/s is considered insignificant (Nicol, Humphreys and Roaf, 2012).

The instruments chosen are detailed in Table 5.2, which displays five different types of instruments, accuracy, quantity, measured parameter, and cost without shopping for each device. The selection of the instruments was based on the research's requirements, considerations, and a budget of 1000 GBP, which includes the cost of the instruments, shipping, and travel. The instruments cost 553.14 GBP which include shipping. The total cost of travel, including accommodation, transportation, and an airline ticket, is approximately 446.86 GBP.

Table 5.2: A list of instruments used in the field study (Alwetaishi, 2015; Shohan and Gadi, 2015)

Name	Instrument manufacturer and model	Accuracy	Quantity	Measured parameter	Cost without shipping for each device
USB temperature and humidity data logger	CEM DT-172	±1 °C Ta ±3.5% RH	4	Temperature and humidity	62.39 GBP
WBGT meter	Extech HT30	±2 °C WBGT ±2 °C Tg ± 1 °C Ta ±3% RH	1	Globe temperature	116.77 GBP
Infrared thermometer	CEM DT-8862	±1% T	1	Surface temperature	24.57 GBP
Hot wire anemometer probe	Testo 405i	±(0.1 m/s + 5 % of measured value) (0 to 2 m/s) ± (0.3 m/s + 5 % of measured value) (2 to 15 m/s)	1	Air velocity and direction	73.57 GBP
External THERMO Hygrometer with external sensor	TECPEL DM-303	+-1 °C T +-5% RH	1	Humidity	13.67 GBP
Laser meter	Leica D810	±1% distance measurements	1	Distance	Gifted
TOTAL					478.14 GBP

5.5.2 Instruments accuracy and calibration

Details about each instrument accuracy is mentioned in Table 6.2. As a general rule, temperature, RH, and air velocity instruments need to have accuracies of ±0.5, ±5%, and ±10%, respectively (Nicol, Humphreys and Roaf, 2012). As per Table 6.2, all the instruments meet this general rule except for the data logger that has an accuracy of 1%. This can be mitigated by taking multiple measurements simultaneously and accounting for accuracy during data analysis. All temperature, humidity, and air velocity instruments were bought new and calibrated by the manufacturer.

5.5.3 Preparation and administration

There were a series of steps taken to ensure a well-prepared field measurement trip. First, approval was requested from the Ministry of Endowment and Religious Affairs, which cordially granted the approval of the field measurement trip and the research for all six mosques.

After securing institutional approval, site visits were conducted at each mosque to gain verbal consent from their respective management teams. During these visits, detailed briefings were provided about the logistics of deploying field measurement instruments, and schedules were coordinated to minimise disruptions to regular activities.

Given the security concerns, special attention was paid to risk mitigation. The mosques were locked outside prayer times, thereby reducing the likelihood of unauthorized access to the instruments. During prayer times, the researcher was present to engage with the community and oversee the data collection process.

On the designated day of field measurement, data loggers were strategically placed within each mosque. A suite of instruments—including an infrared thermometer, globe thermometer, and hot air anemometer—were deployed post-prayer to avoid inconveniencing worshippers (Figure 5.2).

Figure 5.2: Instruments used during the field measurement

The data loggers were left for a period of 48 hours and were periodically checked during prayer times to ensure their proper functioning (Figure 5.3). Upon the completion of this period, the data loggers were retrieved, data integrity was verified, and the researcher proceeded to the next mosque for a similar cycle of measurement (Figure 5.4).

Figure 5.3: Two photos showing where the two first instruments where place inside M1's main prayer hall

Figure 5.4: Two photos showing instruments are used. The WBGT meter in M2 (left), and the laser meter in M3 (right).

5.5.4 Pilot field measurement (September 2020)

A pilot field measurement survey was conducted on two mosques: M1 (Hudayfah Mosque) and M5 (Al Wafi Mosque) as per the start and end times outline in Table 5.3. The pilot field measurement was carried out using a total of four data loggers. Figure 5.10 shows where the temperature and humidity data loggers were placed. This is an addition to one data logger that was placed outside the mosque to measure external dry bulb temperature.

Table 5.3: Pilot field measurement schedule

No.	Mosque's name	Field measurements start time	Field measurement end time
1	Hudhayfah Bin Alyaman Mosque	15:43 8 September 2020	15:40 11 September 2020
5	Al Wafi mosque	19:10 12 September 2020	18:42 15 September 2020

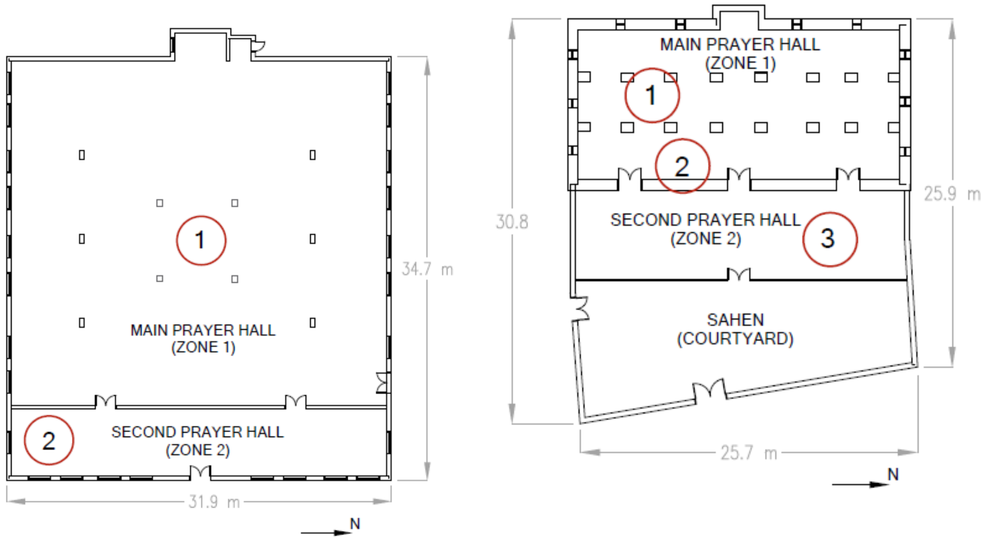


Figure 5.5: Mean ambient air temperature in a typical year in Muscat, Oman. Locations of the instruments placed during the pilot study in (left) Hudhayfah Mosque and (right) Al Wafi mosque.

5.5.5 Winter field measurement (December 2020 to January 2021)

The main instruments used for the first winter field measurement were temperature and humidity data loggers (CEM DT-172). Spot measurements (globe temperature, surface temperature, and air velocity) were not taken during this field measurement, but instead they were taken during the following winter (see section 5.5.7).

Two of the internal data loggers were placed in the main prayer hall (Zone 1) of each mosque, while the third data logger was placed in secondary prayer hall (Zone 2) of each mosque. The fourth data logger was placed outside the mosque to measure external dry bulb temperature. The winter field measurement was conducted for all six mosques as per the schedule in Table 5.4.

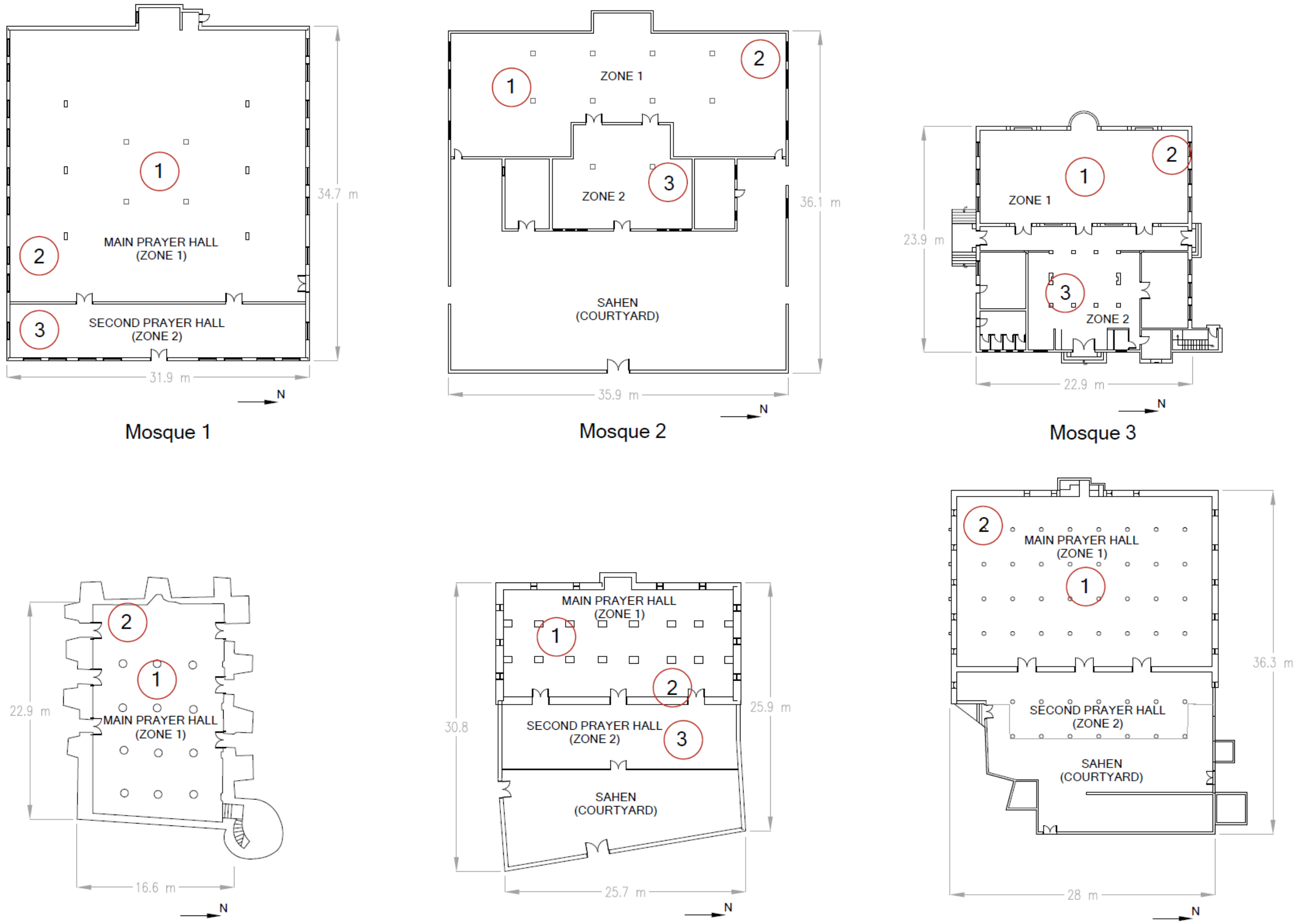
Table 5.4: Internal winter field measurement schedule

No.	Mosque's name	Field measurements start time	Field measurement end time
1	Hudhayfah Bin Alyaman Mosque	12:40 24 December 2020	12:13 27 December 2020
2	Abu Hamza Al Shari Mosque	12:41 27 December 2020	12:38 30 December 2020
3	Othman bin Afan mosque	15:36 30 December 2020	12:37 2 January 2021
4	Sa'al Mosque	14:58 2 January 2021	16:05 5 January 2021
5	Al Wafi mosque	19:28 5 January 2021	12:42 8 January 2021
6	Aal Hamoodah Mosque	15:52 8 January 2021	15:49 10 January 2021

The monitoring of external DBT and RH was ongoing simultaneously with the internal monitoring as per the schedule outlined in Table 5.5. The locations of the instruments are shown in Figure 5.6.

Table 5.5: External winter field measurement schedule

No.	City	Field measurements start time	Field measurement end time
1	Muscat	11:38 24 December 2020	14:00 5 January 2021
2	Al Wafi	20:37 5 January 2021	14:46 10 January 2021



Mosque 1 Mosque 2 Mosque 3

Mosque 4 Mosque 5 Mosque 6

Figure 5.6: Locations of the instruments during the main winter and summer field measurement

5.5.6 Summer field measurement (May 2021)

The summer field measurement was conducted for all six mosques as per the schedule in Table 5.6 for internal measurements and Table 5.7 for external measurements. Spot measurements (globe temperature, surface temperatures, and air velocity) were taken as part of this field measurement.

Table 5.6: Internal winter field measurement schedule

No.	Mosque's name	Field measurements start time	Field measurement end time
1	Hudhayfah Bin Alyaman Mosque	12:53 on 15 May 2021	11:42 on 17 May 2021
2	Abu Hamza Al Shari Mosque	12:06 on 17 May 2021	11:44 on 19 May 2021
3	Othman bin Afan mosque	12:35 on 19 May 2021	11:35 on 21 May 2021
4	Sa'al Mosque	14:50 on 21 May 2021	13:29 on 23 May 2021
5	Al Wafi mosque	12:43 on 24 May 2021	11:16 on 26 May 2021
6	Aal Hamoodah Mosque	12:38 on 26 May 2021	11:40 on 28 May 2021

Table 5.7: External winter field measurement schedule

No.	City	Field measurements start time	Field measurement end time
1	Muscat	11:24 on 15 May 2021	12:02 on 21 May 2021
2	Nizwa	18:32 on 21 May 2021	13:13 on 23 May 2021
3	Al Wafi	13:49 on 24 May 2021	12:25 on 28 May 2021

5.5.7 Winter field measurement 2 (December 2021)

A second winter field measurement was conducted for all six mosques as per the schedule in Table 5.8. This field measurement included only the spot measurement (globe and surface temperatures).

Table 5.8: Second winter field measurement schedule

No.	Mosque's name	Field measurements start time	Field measurement end time
1	Hudhayfah Bin Alyaman Mosque	13:08 on 18 December 2021	06:30 on 19 December 2021
2	Abu Hamza Al Shari Mosque	15:16 on 18 December 2021	06:10 on 19 December 2021
3	Othman bin Afan mosque	06:07 on 18 December 2021	18:30 on 18 December 2021
4	Sa'al Mosque	-	-
5	Al Wafi mosque	19:28 on 5 January 2021	12:42 on 8 January 2021
6	Aal Hamoodah Mosque	15:52 on 8 January 2021	15:49 on 10 January 2021

5.5.8 Guidelines followed during the field measurement

A number of guidelines were followed throughout the field measurement process. Measurements were taken 0.6 metres above floor level to represent a waist level of a seated person as per the ASHRAE Standard 55 (ASHRAE, 2020). The instrument was placed at the centre of the mosque which should be the most representative sample as most worshippers are away from the walls. The dataloggers were set up to take one measurement every 60 seconds.

For air temperature and humidity measurement, a total of four data loggers were used. One datalogger measured external DBT and RH, while the other three measured internal DBT and RH. The three dataloggers were place as such the first datalogger is the centre of the main prayer hall, the second datalogger is at the right or left end of the main prayer hall, and the third data logger is placed at the centre of the second prayer hall.

Pictures were taken of inside and outside the mosque. Air velocity, MRT, and globe temperature measurements were taken once after every prayer during the second field measurement day of each mosque. Surface temperature was measured for the internal and external surfaces of the four walls of each main prayer hall.

5.5.9 Limitations and issues faced during the field measurement

A number of limitations and issues were faced throughout the field measurement process. Most mosques have an inconsistent schedule of air conditioning. This could have affected the field measurements in some way due to the unpredictability of the air conditioning schedule and occupants' behaviour. This was also an issue for computer simulations as it was that there were two periods of air conditioning, the first from 3:00 to 5:00, the second from 12:00 to 21:00 (refer to section 5.8 for more about the computer simulation methodology).

The pilot study was conducted in September 2020 when mosques were closed and not occupied due to the COVID-19 pandemic regulations at the time. Mosques re-opened with limited occupancy by November 2020. The prayers were restricted to 25 minutes from start to finish as per Omani covid-19 regulations of 10 November 2020 (Oman News Agency, 2020). Both winter and summer field measurements were conducted on the mosques whilst they were under limited occupancy.

M1's AC was continuously on for twenty-four hours a day, while M3's and M4's AC were continuously off due to Covid-19 regulations at the time. M2, M5, and M6 had DX split unit AC systems which had a different schedule every day depending on the occupant's thermal comfort.

This does not exactly represent the pre-covid situation as mosques had less than 50% of its regular occupancy. On a positive note, the research itself was easier to conduct. It was not necessary to monitor the instruments all the time as the mosques closes between prayers. It only opens for a period of about 30 minutes for each prayer. This means the total daily occupancy duration of mosques has fallen from 15 hours pre Covid-19 to around 4 hours after Covid-19.

5.6 Computer Simulation

Building energy modelling and computer simulation can be used for a variety of purposes, including construction and research. All stakeholders involved in the building simulation process must agree on a performance criterion with clearly defined measures. Figure 5.7 shows the performance criterion in the centre of the diagram. After the simulation is completed, the results can be compared to the performance measures to generate a set of recommendations for the building's stakeholders (Hensen and Lamberts, 2011).

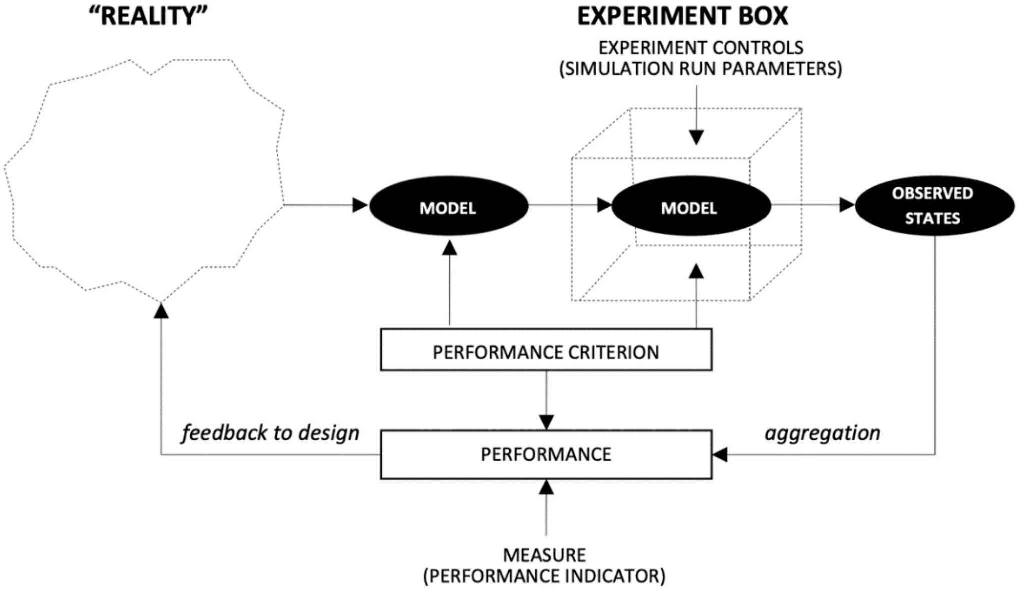


Figure 5.7: A building simulation process (Hensen and Lamberts, 2011).

5.6.1 Selection of computer simulation programme

There is a wide range of thermal comfort software available, including EDSL's Tas Engineering, IES VE, Ecotect, EnergyPlus, and Design Builder. Tas Engineering software, an energy computer simulation software, was used as the research methodology in this study. Tas Engineering software specialises in dynamic thermal performance simulation of buildings and their systems. It estimates energy demand and the resulting internal temperatures and humidity by using a three-dimensional (3D) model and integrating it with natural and forced air flow as well as HVAC systems. It takes into account both dynamic parameters such as air flow and static parameters such as building material thermal capacity (Crawley *et al.*, 2008). Tas Engineering software was used for this study because it was deemed most appropriate for the purposes of this study. It is simple and provides enough tools to investigate the various areas of a building's thermal properties. (EDSL, 2021) (Rotimi *et al.*, 2017).

The computer simulation process mainly consists of (Al Rasbi and Gadi, 2021):

1. Three-dimensional (3D) modelling the building
2. Setting the location and weather data.
3. Assignment of construction materials.
4. Setting internal gains and conditions.
5. Building thermal simulation.
6. Simulation results analysis.

The computer simulation has been completed using EDSL’s Tas Engineering software (version 9.5.1, Environmental Design Solutions Ltd, Milton Keynes, United Kingdom) (EDSL, 2021). Hourly data were analysed during winter design day (day 20) and summer design day (day 179) for all six mosques. Winter design day and summer design day are the minimum and maximum dry bulb temperature days, respectively, based on Muscat International Airport meteorological TMY file.

5.6.2 Software learning and training

After selection of the software to be used, self-learning and training was conducted in order to become competent using the EDSL Tas software. Part of the process was conducting a competency check by using the software on an already published paper. A journal paper by Resuli and Dervishi (2015) was selected. The check resulted in a match between end simulated results and the published results.

A 3-day specialised Tas Engineering Course was (being) completed from 24 to 26 October 2022. The course covered the best practice using the software and its various functions (‘Training’, 2022).

5.7 Pilot computer simulation

The first two mosques, Hudhayfah Mosque (Mosque 1) and Al Wafi Mosque (Mosque 5), computer simulations were conducted as part of the journal paper which was published on 20 July 2021. The paper directly compared between a contemporary mosque, Hudhayfah Mosque, and a traditional mosque, Al Wafi Mosque. The comparison was in terms of dry bulb air temperature and thermal loads. The result of the study showed that the design and construction of a traditional mosque building perform better in a free-running setting. On the other hand, the contemporary mosque achieved less cooling load demand per area (Al Rasbi and Gadi, 2021).

5.8 Input Data

5.8.1 Calendar

The climate in Muscat, Al Wafi, Jaalan, and Nizwa has two seasons: summer and winter. For the purposes of this simulation, the winter season was defined as beginning on November 1 and ending on February 28, while the rest was considered the summer season. The buildings in this simulation were free-running in the winter and air-conditioned in the summer.

5.8.2 Weather Data

The weather data used for all six mosques were Typical Metrological Years (TMY) files in EPW weather format for Muscat International Airport region. The weather data was derived from the period 2004 to 2018(Climate.OneBuilding.Org, 2020; Al Rasbi and Gadi, 2021).

5.8.3 Orientation

All mosques are oriented towards the *Qiblah* (Direction towards the Kabaah), which makes all six mosques' orientation towards the west (Azmi and Ibrahim, 2020; Al Rasbi and Gadi, 2021).

5.8.4 Height

The roofs of the six mosques differ in height and shape. The three modern mosques (M1, M2, and M3) feature a standard Qubba, while Al Wafi and Aal Hamoodah mosques feature arched roofs. Sa'al mosque has a flat roof. The maximum heights of the prayer halls and domes or arches are outlined in Table 5.9.

Table 5.9: Heights and roof types of the six mosques

Mosque name	Main prayer hall height (metre)	Dome/arch height (metre)	Roof type
Hudhayfah Bin Alyaman Mosque	4.2	9	Qubba (Dome)
Abu Hamza Al Shari Mosque	4.3	8.2	Qubba (Dome)
Othman bin Afan mosque	4.1	10.3	Qubba (Dome)
Al Wafi mosque	3.5	5.5	Arched roof
Aal Hamoodah Mosque	3.33	5.95	Arched roof
Sa’al Mosque	5.9	Flat roof	Flat roof

5.8.5 Fenestration

All three modern mosques use double-glazed windows with aluminium frames, while the three traditional mosques have single-glazed windows with timber frames.

5.8.6 Internal Gains

Some buildings in Oman have cooling air conditioning active even during the winter (Al-Saadi *et al.*, 2017). Air conditioning is assumed to be used throughout the year except the winter for five mosque buildings (M2, M3, M4, M5, and M6) are considered free running (from 1 November until 28 February). M1’s AC is active throughout the year. Air conditioning is used for cooling only, so it is assumed no active heating throughout the year.

Mosques are used intermittently, five times a day. The air conditioning is assumed to be running for 24 hours for Mosque 1 as it has a packaged unit system and it needs to run at a lower wattage overnight for maintenance purposes as per the mosque management. Mosque 2, Mosque 5, and Mosque 6’s air-conditioning are assumed to run for two periods. The first period is from 3:00 until 5:00 for the fajr prayer. The second period covers four prayer congregation times, which is from 12:00 until 21:00. Mosques 3 and 4 are assumed to be free-running throughout the year as they are unoccupied. Table 5.10 shows the typical daily prayer times during the day. Each prayer lasts for about 30 minutes, except for Friday congregational prayer which lasts for about 90 minutes (Azmi, Arıcı and Baharun, 2021; Al Rasbi and Gadi, 2021).

Table 5.10: Daily prayer times in Muscat, Oman (*Ministry of Endowments and Religious Affairs*, 2021).

Prayer Sequence during the Day	Prayer Name	Time Held	Prayer Start Time Range (Varies Throughout the Year)
First prayer	Fajr Prayer	Before sunrise	3:52 am–5:32 am
Second prayer	Dhuhr Prayer	At noon	11:55 am–12:26 pm
Third prayer	Asr prayer	Afternoon	3:04 pm–3:45 pm
Fourth prayer	Maghrib prayer	After sunset	5:24 pm–7:03 pm
Fifth prayer	Isha prayer	Night-time	6:39 pm–8:25 pm

Table 5.11: Summary of internal conditions inputs into TAS software for all six mosques

Internal Conditions Inputs	M1	M2	M3	M4	M5	M6
Lighting Gain (W/m2)	17	17	17	0	17	17
Occupancy Sensible Gain (W/m2)	7	8.9	0	0	22	11
Occupancy Latent Gain (W/m2)	3.8	4.8	0	0	12	5.8
Equipment Sensible Gain (W/m2)	0	0	0	0	0	0
Equipment Latent Gain (W/m2)	0	0	0	0	0	0
Metabolic rate (W/p)	130	130	130	130	130	130

A summary of the internal conditions inputs into TAS software for all six mosques are shown in Table 5.11. Lighting Gain (W/m^2) assumed to be 16.5 W/m2 based on 2013 ASHRAE Handbook for religious buildings/audience seating. Occupancy Sensible Gain (W/m^2) assumed to be 7 W/m^2 based on 2013 ASHRAE Handbook for seated, very light work. Occupancy Latent Gain (W/m^2) assumed to be 3.8 W/m^2 based on 2013 ASHRAE Handbook for seated, very light work. No equipment loads assumed inside the mosques, as all equipment is located outside. Any other equipment considered to generate negligible internal equipment loads. Metabolic Rate (W/p): Metabolic rate assumed to be 130 W per male occupant based on 2013 ASHRAE Handbook for seated, very light work (ASHRAE, 2013).

5.8.7 Cooling

The Hudhayfah mosque has a DX roof top packaged units for air conditioning, while all the other five mosques utilize a DX split unit system, which are considered the most common air conditioning type in Oman (Krarti and Dubey, 2017). Hudhayfah mosque’s DX roof top packaged unit introduces 10% fresh air, while the other mosque’s DX split unit systems do not introduce fresh air. For the purposes of this research, it is assumed that all mosques studied have an infiltration of 0.5 air change per hour.

5.8.8 Thermostat setpoint

It is noted that according to a survey conducted most occupants in residential buildings preferred a thermostat setpoint between 20 and 22 °C (Majid *et al.*, 2014), while the government buildings’ thermostat setpoint is around 22 °C (Al-Saadi *et al.*, 2017). On the other hand, 24 °C is considered to be the optimal thermostat set point to achieve thermal comfort according to a pilot measurement study in Oman (Al-Saadi and Shaaban, 2019). For the purposes of this simulation, the thermostat setpoint for the air-conditioning system is set at 23 °C and is set for cooling from 1 March to 31 October. The buildings are considered as naturally ventilated for the rest of the year.

5.9 Case studies selected

5.9.1 Hudhayfah Bin Al Yaman Mosque (M1)

The Hudhayfah bin Al Yaman Mosque was built in 2015 in Muscat, the capital of the Sultanate of Oman. It will be referred to Hudhayfah Bin Al Yaman Mosque throughout this dissertation as Mosque 1 or M1. The area is 1120 m^2 and fits a maximum of 1100 worshippers. Figure 5.8 shows the Hudhayfah Mosque ground floor plan drawing. Figure 5.9 show different Three-dimensional (3D) views from the TAS software and Figure 5.10 shows different photos of the mosque from the inside and the outside. Table 5.11 lists the construction details of the Hudhayfah mosque's building elements. Figures 5.11 and 5.12 show the cross-sectional details for the external walls and roof, respectively. It features a typical construction detail found in most recent buildings in Oman. A typical window size in Hudhayfah Mosque is 1.9 metres by 2.54 metres, while a typical door is 2.4 metres wide by 3 metres high.

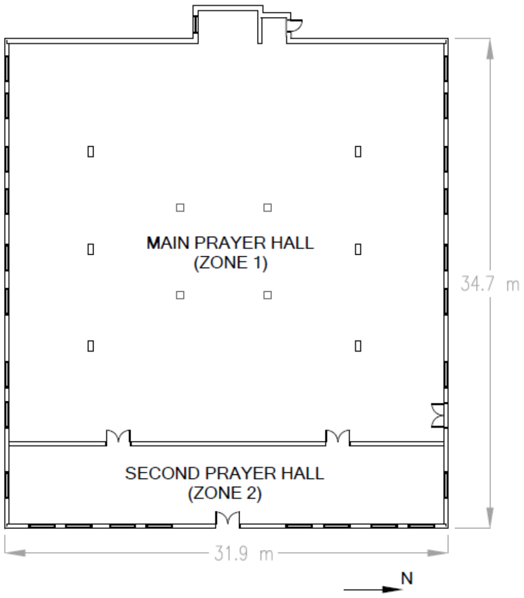


Figure 5.8: Ground floor plan of M1.

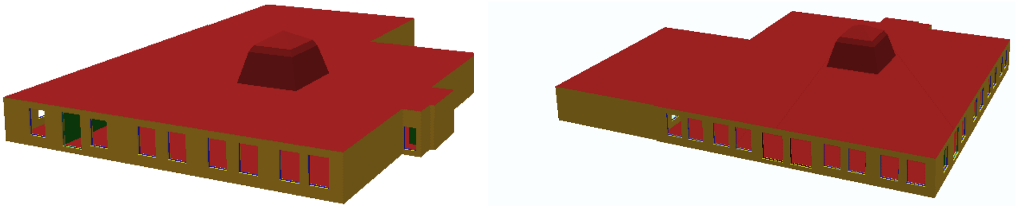
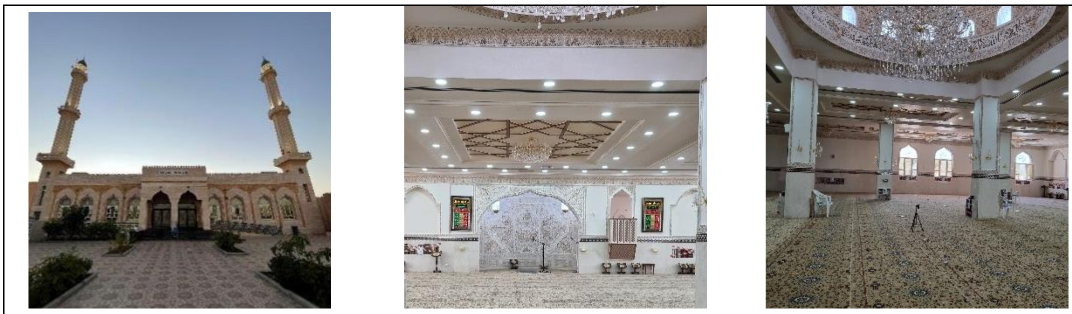


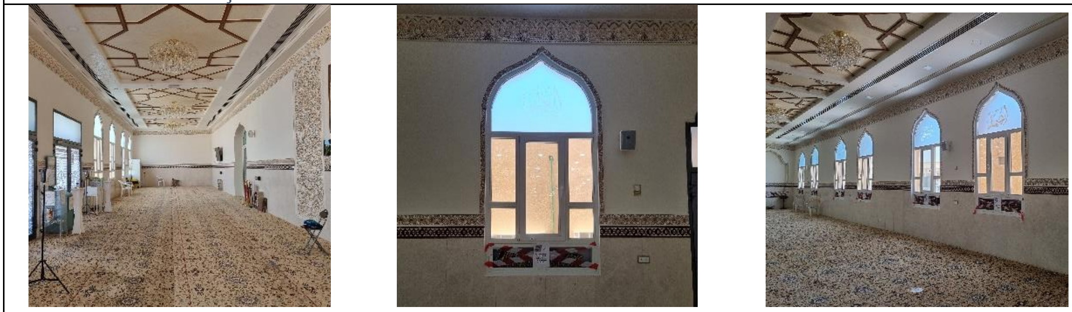
Figure 5.9. Three-dimensional (3D) views of M1.



Front façade

Qibla wall

Inside the main prayer hall



Inside the secondary prayer hall

Typical window

Eastern wall from the secondary prayer hall

Figure 5.10: External and internal photos of M1.

Table 5.12 Construction details of M1.

Construction Type	Construction Detail	Thickness (mm)	U- Value (W/m^2.K)	Time Constant (hours)
External wall	Concrete brick wall insulated with polyurethane board	375	0.54	8.47
Internal wall	Concrete brick wall	225	2.47	3.24
Roof	Concrete slab insulated with polyurethane board	265	0.8	8.27
Window frame	Aluminium	60	5.9	0
Double glazed window pane	3 mm glass + 12 mm air space + 3 mm glass	21	3.1	0
Door frame	Aluminium	60	5.9	0
Door pane	3 mm glass + 12 mm air space + 3 mm glass	31	7.8	0

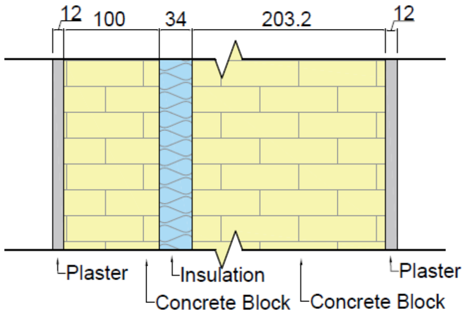


Figure 5.11: M1 external wall cross-sectional detail.

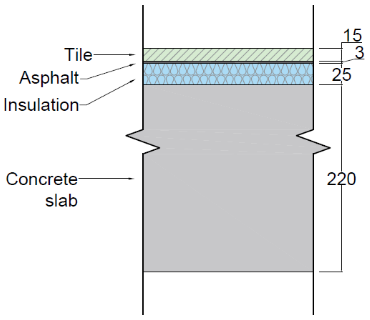


Figure 5.12: M1 roof cross-sectional detail.

5.9.2 Abu Hamza Al Shari Mosque (M2)

Abu Hamza Al Shari Mosque was built in 1994 in Muscat. It will be referred to Abu Hamza Al Shari Mosque throughout this dissertation as Mosque 2 or M2. The area is 727 m^2 and fits about 730 worshippers. Figure 5.13 show different Three-dimensional (3D) views from the Tas software as well as an east elevation view. Figure 5.14 shows the Abu Hamza Mosque ground floor plan drawing. It can be noticed that the mosque features a main prayer hall, second prayer hall, and a *sahen* (a courtyard).

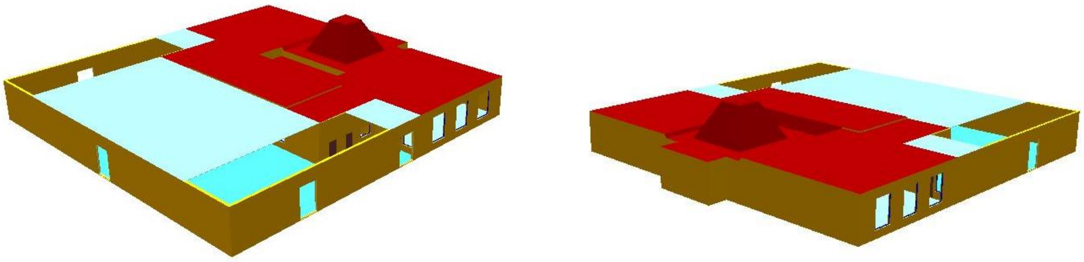


Figure 5.13. Three-dimensional (3D) views of Abu Hamza Al Shari Mosque

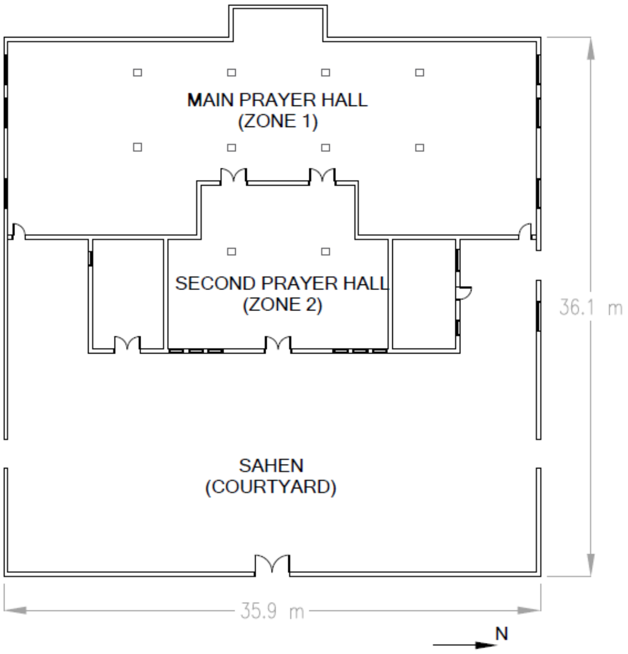
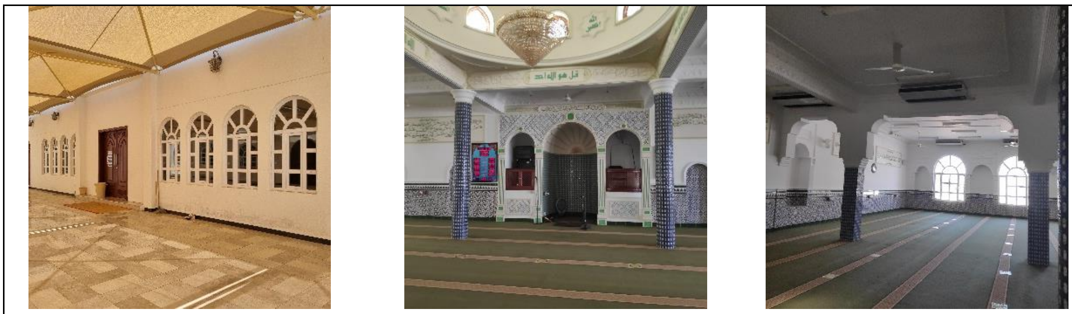


Figure 5.14 Ground floor plan of Abu Hamza Al Shari Mosque

Figure 5.15 shows different photos from the interior and exterior of M2. Table 5.12 lists the construction detail found in most recent buildings in Oman. Figures 5.16 and 5.17 show the cross-sectional details for the external walls and roof, respectively. A typical window size in Abu Hamza Al Shari mosque is 2 metres by 2.7 metres while the main door is 2 metres by 3 metres.



Front façade | Qibla wall | Inside the main prayer hall

Inside the secondary prayer hall | Typical window | Northern wall from the main prayer hall

Figure 5.15: External and internal photos of M2 Mosque

Table 5.13 Construction details of M2 mosque.

Construction Type	Construction Detail	Thickness (mm)	U- Value (W/m^2.K)	Time Constant (hours)
External wall	Concrete brick wall	250	2.43	3.47
Internal wall	Concrete brick wall	257.2	2.4	3.54
Roof	Concrete slab insulated with polyurethane board	193	0.838	4.13
Window frame	Aluminium	12.7	5.9	0
Double glazed window pane	3 mm glass + 12 mm air space + 3 mm glass	21	3.1	0
Door frame	Timber	40	1.94	0
Door pane	Timber	40	1.94	0

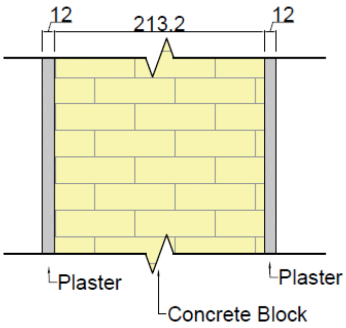


Figure 5.16: M2 external wall Cross-sectional detail. All dimensions are in millimetres.

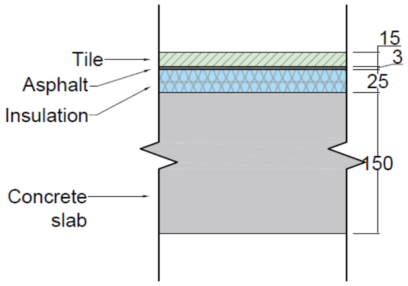


Figure 5.17: M2 roof cross-sectional detail. All dimensions are in millimetres.

5.9.3 Othman bin Afan Mosque (M3)

Othman bin Afan mosque was built in 1990 in Muscat. It will be referred to Othman Bin Afan Mosque throughout this dissertation as Mosque 3 or M3. The area is 466 m^2 and fits about 470 worshippers. Figure 5.18 show different Three-dimensional (3D) views from the Tas software. Figure 5.19 shows the Othman bin Afan mosque ground floor plan drawing and Figure 5.20 shows different photos of the mosque from the inside and the outside.

Table 5.13 lists the construction detail found in most recent buildings in Oman. Figures 5.21 and 5.22 show the cross-sectional details for the external walls and roof, respectively. A typical window size is a full height window in Othman bin Afan mosque that is 1.38 metre by 4.1 m, while the main door is 2.18 metres by 2.69 metres.

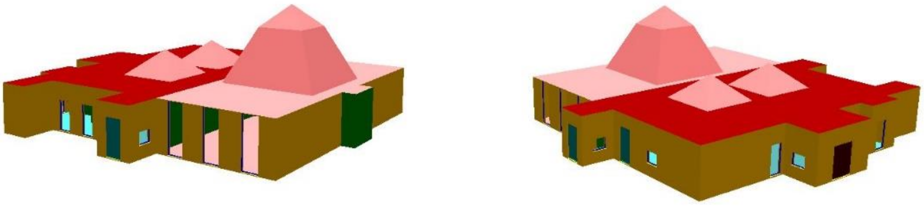


Figure 5.18. Three-dimensional (3D) views of Othman Bin Afan Mosque

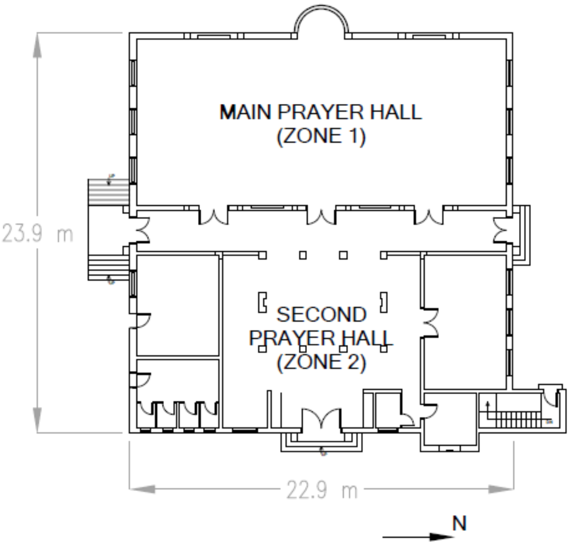


Figure 5.19 Ground floor plan of Othman Bin Afan Mosque

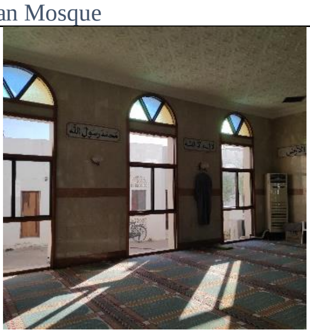
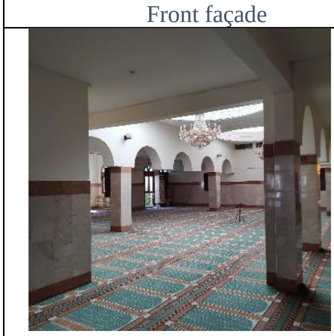
 Front façade	 Qibla wall	 Inside the main prayer hall
 Inside the secondary prayer hall	 Typical window	 Inside the main prayer hall

Figure 5.20: External and internal photos of M3 Mosque

Table 5.14 Construction details of M3 mosque.

Construction Type	Construction Detail	Thickness (mm)	U-Value (W/m^2. K)	Time Constant (hours)
External wall	Concrete brick wall insulated with polyurethane board and cladded with marble	407.2	0.67	8.72
Internal wall	Concrete brick wall	257.2	2.4	3.54
Roof	Concrete slab insulated with polyurethane board	193	0.838	4.13
Window frame	Aluminium	12.7	5.9	0
Single glazed window pane	3 mm glass	3.16	5.78	0
Door frame	Timber	40	1.94	0
Door pane	Timber	40	1.94	0

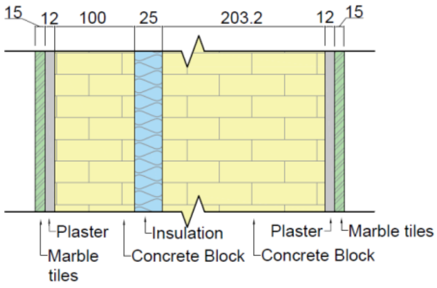


Figure 5.21: M3 external wall cross-sectional detail. All dimensions are in millimetres.

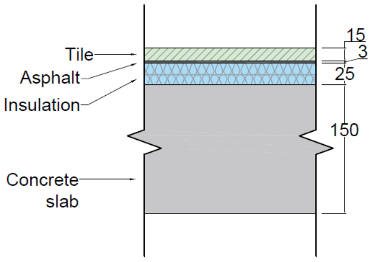


Figure 5.22: M3 roof cross-sectional detail. All dimensions are in millimetres.

5.9.4 Sa’al Mosque (M4)

Sa’al mosque was built in 1252 AD in Nizwa, Oman, has an area of 256.3 m^2,and fits about 324 worshippers (Biancifiori, 1994). It will be referred to Sa’al Mosque throughout this dissertation as Mosque 4 or M4. Figure 5.23 show different three-dimensional views from the Tas software. Figure 5.24 shows the Sa’al mosque ground floor plan drawing. It can be noticed it is the smallest mosque out of the six mosques, and it has only one prayer hall. Figure 5.25 shows different external and internal photos of the mosque. Table 5.14 lists the construction detail of Sa’al mosque. Figures 5.26 and 5.27 show the cross-sectional details for the external walls and roof, respectively. Windows in Sa’al mosque are relatively small and are 0.14 metre by 0.55 m, while doors are 1.4 metre by 2.3 metre.

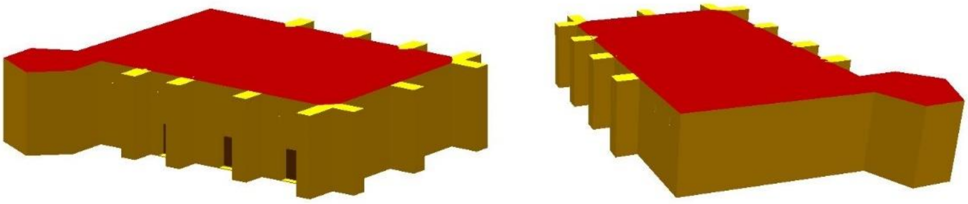


Figure 5.23. Three-dimensional (3D) views of Sa’al Mosque

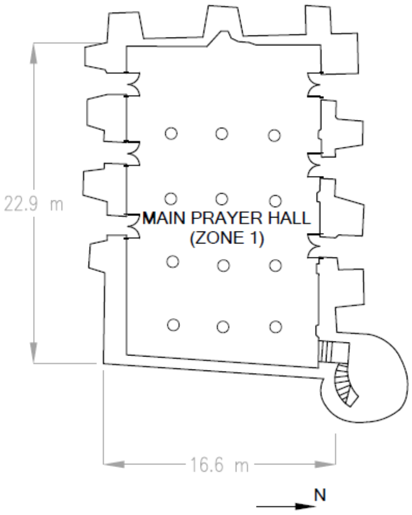


Figure 5.24. Ground floor plan of Sa’al Mosque

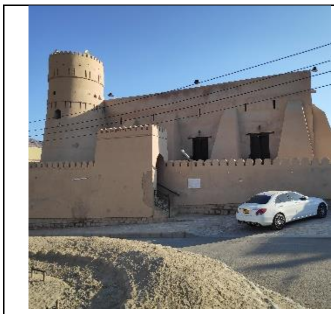
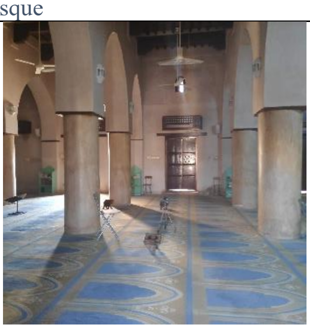
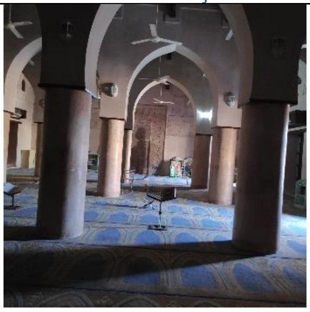
 Front façade	 Qibla wall	 Inside the main prayer hall
 Inside the secondary prayer hall	 Typical door and window	 External photo of the Southern wall

Figure 5.25: External and internal photos of M4 Mosque.

Table 5.15. Construction details of M4 mosque.

Construction Type	Construction Detail	Thickness (mm)	U- Value (W/m^2.K)	Time Constant (hours)
External wall	Clay/Mud wall	Varies between 600 to 1400	Varies between 0.519 and 1.065	Varies between 20.33 and 106
Internal wall	Concrete brick wall	257.2	2.4	3.54
Roof	Clay/Mud roof and wood beams	440	1.198	15.13
Window frame	Timber	40	1.94	0
Single glazed window pane	3 mm glass	3.16	5.78	0
Door frame	Timber	40	1.94	0
Door pane	Timber	40	1.94	0

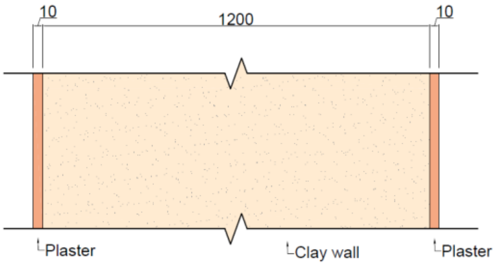


Figure 5.26: M4 external wall cross-sectional detail. All dimensions are in millimetres.

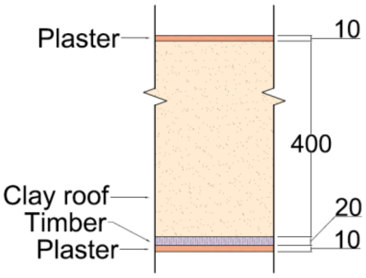


Figure 5.27: M4 roof cross-sectional detail. All dimensions are in millimetres.

5.9.5 Al Wafi Mosque (M5)

Al Wafi Mosque is in Al Kamil and Al Wafi, about 250 km away from Muscat, Oman. It will be referred to Hudhayfah Bin Al Yaman Mosque throughout this dissertation as Mosque 5 or M5. It was built in 1600s (Ministry of Information, 2020), and renovated in 1989, and since then there were minor restorations to the Mosque up till date. The walls vary between 500 and 1000 millimetres in thickness (Biancifiori, 1994) . It is important to mention that this simulation of Al Wafi Mosque is as per its condition in 2015. The courtyard (Zone 3) was recently closed completely, but it was considered as a naturally ventilated open courtyard in the simulations. Figures 5.28 shows Al Wafi mosque ground floor plan, while Figure 5.29 shows three dimensional views of Al Wafi mosque. A typical window size is 0.7 metre by 1 metre, while a typical door is 1.2 metres width by 1.8 metres height.

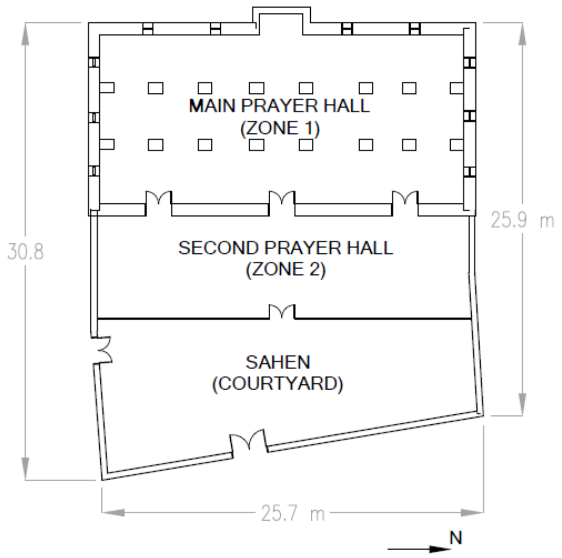


Figure 5.28. Al Wafi Mosque floor plan showing zones in TAS (Reproduced from (Biancifiori, 1994));

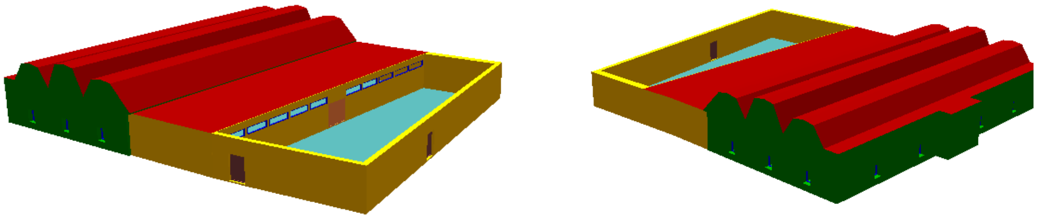


Figure 5.29. Three-dimensional (3D) views of Al Wafi Mosque

External and internal photos of Al Wafi mosque are shown in Figure 5.30 and the construction details are shown in the Table 5.15 featuring clay as the main material in the building. 5.31 and 5.32 show the cross-sectional details for the external walls and roof, respectively. It is common in the region for such clay walls to have a density of about 1730 kg/m^3 (Sayigh and Hamid Marafia, 1998) . ASHRAE 2009 handbook states that clay or adobe walls can have a conductivity that range between 0.7 to 0.85 W/m.K. for a 1730–1800 kg/m^3 dense clay walls (ASHRAE, 2009). Al Wafi mosque walls decrease in thickness as it increases in height, and the thickness varies from a wall to another. This means U-values are different at any given point across all the walls and roof of Al Wafi mosque. For the purposes of this research, it can be estimated that the walls of Al Wafi Mosque (mean thickness of 1 metre) can have a U-value of 0.7 W/m^2.K. The roof (mean thickness of 0.7 metre) is estimated to have a U-value of 1.1 W/m^2.K.

Front façade

Qibla wall

Inside the main prayer hall

Inside the secondary prayer hall

Typical window

Photo taken from the secondary prayer hall looking into the primary prayer hall

Figure 5.30: External and internal photos of M5 Mosque.

Table 5.16. Construction details of Al Wafi mosque.

Construction Type	Construction Detail	Thickness (mm)	U- Value (W/m^2.K)	Time Constant (hours)
Walls	Clay/Mud wall	Varies between 500 and 1200	Varies (average of 0.7)	Varies between 15 and 80
	Aluminium partition wall	12	5.9	0
Roof	Clay/Mud roof and wood beams	Varies between 300 and 750	Varies (average of 1.1)	Varies between 5.8 and 28
Window frame	Timber	40	2	0
Single glazed window pane	3 mm glass	3	5.78	0
Door frame	Timber	40	2	0
Door pane	Timber	40	2	0

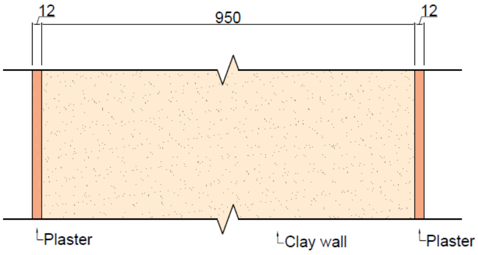


Figure 5.31: M5 external wall cross-sectional detail. All dimensions are in millimetres.

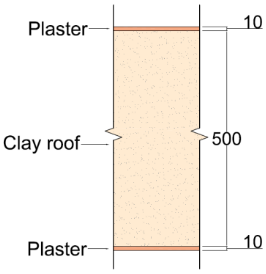


Figure 5.32: M5 roof cross-sectional detail. All dimensions are in millimetres.

5.9.6 Aal Hamoodah Mosque (M6)

Aal Hamoodah mosque was built in 1600s in Jaalan Bani Buali, Oman. It will be referred to Hudhayfah Bin Al Yaman Mosque throughout this dissertation as Mosque 6 or M6. The area is 735 m^2 and fits about 730 worshippers. Figures 5.33 show different three-dimensional views from the Tas software. Figure 5.34 shows the Aal Hamoodah mosque ground floor plan drawing. It can be noticed that it has a unique roof design that features 52 qibbas (domes).

Table 5.16 lists the construction details of Aal Hamoodah Mosque. 5.36 and 5.37 show the cross-sectional details for the external walls and roof, respectively. A typical window size in Aal Hamoodah mosque is relatively small at 0.4 metre by 0.6 m, while a typical door is 1.4 metre by 2.2 metre.

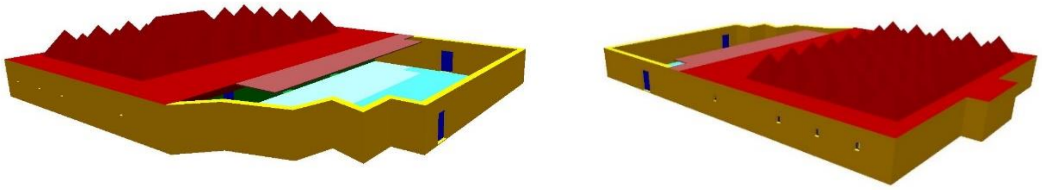


Figure 5.33. Three-dimensional (3D) views of Aal Hamoodah Mosque

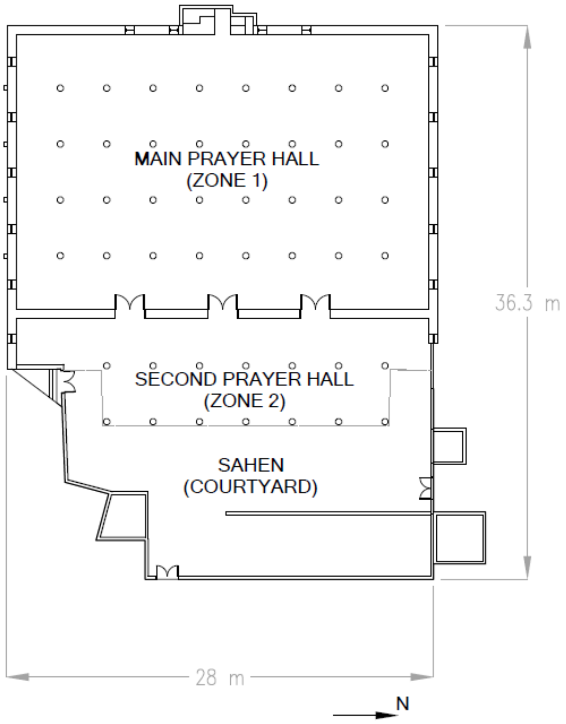


Figure 5.34. Ground floor plan of Aal Hamoodah Mosque

External view of the qibla wall

Internal view of the qibla wall

Inside the main prayer hall

Inside the secondary prayer hall

A typical window and an air conditioning unit

Mosque's from facade

Figure 5.35: External and internal photos of M6 Mosque.

Table 5.17. Construction details of Aal Hamoodah mosque.

Construction Type	Construction Detail	Thickness (mm)	U- Value (W/m^2.K)	Time Constant (hours)
Walls	Clay/Mud wall	Varies between 500 and 1000	Varies between 0.698 and 1.226	Varies between 14.33 and 54.8
Roof	Clay/Mud roof	500	1.1	Varies between 5.8 and 28
Window frame	Timber	40	1.942	0
Single glazed window pane	3 mm glass	3	5.78	0
Door frame	Timber	40	1.942	0
Door pane	Timber	40	1.942	0

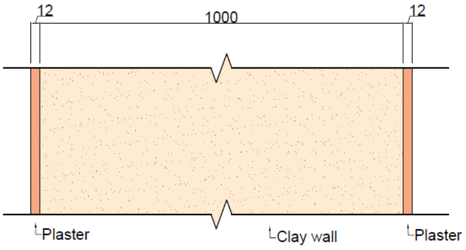


Figure 5.36: M6 external wall cross-sectional detail. All dimensions are in millimetres.

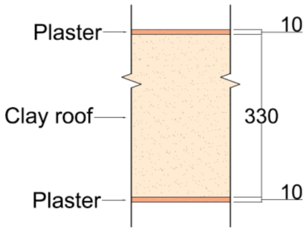


Figure 5.37: M6 roof cross-sectional detail. All dimensions are in millimetres.

5.10 Limitations and issues faced during computer simulations

There were a few issues and limitations faced during the computer simulations. As discussed in section 5.7, two of the mosques' distinctive architectural features are Qubba (dome) and minaret (tall tower attached to mosques). Minaret can be disregarded from the computer simulations as they are detached from the mosque and not occupied. Qubbas, though, are an integral part of the mosque and need to be modelled and simulated. The closest shape that EDSL Tas software (version 9.5.1) can model is a pyramid shape. Obtaining exact measurements of U-values was challenging. Estimations were made to obtain the closest possible U-value. The COVID-19 pandemic exerted an impact on the computer simulations, primarily due to the imposition of lockdown measures that limited access to mosques.

5.11 Conclusion

The research methodology employed in this research consists of two main parts: computer simulation and field measurement. The careful selection of six mosque buildings, each with distinct characteristics, triangulated the data and minimised errors, thereby promising a research output that is robust and reliable. This thorough approach to research design, which encompasses a workflow spanning various stages including pilot studies, main studies, and the collection of meteorological data and electricity bills, has laid a strong foundation for this research. The chapter also sheds light on the challenges encountered during the research process, offering a transparent view of the research undertaken, and setting the stage for a deeper exploration in the subsequent chapters.

Chapter 6. FIELD MEASUREMENT RESULTS

6.1 Introduction

In this chapter, the focus is on the results gathered from field measurements, starting the first of two chapters that get into the research findings in depth. This chapter presents the detailed field measurement data from six chosen mosques, offering analyses and discussions of different internal thermal parameters of the building such as dry bulb temperature (DBT), mean radiant temperature (MRT), relative humidity (RH), and indoor air velocity.

The field measurements, a vital part of this research, provide a rich set of data including DBT and humidity RH taken every minute for two full days, and spot measurements taken at different times during the summer. This chapter takes a careful approach to presenting this large amount of data, focusing on hourly temperature and humidity readings over a single day for each mosque, aiming to give a clear picture of the conditions in each location.

The objective of the data analysis in this research is to assess the current indoor thermal comfort in mosque buildings in the Sultanate of Oman by comparing traditional and contemporary mosque buildings' thermal performance during winter design day (day 20) and summer design days (day 179). This is a step towards understanding how well these buildings were designed to maintain comfort levels during the two extreme seasons.

As discussed in section 5.6.2, the FM instruments have been bought new and were calibrated from the manufacturer. Furthermore, the inclusion of WS (Weather Station) External DBT data, in addition to the FM (Field Measurement) External DBT, validates the accuracy and reliability of the field measurements against the data obtained from the Muscat International Airport weather station. Figures 6.1 to 6.6 include data points from both FM instruments and Muscat International Airport weather station, which show that they are closely aligned.

6.2 Indoor Dry Bulb Temperature

Dry bulb temperature is one of the most significant parameters in building thermal performance analysis as discussed in section 2.2.1. This section presents the dry bulb temperature results as per the field measurement methodology. Note that the figures in this section show the air conditioning period during the day with an "**AC on**" note in the figure, and the thermal comfort zone as per the bioclimatic chart (Figure 3.3) as a LIGHT AMBER area.

6.2.1 Hudhayfah Bin Al Yaman Mosque (M1)

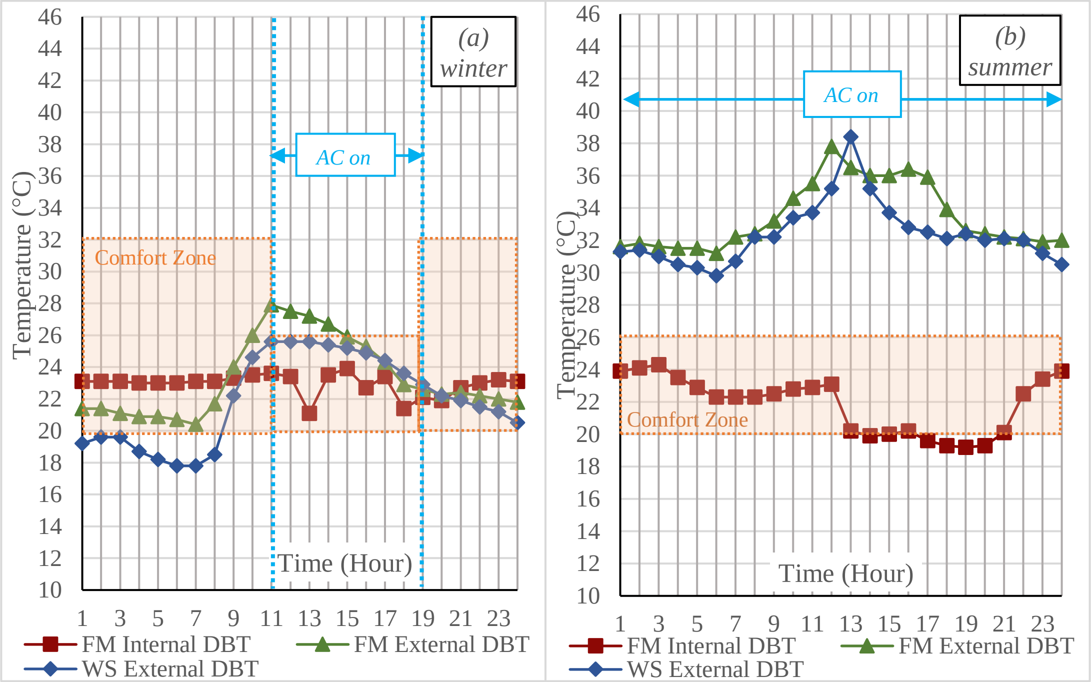


Figure 6.1: Field measurement Dry Bulb Temperature for Mosque 1 (a) during winter on 25 December 2020 (b) and during summer on 15 May 2021

In winter, the field measurement internal dry bulb temperature (FM internal DBT) range for Mosque 1 (M1) remained relatively stable between 22.2 and 23.9 °C, except for a drop to 21.1 °C at around 13:00 and another drop to 21.4 °C at 18:00. In contrast, the measured external DBT (FM External DBT) has a wider range, fluctuating between 20.4 and 27.9 °C.

The peak FM internal DBT of 23.9 °C occurred at 15:00, coinciding with the higher FM external DBT, which reached 25.2 °C at the same time. FM internal DBT reaches a trough of 21.1°C at 13:00, possibly due to the air conditioning system operating at full power. It should be also noted that at 13:00 most of the worshippers have completed their Dhuhr prayers, so the mosque was mostly unoccupied and had lower heat gains.

The peak FM external DBT of 27.9 °C occurred at 11:00, which coincided with the activation of the air conditioning system. The lowest FM external DBT measured 20.4 °C at 7:00.

The difference between the maximum internal DBT (23.9 °C) and the minimum internal DBT (21.1 °C) is 2.8 °C. This indicates that the internal DBT remained relatively stable throughout the day despite the FM external DBT fluctuating between 17.8 and 25.8 °C. This can be firstly attributed to the effective insulated building envelope. The walls feature a U-value of 0.543 W/m^2.K and roof's u-value is 0.816 W/m^2.K. This helped it keep external heat gain to a minimum when unconditioned. The second reason it stayed within the comfort zone was the active air conditioning during the afternoon, which counteracted the rising external DBT at that time (Figure 6.1a).

M1 maintained a comfortable indoor environment during the winter design day with an average Relative Humidity (RH) of 55% and an internal DBT within the comfort zone as per Figure 6.1. The external DBT also remained within the comfort zone for the most part, suggesting that achieving thermal comfort did not require significant insulation or high thermal performance measures during winter.

This may also suggest that the air conditioning system may not have been needed during winter. The FM internal DBT would have been within the thermal comfort zone if it was in a free-running mode. This finding challenges the necessity of air conditioning during winter for Mosque 1, indication that natural ventilation was sufficient to achieve thermal comfort.

In summer, the measured internal dry bulb temperature (FM internal DBT) range for Mosque 1 (M1) between 19.2 and 24.3 °C. In contrast, the measured external DBT (FM External DBT) has a higher range, fluctuating between 31.2 and 37.8 °C.

The peak FM external DBT of 37.8 °C at 12:00, which coincided with the declining FM internal DBT of 23.1 °C at the same time, which reaches 20.2 °C an hour later at 13:00. This is possibly due to the air conditioning system operating at full power during this time. The FM internal DBT remains between 19.2 and 20.2 °C until 21:00, when the last prayer of the day was completed, and the mosque is closed for the day. After 21:00, FM internal DBT increases gradually to reach a maximum of 24.3 at 3:00 just before the Fajr prayer.

The difference between the maximum internal DBT (24.3 °C) and the minimum internal DBT (19.2 °C) is 5.1 °C. The internal DBT remained relatively stable during the afternoon between 13:00 and 21:00 with internal DBT maintained between 19.2 and 20.2 due to air conditioning system operating at full power at a 20 °C setpoint. The rest of the day saw temperatures rising to a level between 23.1 °C and 24.3 °C due to air conditioning system operating at a 23 °C setpoint.

M1 effectively maintained an indoor environment within the comfort zone despite the high external DBT of a summer design day in one of the hottest cities worldwide. The external DBT was above the thermal comfort zone for the most part, but the internal DBT maintained within the comfort zone with the help of an active air conditioning throughout the 24 hour period.

This does suggest that achieving thermal comfort in summer does require an active air conditioning. Nevertheless, it raises questions regarding the need for continuous operation throughout the entire 24-hour period.

6.2.2 Abu Hamza Al Shari Mosque (M2)

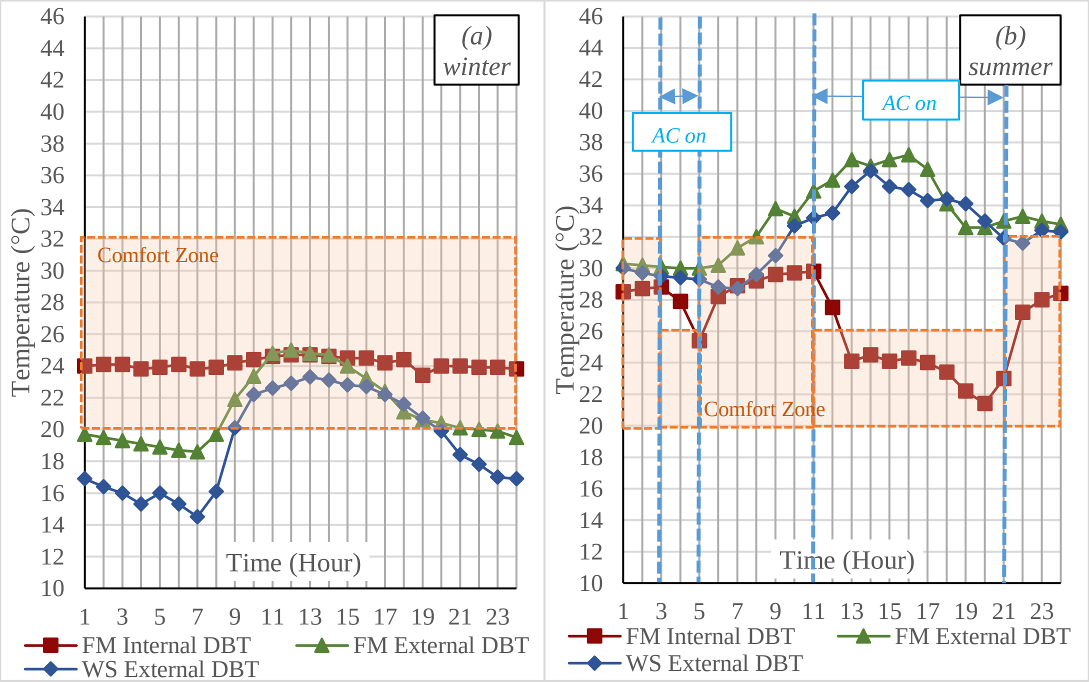


Figure 6.2: Field measurement Dry Bulb Temperature for Mosque 2 (a) during winter on 28 December 2020 (b) and during summer on 18 May 2021

In winter, the field measurement internal dry bulb temperature (FM internal DBT) range for Mosque 2 (M2) remained relatively stable between 23.4 and 24.7 °C. In contrast, the measured external DBT (FM External DBT) has a wider range, fluctuating between 18.6 and 25 °C.

The difference between the maximum internal DBT (24.7 °C) and the minimum internal DBT (23.4 °C) is 1.3 °C. This indicates that the internal DBT remained relatively stable throughout the day despite the FM external DBT fluctuating between 18.6 and 25 °C. This can be attributed to the internal heat gains keeping the internal DBT of the prayer hall at the high extreme of the external DBT.

M2 maintained a comfortable indoor environment during the winter design day with an average Relative Humidity (RH) of 42% and an internal DBT within the comfort zone as per Figure 6.1. The external DBT also remained within the comfort zone suggesting that achieving thermal comfort did not require significant insulation or high thermal performance measures during winter. The external walls are uninsulated and have a U-value of 2.427 W/m^2.K. The roof is insulated and has a U-value of 0.86 W/m^2.K. This suggests that the building is thermally comfortable without the need of wall insulation or any cooling and heating systems during the winter.

In summer, the measured internal dry bulb temperature (FM internal DBT) range for Mosque 2 (M2) between 21.4 and 29.8 °C. In contrast, the measured external DBT (FM External DBT) has a higher range, fluctuating between 30 and 37.2 °C.

The FM internal DBT starts at 28.8 C at 03:00, while the external DBT is at 30.1 C at the same time. The AC was turned on between 03:00 and 05:00, the internal DBT decreases to 27.9 C at 04:00 and to 25.4 at 05:00. It quickly returns to a higher DBT at 28.2 at 06:00 when the AC has been off for about an hour. The FM internal DBT reaches a peak of 29.8 C at 11:00, while the external DBT is also increasing at reached 34.9 C at the same time. The AC is turned on at 11:00 (before Al-Dhuhr prayer). The internal DBT keep decreasing to reach a trough of 21.4 at 20:00. The internal DBT quickly increases from 23.0 C at 21:00 to 28.4 at 00:00 as the AC was turned off.

The difference between the maximum internal DBT (29.8 °C) and the minimum internal DBT (21.4 °C) is 8.4 °C. The internal DBT remained between a range of relatively stable during the afternoon between 13:00 and 20:00 with internal DBT maintained between 24.1 and 21.4. The cooling setpoint was set at 23 °C , but it seemed that it was changed between 15:00 and 18:00 to a 21 °C setpoint. The rest of the day saw internal DBT rising to a level up to 29.8 °C due to the air conditioning system being inactive.

M2 effectively maintained an indoor environment within the comfort zone despite the high external DBT of a summer design day in one of the hottest cities worldwide. The average RH during the summer measurement day for M2 was 34%. The external DBT was above the thermal comfort zone for the most part, but the internal DBT maintained within the comfort zone with the help of an active air conditioning between 03:00 and 05:00 and between 11:00 and 21:00. This does suggest that achieving thermal comfort in summer does require an active air conditioning.

6.2.3 Othman bin Afan Mosque (M3)

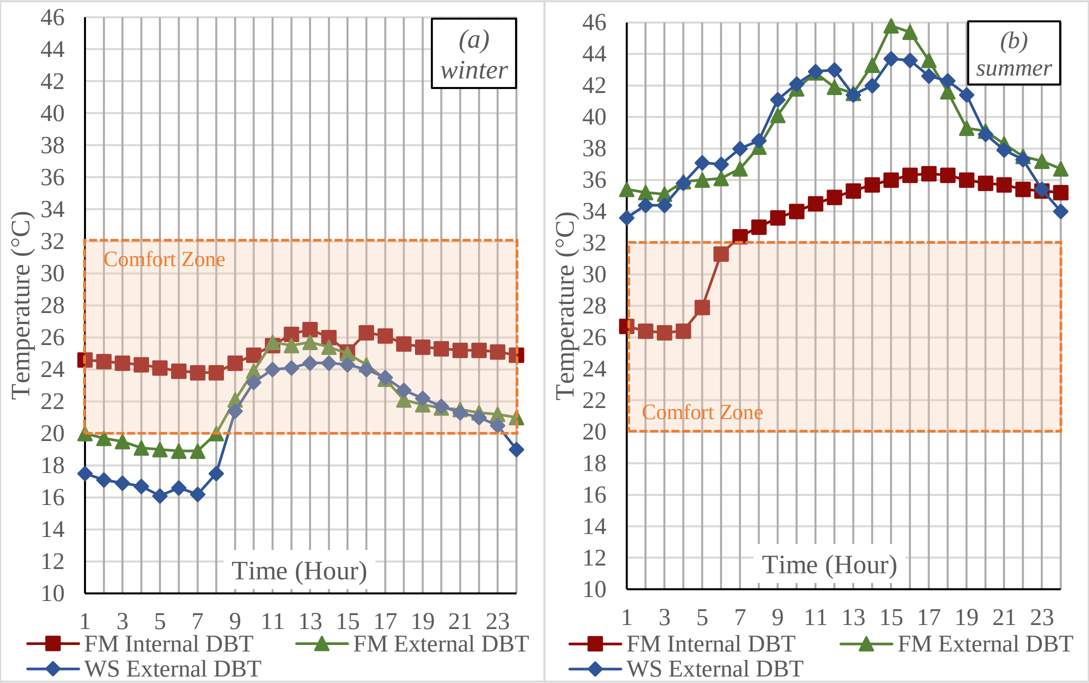


Figure 6.3: Field measurement Dry Bulb Temperature for Mosque 3 (a) during winter on 30 December 2020 (b) and during summer on 20 May 2021

In winter, the field measurement internal dry bulb temperature (FM internal DBT) range for Mosque 3 (M3) remained relatively stable between 23.8 and 26.5 °C. In contrast, the measured external DBT (FM External DBT) has a wider range, fluctuating between 18.9 and 25.7 °C.

The difference between the maximum internal DBT (23.8 °C) and the minimum internal DBT (26.5 °C) is 2.7 °C. Similar to M2, this indicates that the internal DBT remained relatively stable throughout the day despite the FM external DBT fluctuating between 18.9 and 25.7 °C. This can be attributed to the internal heat gains keeping the internal DBT of the prayer hall at the high extreme of the external DBT.

M3 maintained a comfortable indoor environment during the winter design day with an average Relative Humidity (RH) of 45% and an internal DBT within the comfort zone as per Figure 6.1. The external DBT also remained within the comfort zone suggesting that achieving thermal comfort did not require significant insulation or high thermal performance measures during winter.

This suggests that the building is thermally comfortable without the need of any cooling and heating systems during the winter.

In summer, the measured internal dry bulb temperature (FM internal DBT) range for Mosque 3 (M3) between 26.3 and 36.4 °C. In contrast, the measured external DBT (FM External DBT) has a higher range, fluctuating between 35.1 and 45.8 °C.

The peak FM external DBT of 45.8 °C at 15:00, which coincided with the increasing FM internal DBT of 36 °C at the same time, which reaches 36.4 °C two hours later at 17:00. Mosque 3 main mosque building was unoccupied and unconditioned during this measurement day, due to COVID-19 restrictions. Prayers were instead held at another separate new building within the vicinity. Mosque 3 main building did not have a set air conditioning schedule. It was air conditioned using only one air conditioning unit with a set point of 23 °C from the night prior until the end of fajr prayer (From 00:00 to 04:00). That is why the internal DBT was at 26.4 °C at 04:00. After that, the internal DBT increased rapidly to 32.4 °C at 07:00. Then, the internal DBT increased gradually as the external DBT is increasing to reach peak internal DBT of 36.4 °C at 17:00. The internal DBT decreased gradually from that point to reach 35.2 °C at 00:00 due to decreasing external DBT.

The difference between the maximum internal DBT (36.4 °C) and the minimum internal DBT (26.3 °C) is 10.1 °C. This is due to air conditioning of the space that kept it lower at 26.3 °C during the beginning of the day, and then the high external DBT that peaks at 45.8 °C caused the internal DBT of the unconditioned space to increase to a peak of 36.4 °C at 17:00.

M3 maintained an indoor environment within the comfort zone when it was air conditioned. The average RH during the summer measurement day for M3 was 29% which is right at the lower limit of RH comfort zone. As soon as the air conditioning was turned off, the internal DBT increased to move outside the comfort zone. Although the internal DBT peaked at 36.4 °C, the external DBT at the time was 43.6 °C. That is a difference of 7.2 °C between internal DBT and external DBT at 17:00, which is due to the higher thermal mass wall with a marble cladding. The external walls have a u-value of 0.67 W/m^2.K and the roof has a u-value of 0.86 W/m^2.K. This does suggest that achieving thermal comfort in summer does require an active air conditioning.

6.2.4 Sa’al Mosque (M4)

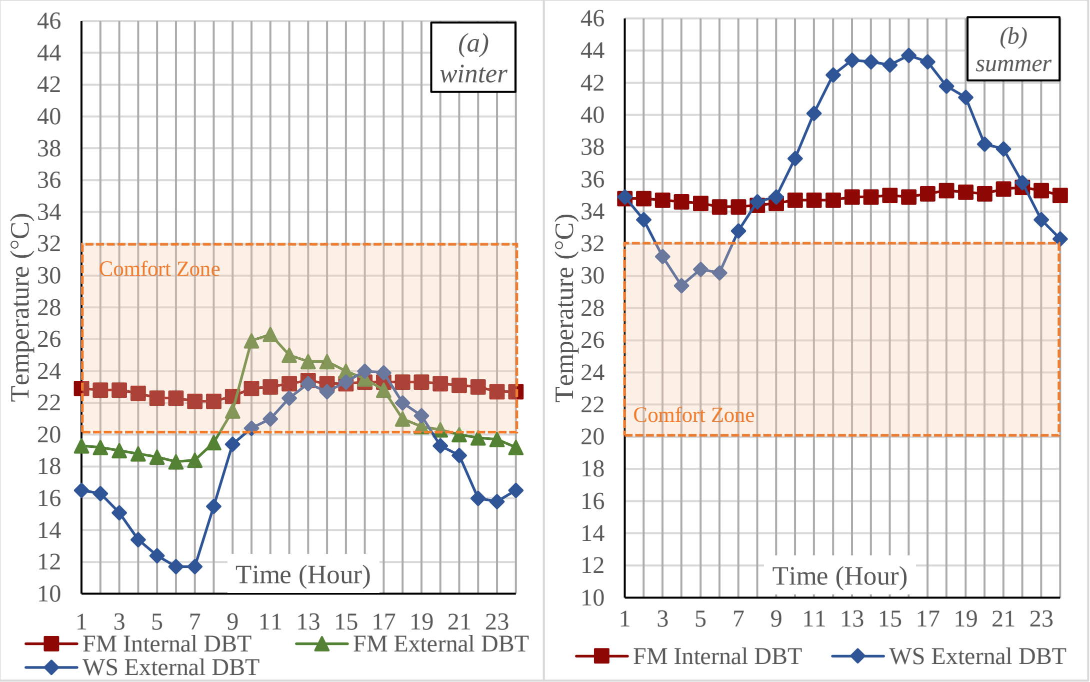


Figure 6.4: Field measurement Dry Bulb Temperature for Mosque 4 (a) during winter on 2 January 2021 (b) and during summer 22 May 2021

In winter, the field measurement internal dry bulb temperature (FM internal DBT) range for Mosque 4 (M4) remained relatively stable between 22.1 and 23.4 °C. In contrast, the measured external DBT (FM External DBT) has a wider range, fluctuating between 18.3 and 26.3 °C.

The difference between the maximum internal DBT (22.1 °C) and the minimum internal DBT (23.4 °C) is 1.3 °C. Similar to M2, this indicates that the internal DBT remained relatively stable throughout the day despite the FM external DBT fluctuating between 18.3 and 26.3 °C. This can be attributed to the high thermal mass of the clay walls and roof keeping the internal DBT at a relatively constant temperature despite the external DBT swings. Mosque 4 was unconditioned and unoccupied during this measurement day due to COVID-19 restrictions.

M3 maintained a comfortable indoor environment during the winter design day with an average Relative Humidity (RH) of 40% and an internal DBT within the comfort zone as per Figure 6.1. This suggests that the building is thermally comfortable without the need of any cooling and heating systems during the winter.

In summer, the measured internal dry bulb temperature (FM internal DBT) range for Mosque 4 (M4) between 34.4 and 35.5 °C. WS External DBT was used as the measured data was not available for that day during M4 field measurements. WS External DBT has a higher range, fluctuating between 29.4 and 43.7 °C.

The difference between the maximum internal DBT (35.5 °C) and the minimum internal DBT (34.3 °C) is 1.2 °C despite the external DBT fluctuating between 29.4 C and 43.7 C during this summer measurement day. Similar to winter, the high thermal mass of the clay walls and roof (U-value of 0.595 W/m^2.K for external walls and a U-value of 1.198 W/m^2.K for roof) have helped keep the internal DBT stable and consistent throughout the day.

M4 was unconditioned and unoccupied during a hot and dry summer design day, so the internal DBT was outside the comfort zone. The RH was also outside the thermal comfort zone as it averaged about 19% throughout the day. However, it was interesting to see the building keep a stable of 34.9 °C even at an external DBT of 43.7 °C. This does suggest that achieving thermal comfort in summer does require cooling.

6.2.5 Al Wafi Mosque (M5)

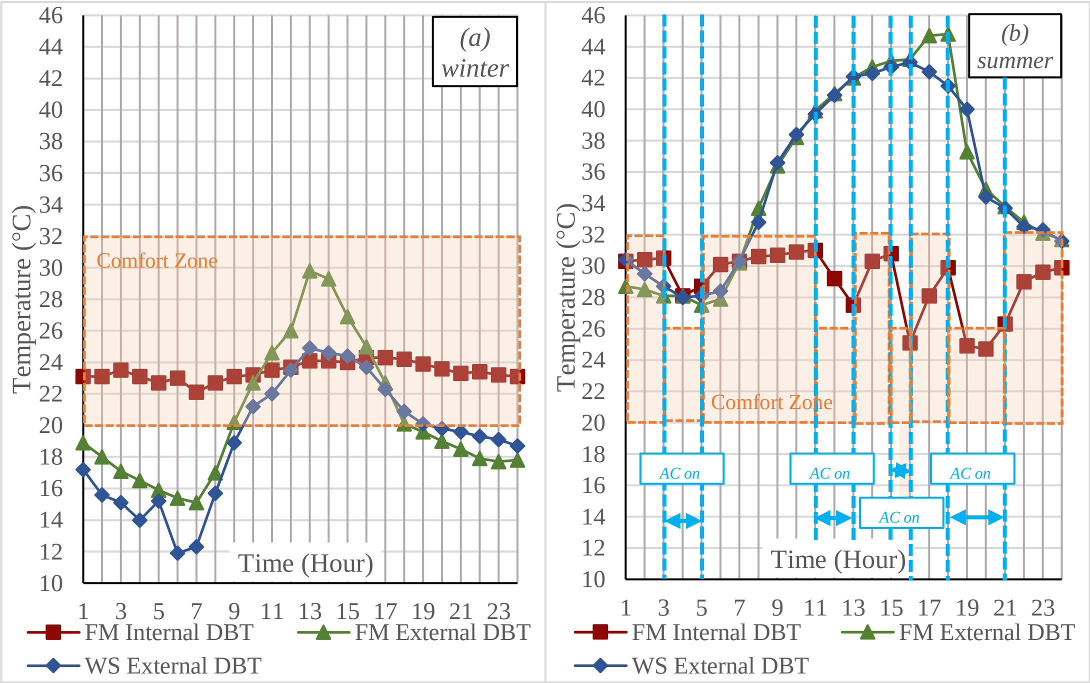


Figure 6.5: Field measurement Dry Bulb Temperature for Mosque 5 (a) during winter on 5 January 2021 (b) and during summer on 25 May 2021

In winter,

the field measurement internal dry bulb temperature (FM internal DBT) range for Mosque 5 (M5) remained relatively stable between 22.1 and 24.3 °C. In contrast, the measured external DBT (FM External DBT) has a wider range, fluctuating between 15.1 and 29.8 °C.

The difference between the maximum internal DBT (22.1 °C) and the minimum internal DBT (24.3 °C) is 2.2 °C. This indicates that the internal DBT remained relatively stable throughout the day despite the FM external DBT fluctuating between 15.1 and 29.8 °C. This can be attributed to the high thermal mass of the clay walls (0.722 W/m^2.K U-value) and roof (1.25 W/m^2.K U-value) keeping the internal DBT at a relatively constant temperature despite the external DBT swings. Mosque 5 was unconditioned and occupied during this winter measurement day.

M5 maintained a comfortable indoor environment during the winter design day with an average Relative Humidity (RH) of 38% and an internal DBT within the comfort zone as per Figure 6.5(a). This suggests that the building is thermally comfortable without the need of any cooling and heating systems during the winter.

In summer, the measured internal dry bulb temperature (FM internal DBT) range for Mosque 5 (M5) between 24.7 and 31 °C, except for. In contrast, the measured external DBT (FM External DBT) has a higher range, fluctuating between 27.5 and 44.8 °C.

The difference between the maximum internal DBT (31 °C) and the minimum internal DBT (24.7 °C) is 6.3 °C despite the external DBT fluctuating between 27.5 and 44.8 °C during this summer measurement day. Mosque 5 was intermittently occupied and air conditioned during each prayer, which resulted in sharp increases and decreases of the internal DBT as seen in Figure 6.5(b)

Similar to winter, the high thermal mass of external clay walls (0.722 W/m^2.K U-value) and high thermal mass of the roof (1.25 W/m^2.K U-value) have helped keep the internal DBT stable and consistent when it is unconditioned (from 07:00 to 11:00 as an example). The average internal RH during the summer measurement day for M5 was 43%. Mosque 5 was mostly within the comfort zone with the aid of active air conditioning.

6.2.6 Aal Hamoodah Mosque (M6)

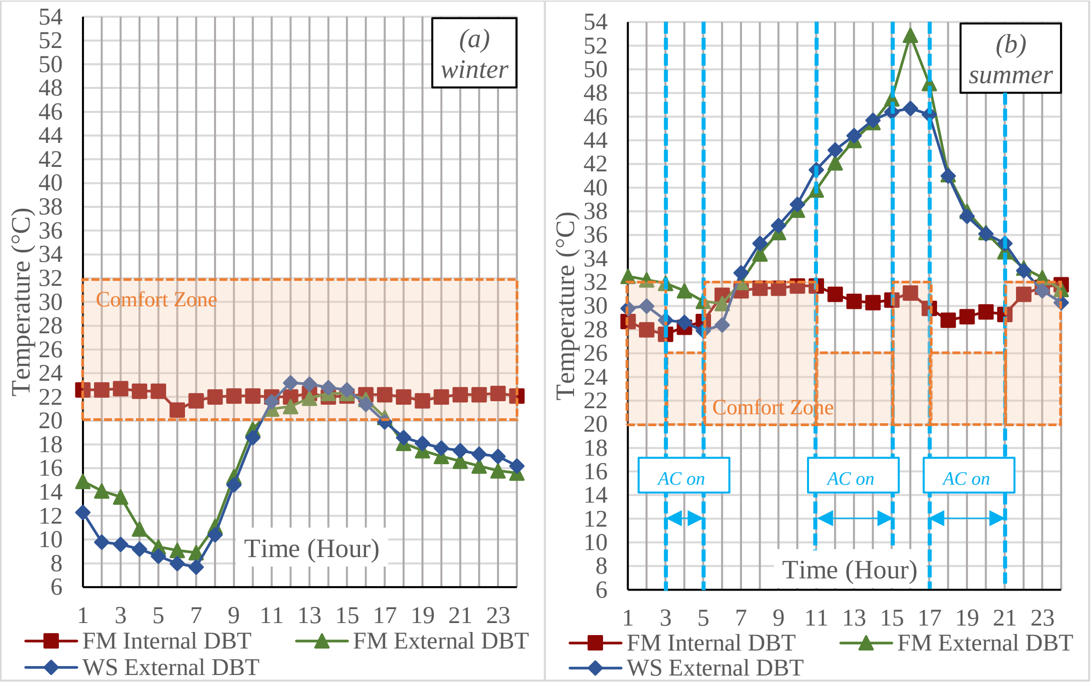


Figure 6.6: Field measurement Dry Bulb Temperature for Mosque 6 (a) during winter on 8 January 2021 (b) and during summer on 27 May 2021

In winter, the field measurement internal dry bulb temperature (FM internal DBT) range for Mosque 6 (M6) remained relatively stable between 20.9 and 22.7 °C. In contrast, the measured external DBT (FM External DBT) has a wider range, fluctuating between 8.9 and 22.3 °C.

The difference between the maximum internal DBT (22.7 °C) and the minimum internal DBT (20.9 °C) is 1.8 °C. This indicates that the internal DBT remained relatively stable throughout the day despite the FM external DBT fluctuating between 8.9 and 22.3 °C. This can be attributed to the high thermal mass of the clay walls and roof keeping the internal DBT at a relatively constant temperature despite the external DBT swings.

M6 maintained a comfortable indoor environment during the winter design day with an average Relative Humidity (RH) of 34% and an internal DBT within the comfort zone as per Figure 6.1. This suggests that the building is thermally comfortable without the need of any cooling and heating systems during the winter.

In summer, the measured internal dry bulb temperature (FM internal DBT) range for Mosque 6 (M6) between 27.6 and 31.8 °C, except for. In contrast, the measured external DBT (FM External DBT) has a higher range, fluctuating between 30.2 and 52.9 °C.

The difference between the maximum internal DBT (31.8 °C) and the minimum internal DBT (27.6 °C) is 4.2 °C despite the external DBT fluctuating between 30.2 and 52.9 °C during this summer measurement day. The average internal RH during the summer measurement day for M6 was 38%. Mosque 6 was intermittently occupied and air conditioned during each prayer, which resulted in slight increases and decreases of the internal DBT as seen in Figure 6.6(b). The air conditioning system was not sufficient to lower the internal DBT to reach comfort zone. This can be due to the high thermal mass of the roof and walls that require higher cooling output to lose all the heat absorbed during the day.

On the other hand, the low thermal conductivity of the external clay walls (0.698 W/m^2.K U-value) and the low thermal conductivity of the roof (1.736 W/m^2.K U-value) have helped keep the internal DBT relatively consistent.

6.2.7 Summary

Dry bulb air temperature is one of the most important parameters in the thermal performance assessment (Szokolay, 2008). Internal dry bulb temperatures of all six mosques range between 20.9 and 26.5 °C during the field measurement as per Figure 6.7. This range means all six mosques are within the comfort zone as per Muscat bioclimatic chart (Figure 2.3). The internal dry bulb temperature stability was aided by high thermal mass, insulation, and/or internal heat gains.

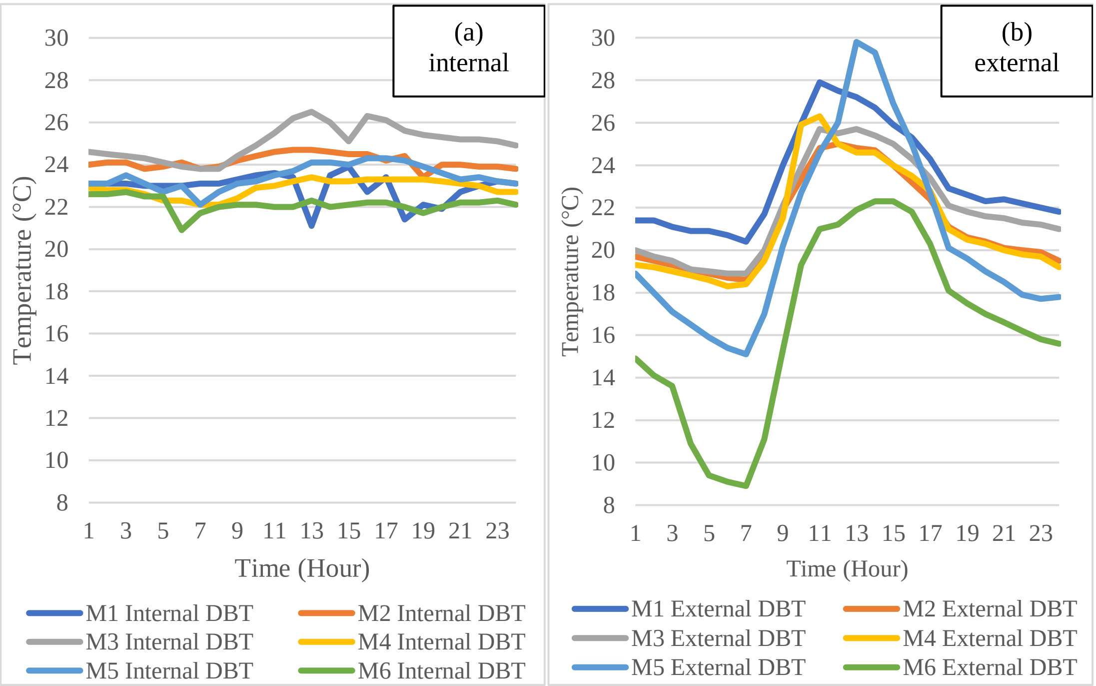


Figure 6.7. Internal DBT of all six mosques as per winter field measurement results (a). External DBT of all six mosques as per winter field measurement results (b).

Each of the six mosques feature a different temperature profile during summer. Figure 6.8 (a) shows the internal DBT for each mosque while Figure 6.8 (b) shows the external DBT for each mosque since each mosque's field measurement is on a different day. As per Figure 6.8 (a), M1 temperatures are within the comfort zone throughout the day. This is due to the mosque is being air controlled throughout the day. M2's range is between 21.4 °C. And 29.2 °C. During Fajr prayer (at around 5:00), the temperature decreases from 28.7 °C to 25.4 °C due to air conditioning. The air conditioning is also turned on between 12:00 and 20:00, which makes the temperature range between 21.4 °C and 24.5 °C. Outside of these two periods, M2 is naturally ventilated and reaches a temperature of almost 30 °C. It is within the comfort zone throughout the day.

M3 and M4 are not occupied due to Covid-19 regulations. Sometimes the air conditioning is turned on to maintain it. In this case, M3 air conditioning was turned on throughout the night until 5:00 when it had the temperature increase from 26.4 °C until it reached its peak at 36.4 °C at 16:00. M4 was naturally ventilated and had a temperature range between 34.3 and 35.5 °C. Both M3 and M4 are outside the comfort zone.

M5 and M6 have similar temperature profiles. M5's DBT is 30.5 °C at 3:00 and decreases to 28.2 °C during Fajr, to 27.5 °C during Dhur prayers, to 25.1 °C during Asr, and to 24.7 °C Maghrib and Isha prayers. The air conditioning is only used during prayers and when it is not occupied, the air conditioning is turned off and the DBT increases again to around 30 °C. M6 is similar except that the DBT range is around 3.1 °C instead of 7 °C in M5.

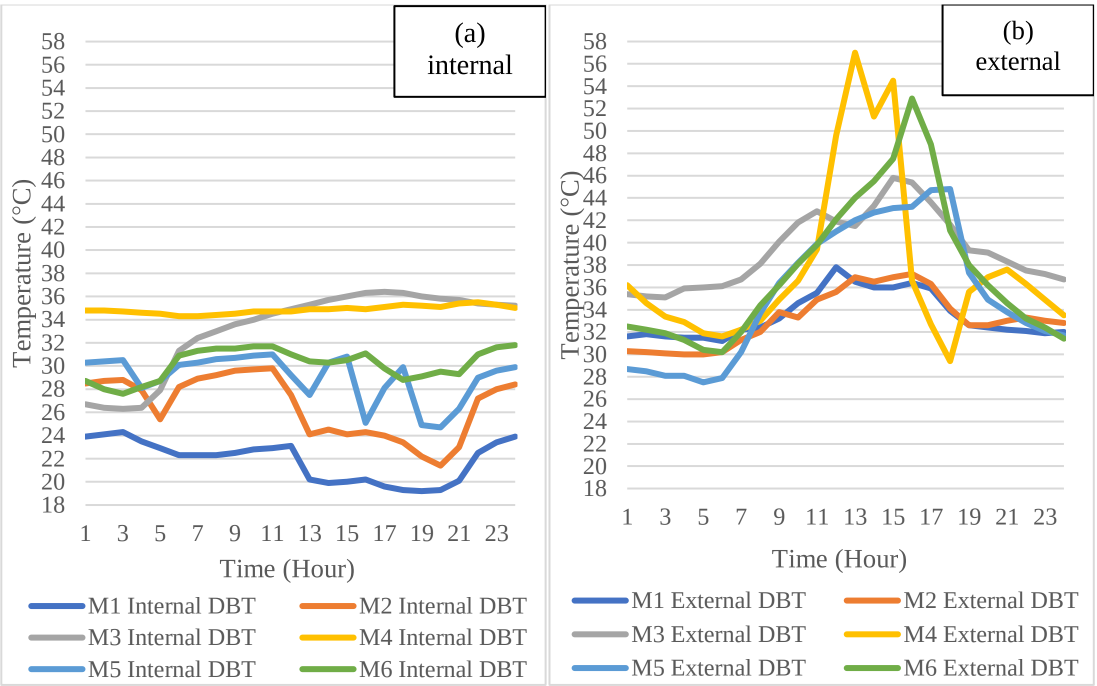


Figure 6.8. Internal DBT of all six mosques as per summer field measurement results (a). External DBT of all six mosques as per summer field measurement results (b).

Active air conditioning is important for preserving thermal comfort throughout the mosques during summer. Even though the walls and roofs' high thermal mass contributed to stability, the higher external DBT created temperature challenges that needed active cooling to make people comfortable. Mosques with intermittent occupancy and air conditioning during prayers provided evidence of the need for cooling systems to control temperature swings. The FM measurements during summer showed the importance of active cooling, particularly in high-temperature situations, while also emphasising the contribution of thermal mass to temperature stabilisation during times without air conditioning.

6.3 <u>Indoor Relative Humidity</u>

Relative humidity for all six mosques has stayed almost steady throughout the day as shown in Figure 6.15 (a). For M6’s internal RH is higher than its external RH by an average of 7.3% at any one hour during the 24-hour field measurement as per Figure 6.15 (b). For the other remaining five mosques, the internal RH is lower than the external RH by 3.4% to 11.6% at any one hour throughout the day.

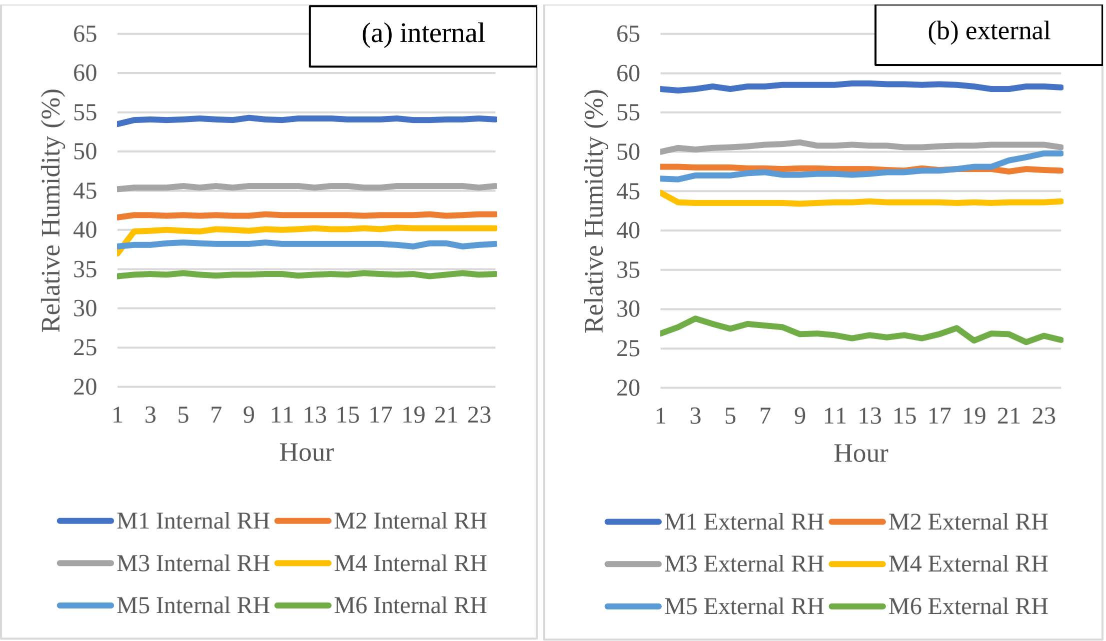


Figure 6.9. (a) Internal RH of all six mosques as per winter field measurement results, b) External RH of all six mosques as per winter field measurement results

Similar to the relative humidity situation in winter, relative humidity is constant throughout the day during summer field measurement periods. As per Figure 6.16 (a), M1, M5 and M6 all stay within the comfort zone. M2 also stays at around 38.2% RH despite an external RH of 84.5% as can be seen in Figure 6.16 (b). M3 and M4 are both naturally ventilated throughout the day, and both stay dry at 28.9% and 15.5%, respectively.

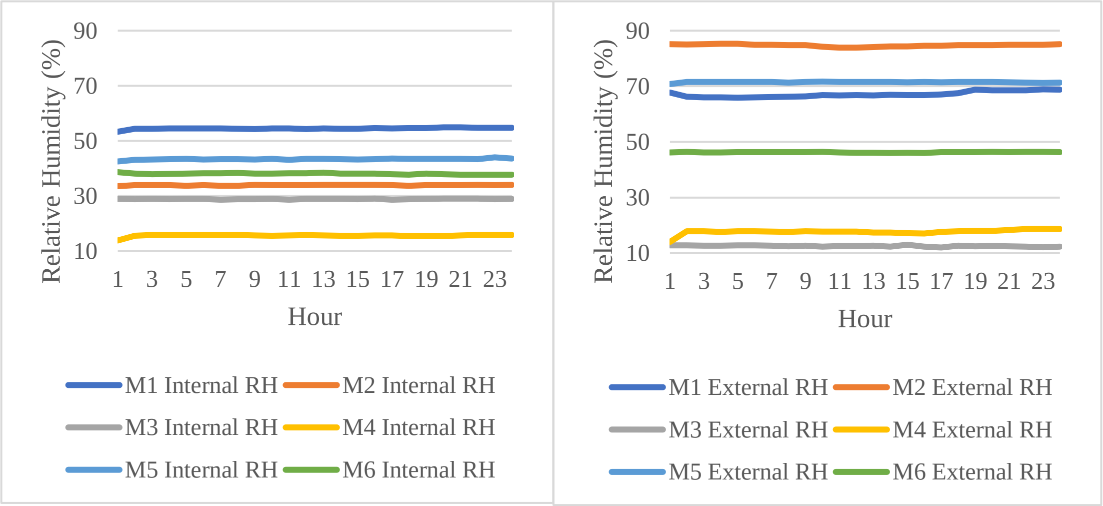


Figure 6.10. (a) Internal RH of all six mosques as per summer field measurement results, (b) External RH of all six mosques as per summer field measurement results

6.4 Indoor Air Velocity

Air velocity for all mosques studied stayed below 1 m/s in most cases. It increases above 1 m/s at a maximum distance of 1 metre directly in front of an AC. Allocated spaces for worshippers are further away from the AC of at least 2 metres in all mosques studied. For the rest of the area, air velocities stay between 0.01 and 0.6 m/s, which is not uncomfortable (Adaptive thermal comfort by Nicol, 2012).

6.5 Conclusion

The internal dry bulb temperature, relative humidity, and air velocity are all crucial factors in assessing buildings' thermal performance. Theses parameters were measured for all six mosques during the winter and summer seasons.

During winter, the internal dry bulb temperatures of all six mosques ranged between 20.9 °C and 26.5 °C, indicating that they all fall within the Muscat bioclimatic chart's comfort zone (Figure 2.3) while the external temperature ranged between 8.9 °C and 29.8 °C for all six mosques. The internal dry bulb temperature stability during winter was aided by high thermal mass, insulation, and/or internal heat gains. The difference in internal temperatures among the mosques is because the field measurements were taken on different days for each mosque, as well as the different design, building elements, and internal conditions. During winter, all mosque buildings are within the comfort range of RH except for M6 that had an internal RH of 34.4% due to the external RH in its location being too dry at 26.7%.

During summer, M1, M2, M5, and M6 all fall mostly within the comfort zone as they are air conditioned. M3 and M4 were closed due to COVID-19 regulations at the time, so the internal DBT was outside the comfort zone as they were unoccupied and unconditioned. The external temperature ranged between 27.9 °C and 52.9 °C. During summer, the internal RH was also directly corelated to the external RH at the time. All mosque buildings were within the comfort zone of RH except for M3 and M4 as they were unoccupied and unconditioned. Measured air velocity was between 0.01 and 0.6 m/s, which is not uncomfortable (Nicol, Humphreys and Roaf, 2012).

Despite thermal mass contributing to stability, active cooling is vital to counter higher external temperatures, particularly evident in intermittent occupancy situations, showing the significance of both cooling systems and thermal mass in maintaining comfort during summer.

Chapter 7. COMPUTER SIMULATION RESULTS

7.1 Introduction

The second of the two results' chapters presenting the findings derived from a series of computer simulations carried out for each of the six mosques under study. The analytical depth of the research is highlighted by the considerable number of simulations conducted, which exceeds 1,000, in order to reach the findings presented in this thesis dissertation. The simulations offer a detailed view into various aspects including dry bulb temperature (DBT), mean radiant temperature (MRT), as well as a comprehensive analysis of heat gain, heat loss, and the breakdown of different loads.

The volume of data collected is massive, requiring a structured analysis to align the findings precisely with the research objectives. The data collection involved detailed field measurements capturing minute-by-minute DBT and RH readings over 48 hours, alongside other critical data points such as surface and globe temperatures recorded during the summer. The computer simulations further enriched this data pool, providing hourly insights into DBT, RH, and load breakdowns throughout the year.

In this chapter, the spotlight is on the computer simulation results, offering a deep dive into the hourly data scrutinised for the two design days - the winter design day (day 20) and the summer design day (day 179). These days represent the periods with the minimum and maximum DBT, respectively, based in the meteorological data sourced from the Muscat International Airport's TMY file.

In this chapter, computer simulation results are presented to illustrate the thermal performance of each mosque on winter and summer design days. The analysis aims to increase the understanding of the buildings' thermal performance to arrive to a solid basis for the suggested improvement and conclusions chapters.

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7.2 Indoor Dry Bulb Temperature

7.2.1 Hudhayfah Bin Al Yaman Mosque (M1)

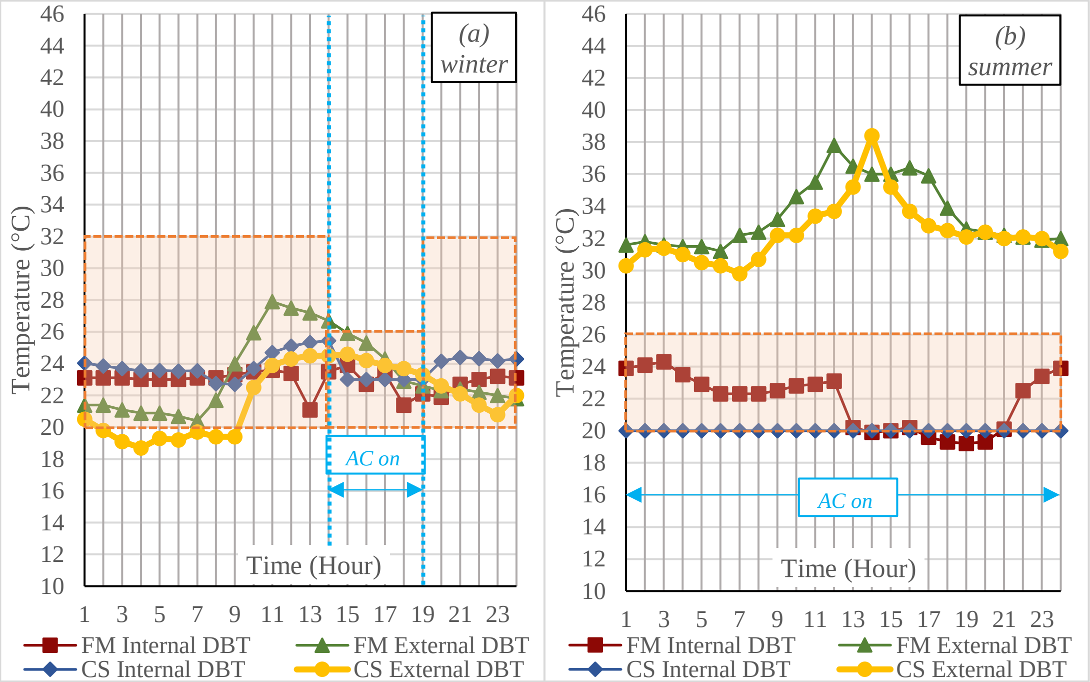


Figure 7.1: Computer Simulation Dry Bulb Temperature for Mosque 1 during (a) winter and (b) summer.

In winter, the computer simulation internal dry bulb temperature (CS internal DBT) is mostly aligned with FM internal DBT for M1 during winter as shown in Figure 7.1(a). The difference between FM and CS internal DBT from 10:00 and 19:00 is because of the difference in AC operation. While it was presumed for the computer simulation that the AC is operational between 14:00 and 19:00, the conditions observed during the field measurement was affected by the intermittent occupancy patterns and changes in air conditioning operation accordingly. Thermal comfort was achieved throughout the 24 hour period (Figure 7.1a).

In summer, FM Internal DBT ranges between 19 and 24 °C, while CS Internal DBT is constant throughout the 24 hour period at 20 °C. The AC was on throughout the 24 hour period for AC maintenance purposes, hence the relatively low temperatures shown in both CS and FM compared to the external temperatures that range between 29.8 and 38.4. Given that it was assumed during the computer simulation that the thermostat set point is set at 20 °C, the CS Internal DBT is a straight line in contrast to the FM Internal DBT appears to be more natural (Figure 7.1b).

Thermal comfort was achieved when the AC is on. Between 16:00 and 21:00, the AC was on full power causing FM Internal DBT to drop to 19 °C, which is 1 °C below the thermal comfort zone.

7.2.2 Abu Hamza Al Shari Mosque (M2)

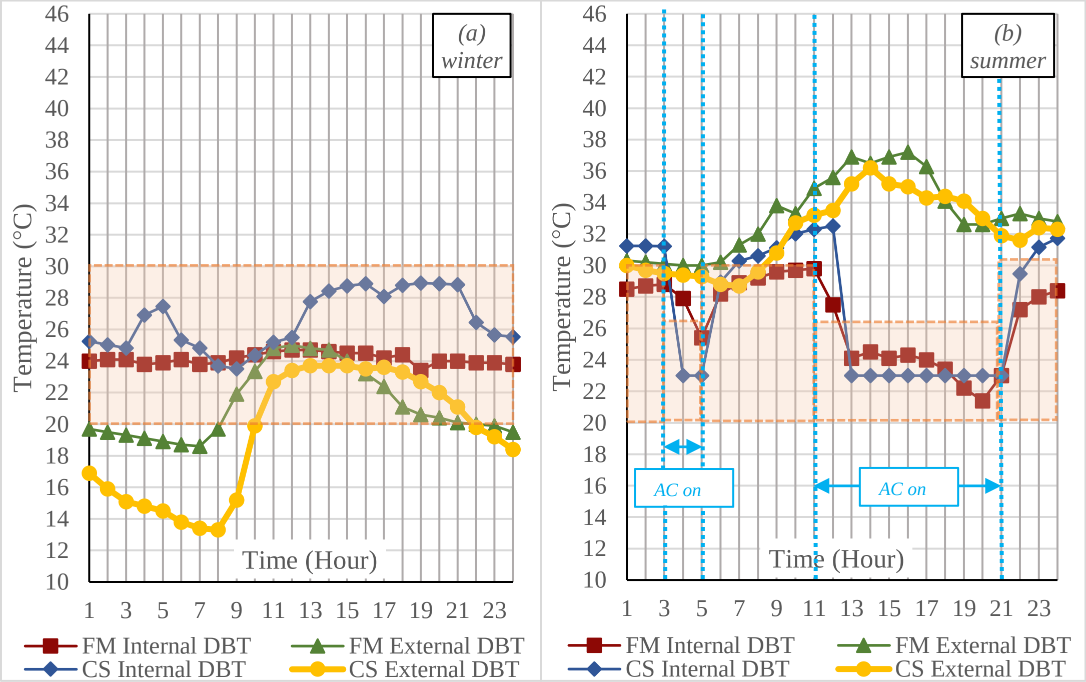


Figure 7.2: Computer Simulation Dry Bulb Temperature for Mosque 2 during (a) winter and (b) summer.

In winter, FM Internal DBT stay relatively steady at around 24 °C, while CS Internal DBT ranges between 21 and 28.9 °C as it reacts to fajr prayer occupancy between 4:00 and 5:00, and to the increase in external temperature during the day. FM External DBT and CS External DBT stay mostly below their internal DBT counterparts. Thermal comfort was achieved throughout the 24 hour period (Figure 7.2a).

In summer, during the two occupied periods of between 03:00 and 05:00, and between 12:00 and 21:00, both FM Internal DBT and CS Internal DBT decrease because of air conditioning set at 23 °C. During the unoccupied periods, FM Internal DBT and CS Internal DBT increase to a maximum of 29.8 and 33.5 °C, respectively (Figure 7.2b).

FM External DBT and CS External DBT range between 30 and 37 °C. The large difference between internal and external dry bulb temperature during the occupied periods is due to the operation of the AC system. Thermal comfort was achieved when the AC is on.

7.2.3 Othman bin Afan Mosque (M3)

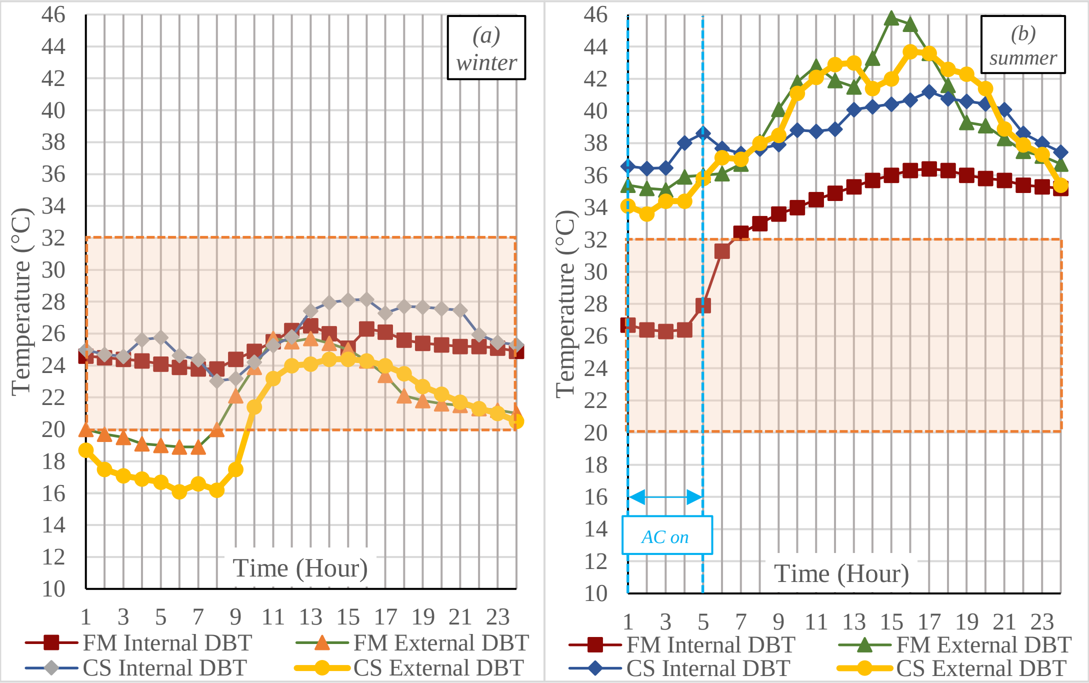


Figure 7.3: Computer Simulation Dry Bulb Temperature for Mosque 3 during (a) winter and (b) summer.

In winter, FM Internal DBT and CS Internal DBT remain between 24 and 28 °C, while FM External DBT and CS External DBT remain at mostly lower temperatures that range between 15 and 25 °C. The internal temperature stayed relatively steady and did not reflect the external temperature fluctuations (Figure 7.3a). This could be due to the low thermal conductivity of the wall construction that features marble cladding. The external walls have a u-value of 0.67 W/m^2.K and the roof has a u-value of 0.86 W/m^2.K. Thermal comfort was achieved throughout the 24 hour period.

In summer, M3 was in a free running mode this day starting from after fajr prayer at 06:00 and it remained air conditioned the day before. That is why FM Internal DBT was at 26 °C between 00:00 and 05:00. It can be noticed that all internal and external DBT increase consistently to reach their high peak of the day between 15:00 and 16:00. The internal temperature was affected by the steady raise of external temperature during the day and the difference between external and internal temperatures from the early morning hours. It can be noticed that despite the large difference between FM Internal DBT and FM External DBT of around 10 °C during the beginning of the day, FM Internal DBT gradually increased in temperature from 31.3 °C at 6:00 to 36.4 °C at 17:00. This maintained the average differential between FM Internal DBT and FM External DBT from 05:00 to 17:00 at 7 °C. This could be due to the low thermal conductivity of the wall construction. The external walls have a u-value of 0.67 W/m^2.K and the roof has a u-value of 0.86 W/m^2.K. Thermal comfort was not achieved as the air conditioning was off during the day (Figure 7.3b).

7.2.4 Sa'al Mosque (M4)

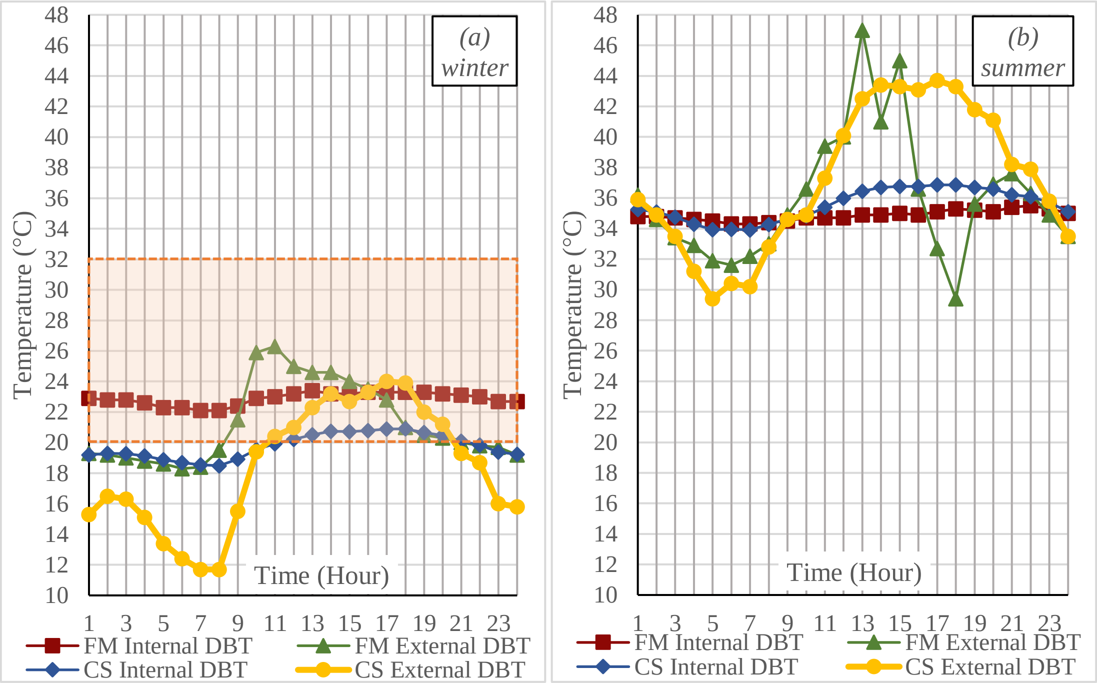


Figure 7.4: Computer Simulation Dry Bulb Temperature for Mosque 4 during (a) winter and (b) summer.

In winter, FM Internal DBT and CS Internal DBT are both consistent throughout the day at 23 and 20 °C respectively while external temperature range is between 11.7 and 22.8 °C. It is noticed that the internal temperatures are consistent for both the CS and FM despite the fluctuation of external temperatures, which could be attributed to the high thermal capacity and low thermal conductivity of the building envelope. FM Internal DBT is within the comfort zone, while CS Internal DBT is slightly below the comfort zone except between 13:00 and 20:00, when it is within the comfort zone (Figure 7.4a).

In summer, FM Internal DBT and CS Internal DBT are almost identical until 9:00 at around 35 °C. External temperature range is between 29.4 and 47 °C (Figure 7.4b). Both FM External DBT and CS External DBT begin to increase from sunrise until 13:00. FM External DBT suddenly drops at 18:00 to reach a low of 29.4 °C, which could be because of winds in the mosque area. FM Internal DBT and CS Internal DBT reach a range between 33.5 and 36.3 °C between 21:00 and 00:00. M4 during summer is totally outside the comfort zone as it is below RH of 24% and has internal temperatures always above 30 °C. In parallel with the winter results, both the CS and FM methods demonstrated that M4 maintained consistent internal temperatures throughout the day, even in the face of external temperature variations. This can be attributed to the high thermal capacity and low thermal conductivity of the building envelope. The external clay walls with a U-value of 0.595 W/m²·K and the roof with a U-value of 1.198 W/m²·K was essential in maintaining internal DBT stable and consistent over the course of the day.

7.2.5 Al Wafi Mosque (M5)

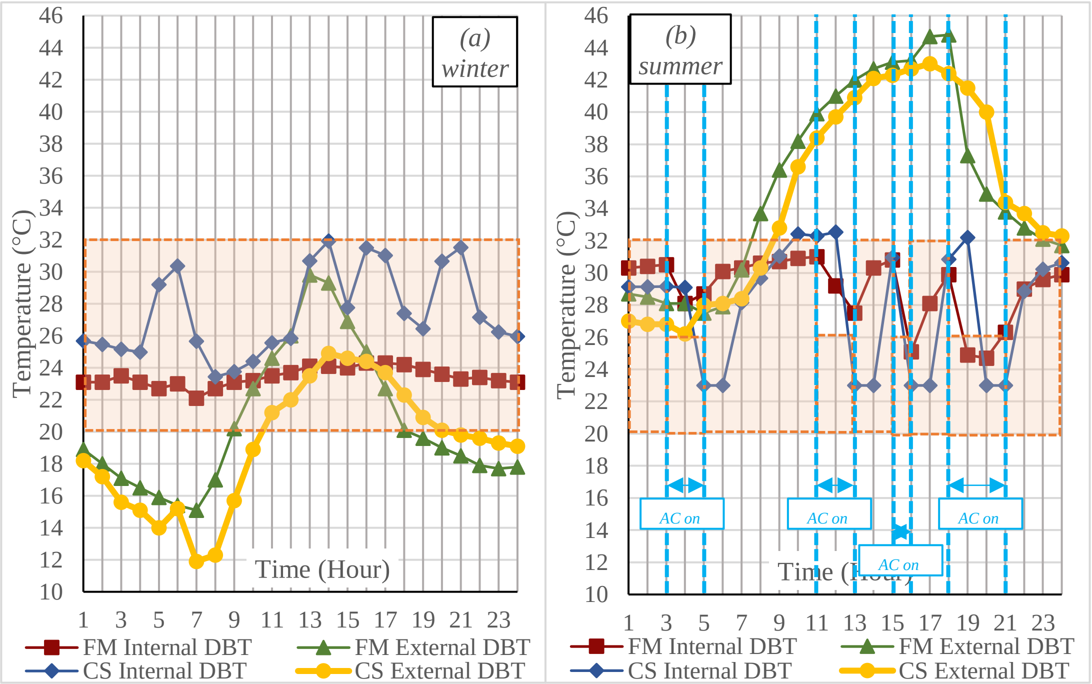


Figure 7.5: Computer Simulation Dry Bulb Temperature for Mosque 5 during (a) winter and (b) summer.

In winter, FM Internal DBT stayed consistent between 22.1 and 24.3 °C, while CS Internal DBT was fluctuating between 22.7 and 31.9 °C (Figure 7.5a). External DBT range between 11.9 and 29.8 °C. It is noticed that the FM Internal DBT stayed consistent throughout the 24 period, which represents measurement of one single point inside the mosque. CS Internal DBT fluctuated sharply because of changes in ventilation, occupation, and external temperature. In the real world as represented by the FM Internal DBT, the changes cancel each other and do not occur suddenly, hence a mostly consistent line for FM Internal DBT. This could be also attributed to the high thermal capacity and low thermal conductivity of the building envelope. M5 external walls feature an average U-value of 0.722 W/m^2.K and the roof feature an average U-value of 1.25 W/m^2.K.

In summer, FM and CS internal DBT ranged between 23 and 32.5 °C, while FM and CS external DBT range between 26.2 and 44.8 °C (Figure 7.5b). FM Internal DBT increased by of 3.1 °C while CS Internal DBT increased by 9.5 °C during the morning natural ventilation period (a 6 hour period from 6:00 to 12:00), which shows a discrepancy between the field measurement and computer simulation, because of the nature of the two methodologies. Field measurements capture temperature data at a specific location, whereas computer simulations provide an average temperature estimation across the entire prayer hall zone. Consequently, areas proximate to the external wall show a more rapid and elevated temperature increase, while the interior zones experience a more gradual thermal shift. During the rest of the day, both FM Internal DBT and CS Internal DBT represent a decrease in temperature when the mosque is occupied and air conditioned, and an increase when it is unoccupied and unconditioned.

7.2.6 Aal Hamoodah Mosque (M6)

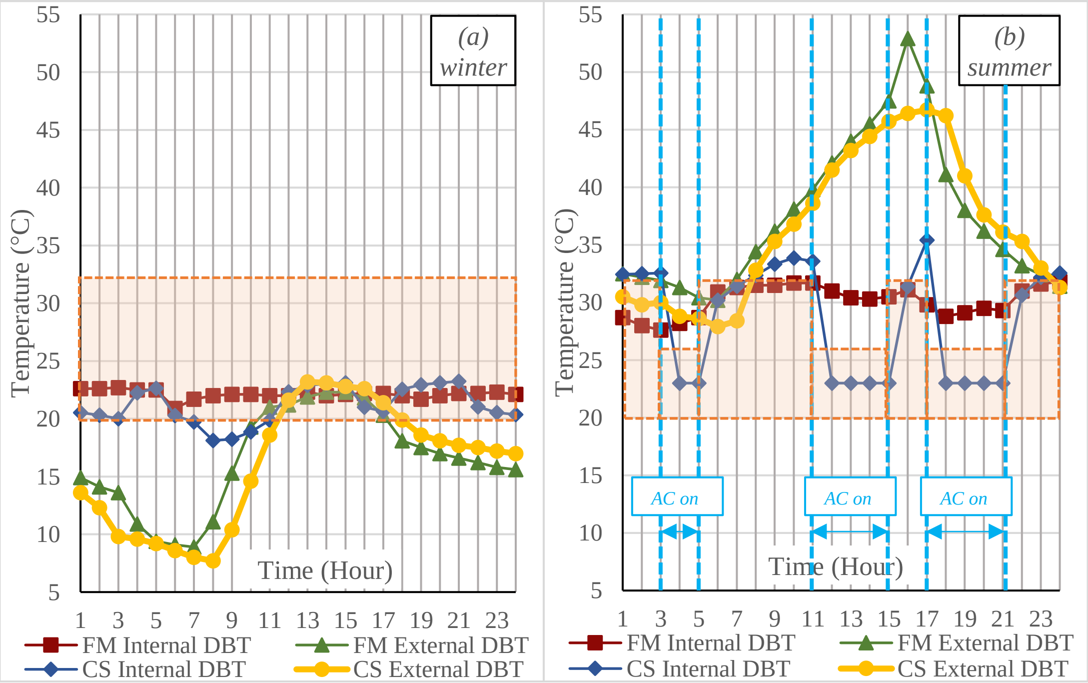


Figure 7.6: Computer Simulation Dry Bulb Temperature for Mosque 6 during (a) winter and (b) summer.

In winter, FM Internal DBT stayed between 18.2 and 23.4 °C, while CS Internal DBT was fluctuating between 7.7 and 23.2 °C (Figure 7.6a). It was noticed that the internal DBT stays almost constant throughout the 24 period despite the low external temperatures. There were some fluctuations especially for CS Internal DBT due to the internal conditions.

In summer, FM Internal DBT stayed consistent between 27.6 and 31.7 °C while CS Internal DBT was fluctuating between 27.9 and 52.9 °C (Figure 7.6b). Although the external temperature increased by 10 °C from 30 to 40 °C during the morning natural ventilation period (a 6 hour period from 5:30 to 11:30), FM Internal DBT showed an increase of 4 °C from 28 to 32 °C. This could be attributed to the high thermal capacity and low thermal conductivity of the building envelope. The external clay walls has U-value of 0.698 W/m2.K while the clay roof has a U-value of 1.736 W/m2.K.

FM Internal DBT increased by of 3 °C while CS Internal DBT increased by 10.6 °C during the morning natural ventilation period (a 6 hour period from 6:00 to 12:00), which shows a discrepancy between the field measurement and computer simulation. Similar to Mosque 5, the reason behind this discrepancy is the nature of the two methodologies of field measurements and computer simulations. Field measurements capture temperature data at a specific location, whereas computer simulations provide an average temperature estimation across the entire prayer hall zone. Consequently, areas proximate to the external wall show a more rapid and elevated temperature increase, while the interior zones experience a more gradual thermal shift. During the rest of the day, both FM Internal DBT and CS Internal DBT represent a decrease in temperature when the mosque is occupied and air conditioned, and an increase when it is unoccupied and unconditioned. Contrary to Mosque 5, Mosque 6 exhibits a more modest reduction in FM Internal DBT of 2.3°C during the night occupancy period. In contrast, Mosque 5 experiences a more substantial decrease of 5.2°C in FM Internal DBT when occupied at night, due to the size difference of the two mosques. Mosque 6 is 735 m^2, while Mosque 5 is 470 m^2, which made the field measurement thermal shift in Mosque 6 more gradual than Mosque 5.

7.2.7 Summary

Across all mosques, both the field measurement (FM) and computer simulation (CS) methods have revealed key insights into their thermal performance during winter and summer conditions. One common theme is the significance of the building envelope in maintaining stable internal temperatures. The high thermal capacity and low thermal conductivity of the walls and roofs contribute to internal temperature consistency despite external temperature fluctuations.

In winter, both FM and CS methods consistently show that most mosques maintained thermal comfort, with internal temperatures generally falling within the comfort zone throughout the day. The stability of internal temperatures is attributed to the effective insulation, high thermal mass, and internal heat gains in the buildings. The discrepancy between FM and CS internal DBT can be attributed to factors such as intermittent occupancy and variations in AC operation between the two methods.

During summer, the importance of AC becomes prominent. AC operation during occupied periods helps maintain thermal comfort. The differences between FM and CS internal DBT during these times reflect variations in AC operation and thermostat settings.

7.3 Indoor Mean Radiant Temperature

7.3.1 Hudhayfah Bin Al Yaman Mosque (M1)

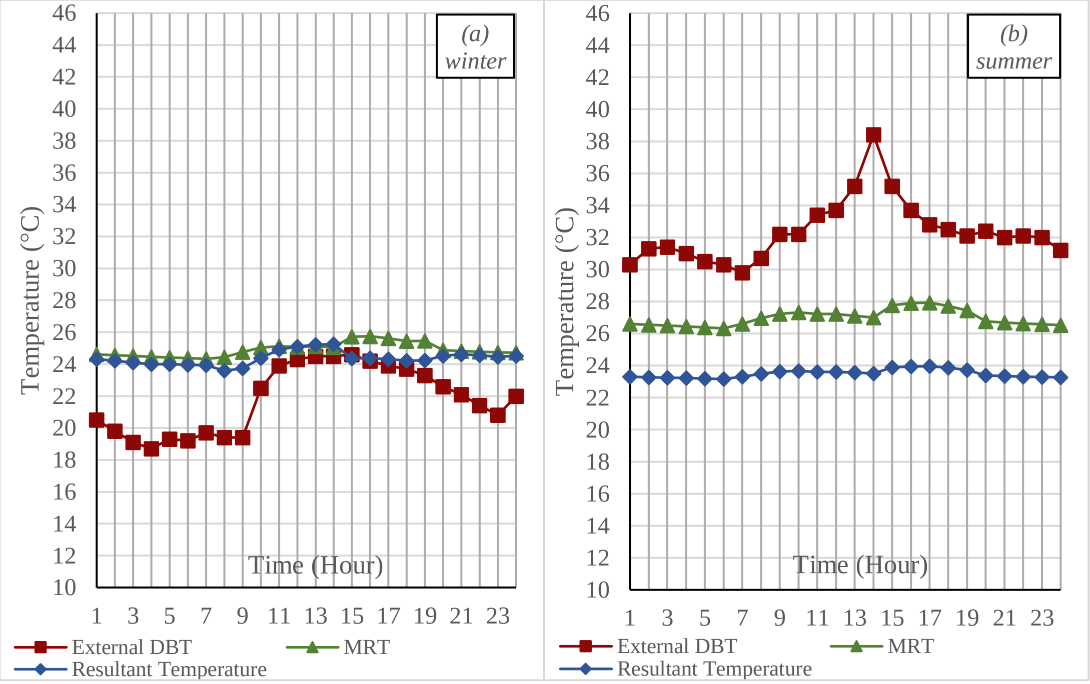


Figure 7.7: Computer Simulation Mean Radiant Temperature for Mosque 1 during (a) winter design day and (b) summer design day.

In winter, MRT and Resultant Temperature (RT) are relatively consistent between 24 and 26 °C throughout the 24 hour period while external temperature is low during the morning between 18.7 and 20.5 °C, and closer to MRT and RT during the afternoon (Figure 7.7a). The external temperature starts to decrease continuously from 24.2 °C at 15:00 to 20.8 at 23:00.

In summer, MRT stays between 26 and 28 °C while RT stayed between 23 and 24 °C (Figure 7.7b). MRT is higher during the summer due to external temperatures causing higher surface temperatures and more radiation from the building envelope. Moreover, the air conditioning set point caused RT to stay consistent around the 23 °C mark throughout the day.

7.3.2 Abu Hamza Al Shari Mosque (M2)

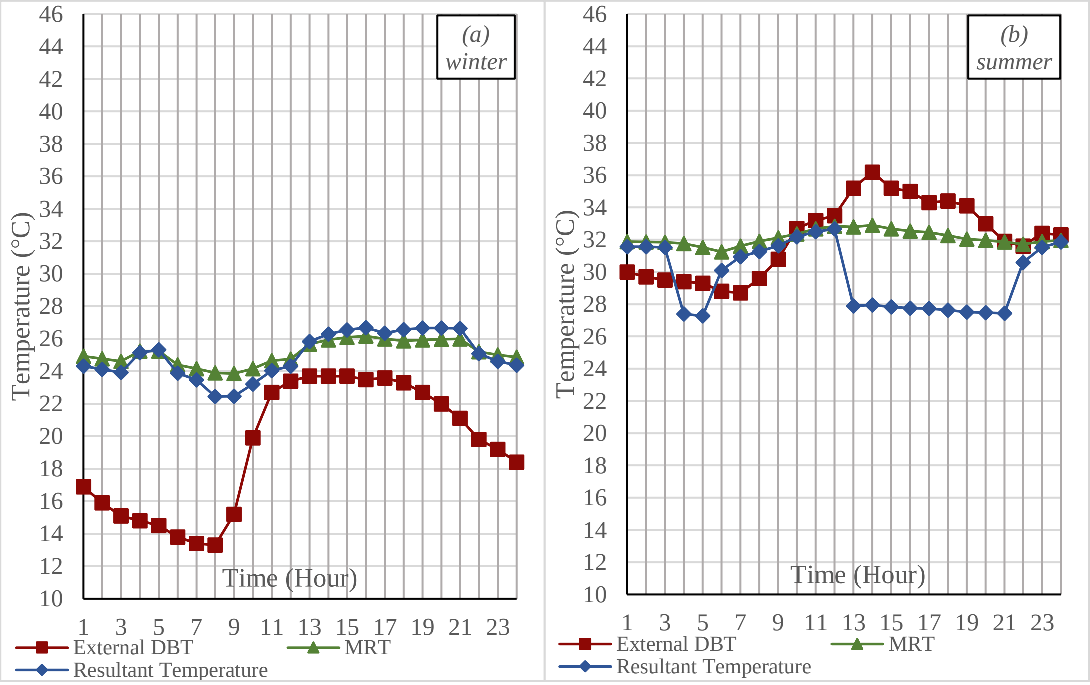


Figure 7.8: Computer Simulation Mean Radiant Temperature for Mosque 2 during (a) winter design day and (b) summer design day.

In winter, MRT and RT are fluctuated between 22 and 27 °C throughout the 24 hour period while external temperature is low during the morning between 16.9 and 13.3 °C, and closer to MRT and RT during the afternoon (Figure 7.8a). The external temperature starts to decrease continuously from 23.6 °C at 17:00 to 18.4 at 00:00.

In summer, RT reaches a low of 27.3 °C range during the morning occupancy period and a low of 27.4 °C during the afternoon occupancy periods (Figure 7.8b). This is due to the air conditioning during the occupancy periods. MRT stayed relatively consistent at around 32 °C mark while the external DBT fluctuated between 28.7 and 36.2 °C throughout the 24 hour period.

7.3.3 Othman bin Afan Mosque (M3)

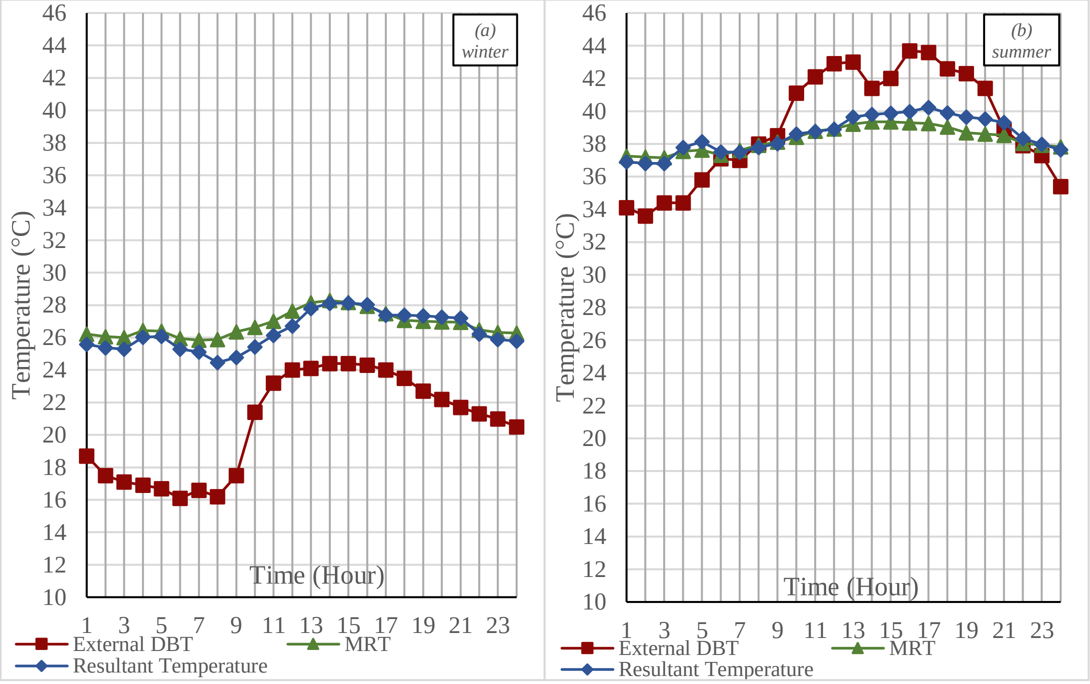


Figure 7.9: Computer Simulation Mean Radiant Temperature for Mosque 3 during (a) winter design day and (b) summer design day.

In winter, the external DBT fluctuated between 16 and 24 °C, but MRT and RT are aligned and stay between 24 and 28 °C, due to the space being unconditioned and unoccupied (Figure 7.9a).

In summer, the DBT fluctuates between 34 and 44 °C, but the MRT and RT are aligned stay between 37 and 40 °C (Figure 7.9b). M3 remained unoccupied and unconditioned during the daytime, resulting in an alignment of MRT and RT throughout the entire day.

7.3.4 Sa'al Mosque (M4)

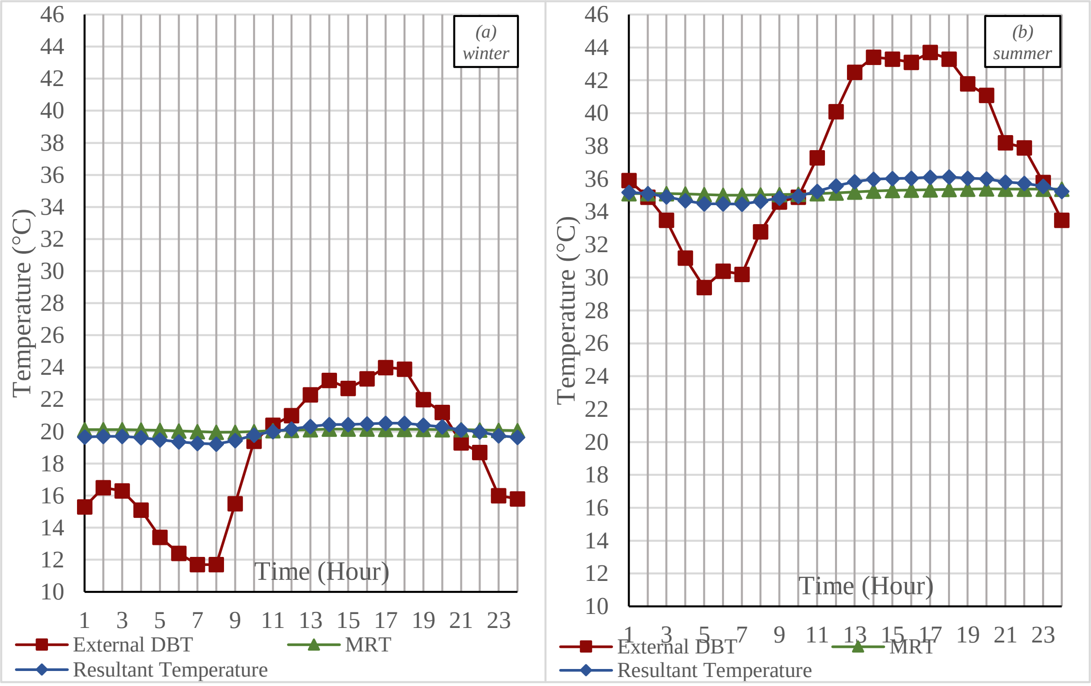


Figure 7.10: Computer Simulation Mean Radiant Temperature for Mosque 4 during (a) winter design day and (b) summer design day.

In winter, the external temperature fluctuates between 12 and 24 °C, but MRT and RT stayed relatively constant at around 19 to 20 °C (Figure 7.10a). There is an alignment between MRT and RT throughout the winter design day, due to unoccupied and unconditioned Mosque 4 during winter.

In summer, the DBT fluctuates between 30 and 44 °C, but the MRT and RT stayed between 34 and 36 °C (Figure 7.10b). There is an alignment between MRT and RT throughout the summer design day, due to unoccupied and unconditioned Mosque 4 during summer.

7.3.5 Al Wafi Mosque (M5)

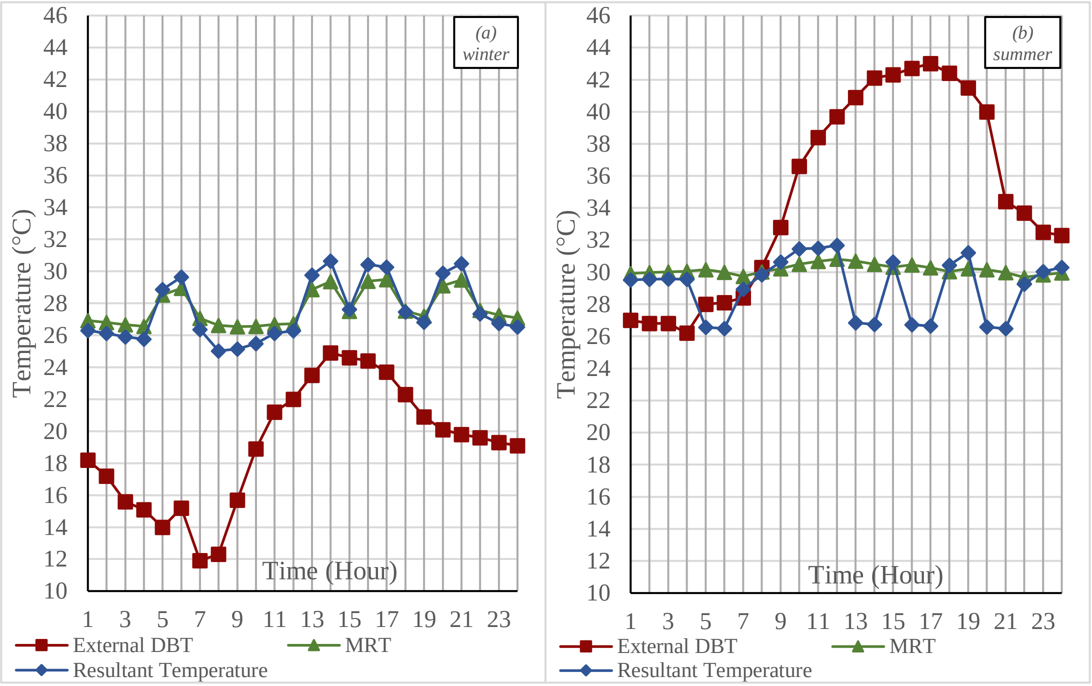


Figure 7.11: Computer Simulation Mean Radiant Temperature for Mosque 5 during (a) winter design day and (b) summer design day.

In winter, external DBT fluctuated between 11.9 and 24.9 °C, but MRT and RT fluctuate between 25 and 31 °C (Figure 7.11a). Mosque 5 was unconditioned during the winter design day.

In summer, external DBT increased from 26.2 °C at 4:00 to 43 °C at 17:00 then it decreased to reach 32.3 °C by 00:00. Since the air conditioning during occupancy periods, RT fluctuate between 26 and 32 °C, but MRT stayed constant at around 30 °C (Figure 7.11b). RT fluctuations are more pronounced and happen rapidly due to the air conditioning decreasing the internal DBT, and hence immediately decreasing the internal RT. MRT changes happen more gradually as it is tied to building envelope surface temperature, which in this case feature a high thermal mass clay walls and roofs that have time constants between 15 and 80 hours.

7.3.6 Aal Hamoodah Mosque (M6)

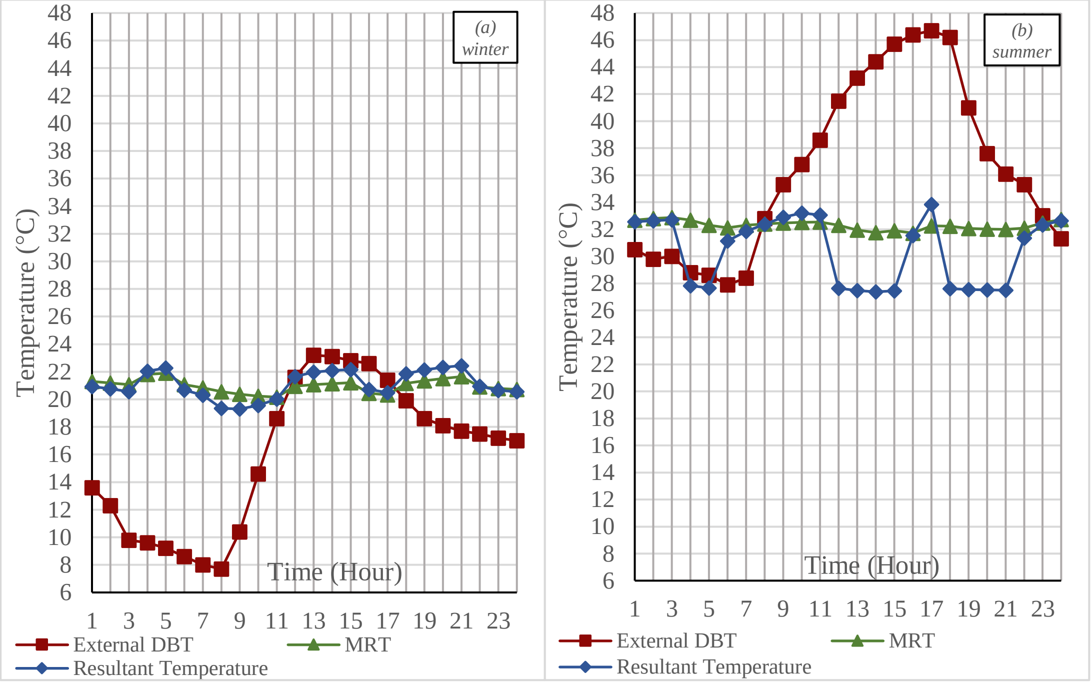


Figure 7.12: Computer Simulation Mean Radiant Temperature for Mosque 6 during (a) winter design day and (b) summer design day.

In winter, the external temperature fluctuates between 7.7 and 23.2 °C, but MRT and RT fluctuate between 19.3 and 22.4 °C (Figure 7.12a).

In summer, external DBT increases from 27.9 at 6:00 to 46.3 °C at 18:00 then it decreases to reach 31.3 °C by 00:00 (Figure 7.12b). Since the air conditioning during occupancy periods, RT fluctuates between 27.6 and 33.8 °C, but MRT stays constant at around 32°C. RT fluctuations are more pronounced and happen rapidly due to the air conditioning decreasing the internal DBT, and hence immediately decreasing the internal RT. MRT changes happen more gradually as it is tied to building envelope surface temperature, which in this case feature a high thermal mass clay walls and roofs that have time constants between 14.3 and 54.8 hours.

7.4 Heat Gain and Loss Analysis

The amount of heat transfer (heat gain or loss) through the different layers of a construction is called "conduction" as per the TAS manual. In the figures of this section, the heat gain and loss are measured in kilowatts (kW). If the value is positive, it means heat gain, and if the value is negative, it means heat loss (*Surface Filter — TSD 9.5.4 documentation*, 2023).

This section analyses and discusses heat gain and loss by conduction through the various elements of the building envelope. Heat gain and loss through convection and radiation are not discussed in this section because they are assumed to be similar between the different mosques. Due to the assumption that external building materials have light colours and almost identical solar absorption and convection coefficients, there is negligible difference in external incident solar and external convection on opaque external building elements.

7.4.1 Hudhayfah Bin Al Yaman Mosque (M1)

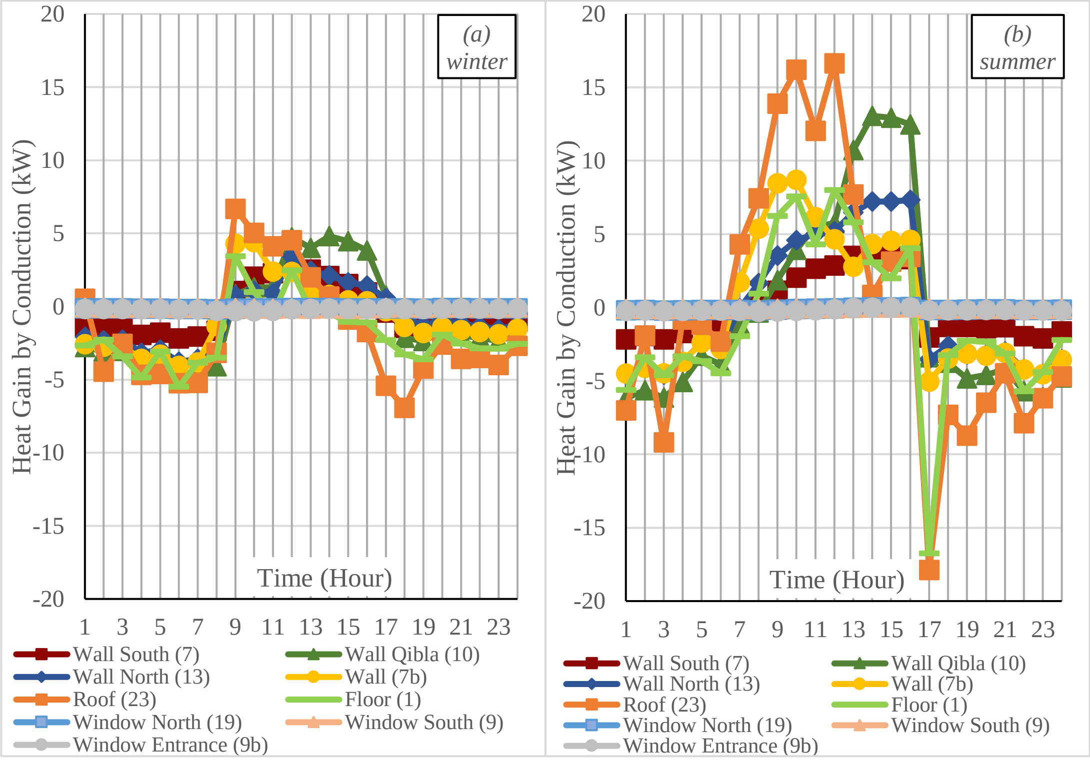


Figure 7.13: Heat gain and loss by conduction of Mosque 1’s building elements during winter design day (a) and summer design day (b).

In winter, all M1’s building fabric elements gain heat through conduction from 09:00 to around 16:00 as shown in Figure 7.13a. After the daytime thermal gain, the building experiences a period of nocturnal heat loss that persists until the following morning. This thermal dissipation is triggered by the internal ST exceeding the external ST. The roof has a diurnal peak heat gain of around 6.7 kW at 09:00 and a diurnal peak heat loss of around 6.9 kW at 18:00.

In summer, all M1’s building fabric elements gain heat through conduction from 06:00 to around 16:00 as shown in Figure 7.13b. After the daytime thermal gain, the building experiences a period of nocturnal heat loss that persists until the following morning. This thermal dissipation is triggered by the internal ST exceeding the external ST. The roof has a diurnal peak heat gain of around 16.6 kW at 12:00 and a diurnal peak heat loss of around 17.9 kW at 17:00. All the other building fabric elements follow a similar pattern and have their peak heat gain and heat loss around the same times during the summer design day (day 179).

7.4.2 Abu Hamza Al Shari Mosque (M2)

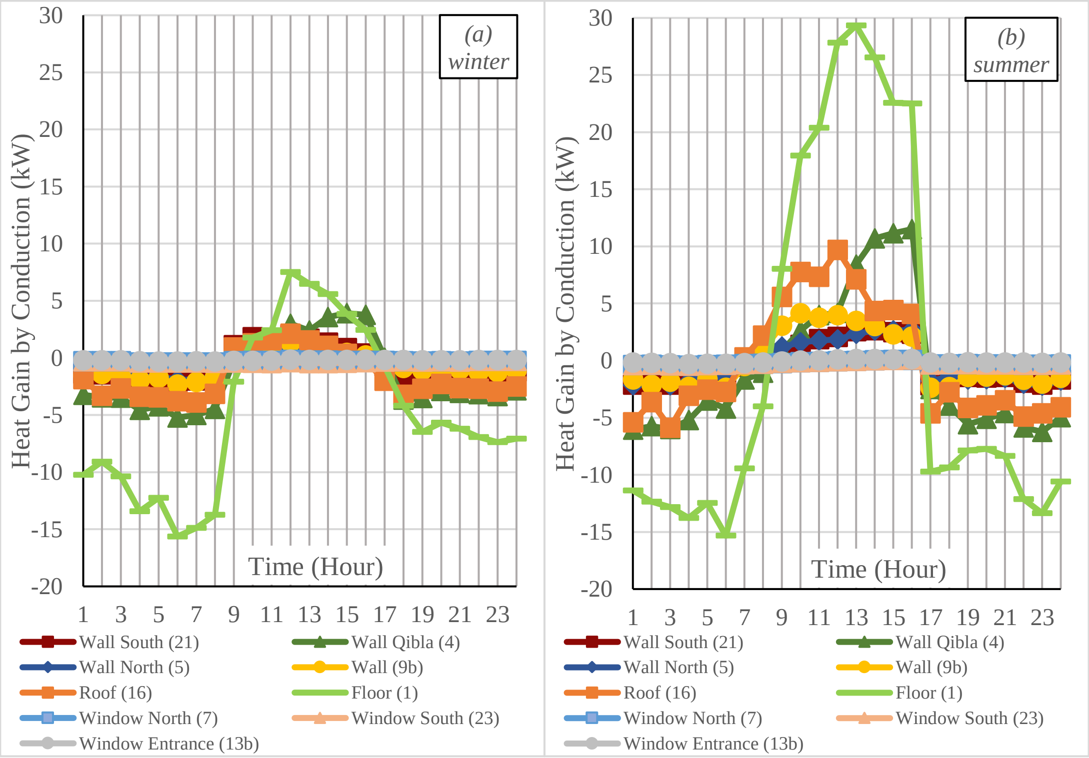


Figure 7.14: Heat gain and loss by conduction of Mosque 2’s building elements during winter design day (a) and summer design day (b).

In winter, all M2’s building fabric elements gain heat through conduction from 10:00 to around 17:00 as shown in Figure 7.14a. After the daytime thermal gain, the building experiences a period of nocturnal heat loss that persists until the following morning. This thermal dissipation is triggered by the internal ST exceeding the external ST. The floor heat gain and heat loss are the highest as part of the mosques as this represents the external courtyard floor, which should be ignored. The second highest peak heat gain in the Figure 7.14a is Qibla Wall heat gain of 3.86 kW at 15:00. The second highest peak heat loss is the Qibla wall heat loss of 5.2 kW at 06:00.

In summer, all M2’s building fabric elements gain heat through conduction from 09:00 to around 16:00 as shown in Figure 7.14b. After the daytime thermal gain, the building experiences a period of nocturnal heat loss that persists until the following morning. This thermal dissipation is triggered by the internal ST exceeding the external ST. The floor has a diurnal peak heat gain of around 29.3 kW at 13:00 and a diurnal peak heat loss of around 15.3 kW at 06:00. The floor heat gain and heat loss are the highest as part of the mosques as this represents the external courtyard floor, which should be ignored. The second highest peak heat gain in the Figure 7.14b is Qibla Wall heat gain of 9.7 kW at 16:00. The second highest peak heat loss is the Qibla wall heat loss of 5.4 kW at 00:00.

7.4.3 Othman bin Afan Mosque (M3)

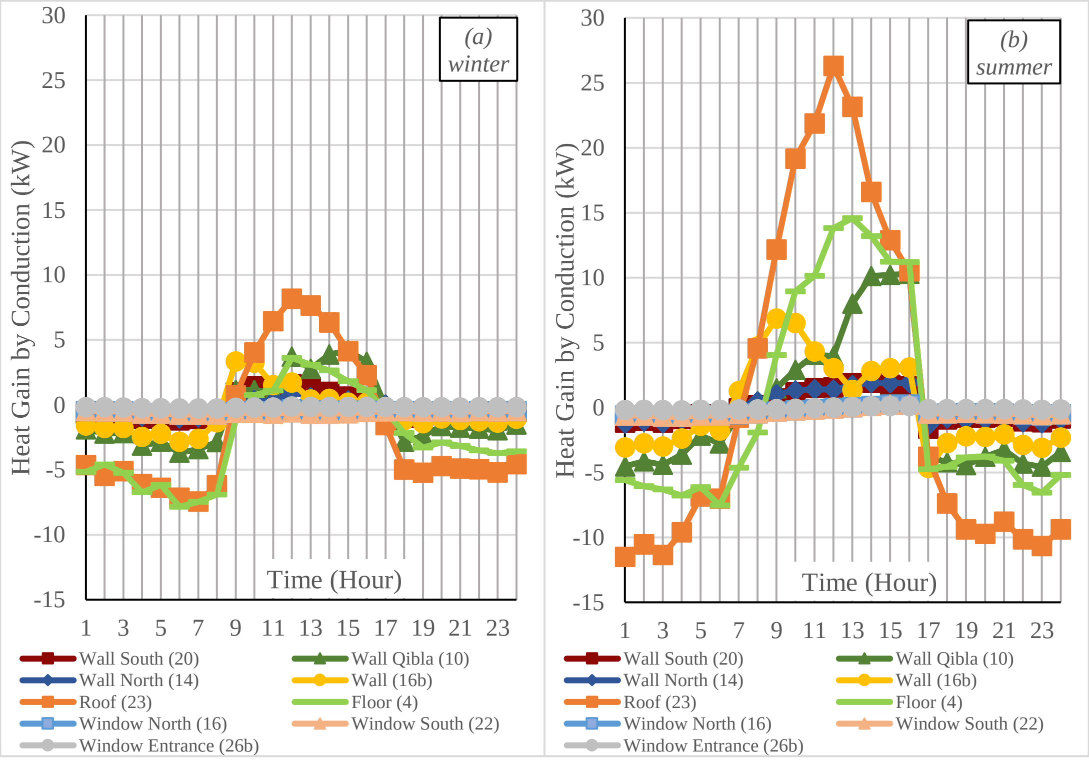


Figure 7.15: Heat gain and loss by conduction of Mosque 3’s building elements during winter design day (a) and summer design day (b).

In winter, all M3’s building fabric elements gain heat through conduction from 09:00 to around 15:00 as shown in Figure 7.15a. After the daytime thermal gain, the building experiences a period of nocturnal heat loss that persists until the following morning. This thermal dissipation is triggered by the internal ST exceeding the external ST. The roof has the highest diurnal peak heat gain of around 8.2 kW at 12:00 while the floor has the highest diurnal peak heat loss of 7.8 kW at 6:00. The roof has close second highest diurnal peak heat loss of 7.45 kW. All the other building fabric elements follow a similar pattern and have their peak heat gain and heat loss around the same times during the winter design day (day 20).

In summer, all M3’s building fabric elements gain heat through conduction from 08:00 to around 16:00 as shown in Figure 7.15b. After the daytime thermal gain, the building experiences a period of nocturnal heat loss that persists until the following morning. This thermal dissipation is triggered by the internal ST exceeding the external ST. The roof has a diurnal peak heat gain of 26.2 kW at 12:00 and a diurnal peak heat loss of 11.5 kW at 01:00. All the other building fabric elements follow a similar pattern and have their peak heat gain and heat loss around the same times during the summer design day (day 179).

7.4.4 Sa’al Mosque (M4)

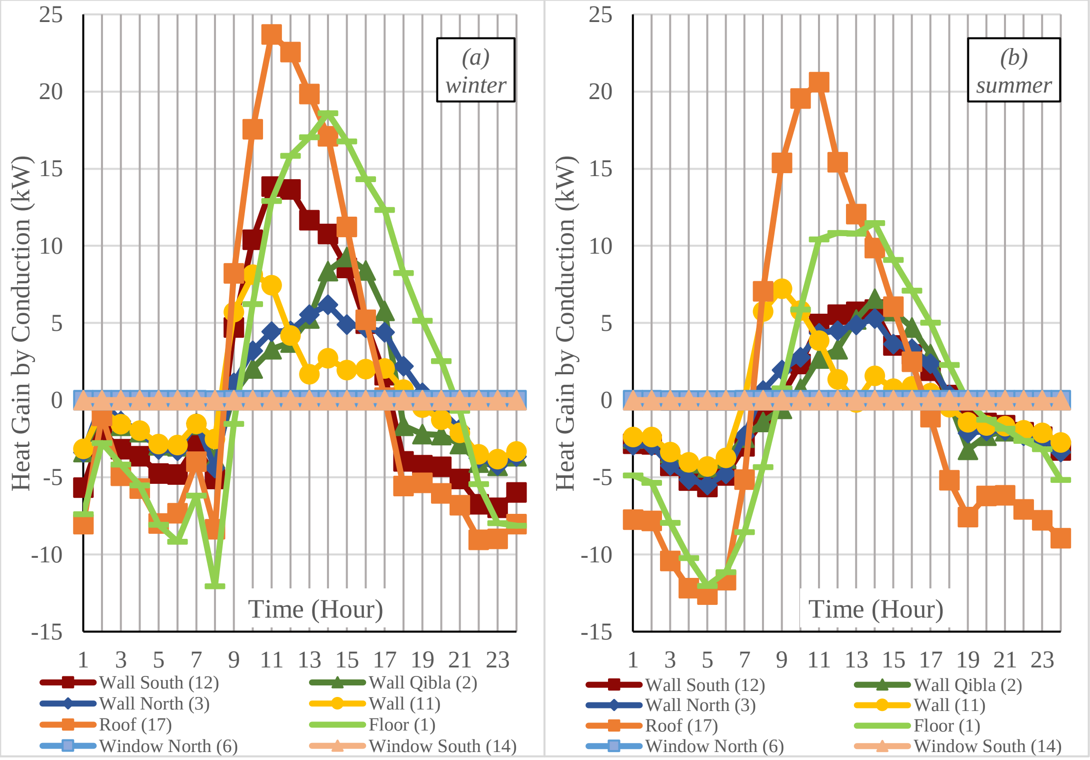


Figure 7.16: Heat gain and loss by conduction of Mosque 4’s building elements during winter design day (a) and summer design day (b).

In winter, all M4’s building fabric elements gain heat through conduction from 09:00 to around 18:00 as shown in Figure 7.16a. After the daytime thermal gain, the building experiences a period of nocturnal heat loss that persists until the following morning. This thermal dissipation is triggered by the internal ST exceeding the external ST. The roof has a diurnal peak heat gain of around 22.5 kW at 11:00. The floor has the highest diurnal peak heat loss of 12 kW at 08:00. The roof has the second highest diurnal peak heat loss of 8.4 kW at 08:00. All the other building fabric elements follow a similar pattern and have their peak heat gain and heat loss around the same times during the winter design day (day 20).

In summer, all M4's building fabric elements gain heat through conduction from 08:00 to around 16:00 as shown in Figure 7.16b. After the daytime thermal gain, the building experiences a period of nocturnal heat loss that persists until the following morning. This thermal dissipation is triggered by the internal ST exceeding the external ST. The roof has a diurnal peak heat gain of around 20 kW at 11:00 and a diurnal peak heat loss of around 12.6 kW at 05:00. All the other building fabric elements follow a similar pattern and have their peak heat gain and heat loss around the same times during the summer design day (day 179).

7.4.5 Al Wafi Mosque (M5)

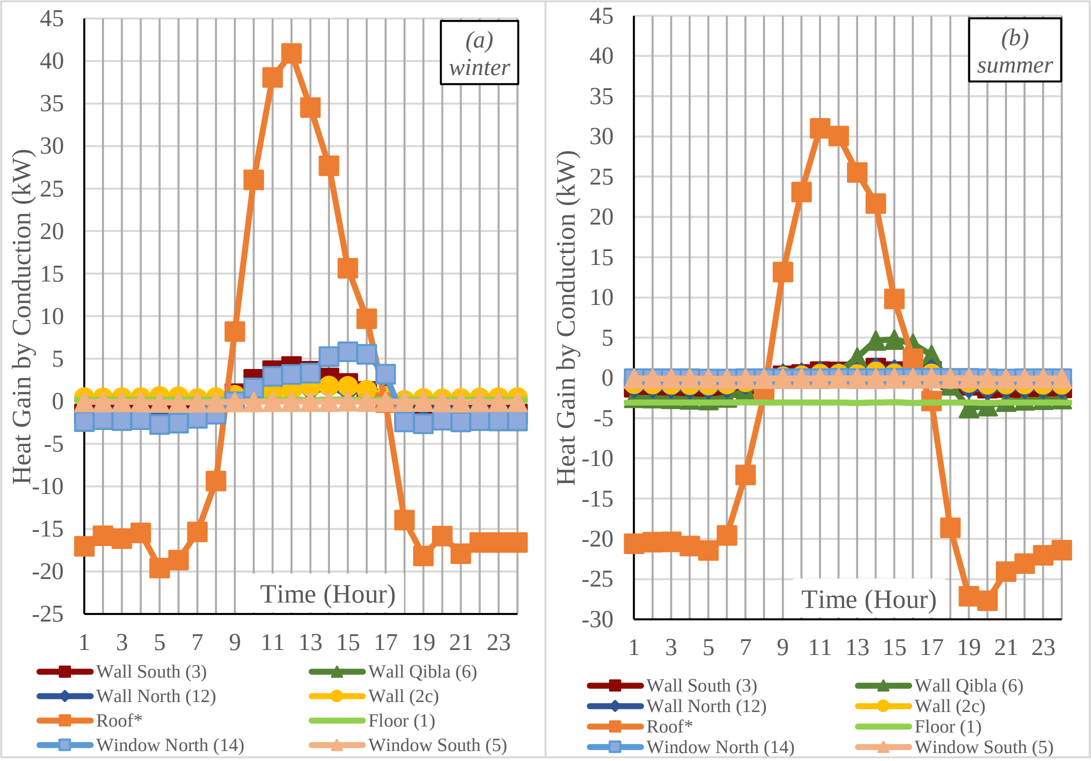


Figure 7.17: Heat gain and loss by conduction of Mosque 5's building elements during winter design day (a) and summer design day (b).

In winter, all M5's building fabric elements gain heat through conduction from 09:00 to around 17:00 as shown in Figure 7.17a. After the daytime thermal gain, the building experiences a period of nocturnal heat loss that persists until the following morning. This thermal dissipation is triggered by the internal ST exceeding the external ST. The roof has a diurnal peak heat gain of around 40.9 kW at 12:00 and a diurnal peak heat loss of around 19.5 kW at 05:00. All the other building fabric elements follow a similar pattern and have their peak heat gain and heat loss around the same times during the winter design day (day 20).

In summer, all M5's building fabric elements gain heat through conduction between 08:00 and 17:00 as shown in Figure 7.17b. After the daytime thermal gain, the building experiences a period of nocturnal heat loss that persists until the following morning. This thermal dissipation is triggered by the internal ST exceeding the external ST. The roof has a diurnal peak heat gain of around 30 kW at 11:00 and a diurnal peak heat loss of around 27.7 kW at 20:00. All the other elements follow a similar pattern and have their peak heat gain and heat loss around the same times during day 179.

7.4.6 Aal Hamoodah Mosque (M6)

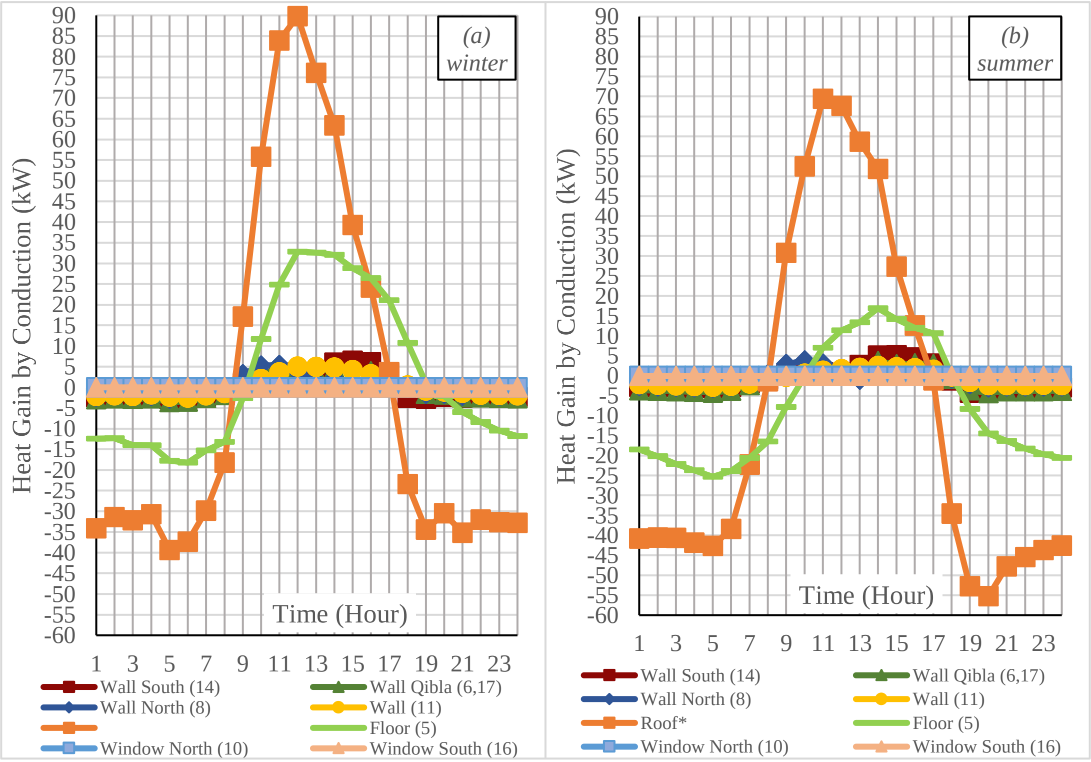


Figure 7.18: Heat gain and loss by conduction of Mosque 6's building elements during winter design day (a) and summer design day (b).

In winter, all M6's building fabric elements gain heat through conduction from 09:00 to around 15:00 as shown in Figure 7.18a. After the daytime thermal gain, the building experiences a period of nocturnal heat loss that persists until the following morning. This thermal dissipation is triggered by the internal ST exceeding the external ST. The roof has a diurnal peak heat gain of around 89.8 kW at 12:00 and a diurnal peak heat loss of 39.4 kW at 05:00. All the other building fabric elements follow a similar pattern and have their peak heat gain and heat loss around the same times during the winter design day (day 20).

In summer, all M6's building fabric elements gain heat through conduction from 06:00 to around 16:00 as shown in Figure 7.18b. After the daytime thermal gain, the building experiences a period of nocturnal heat loss that persists until the following morning. This thermal dissipation is triggered by the internal ST exceeding the external ST. The roof has a diurnal peak heat gain of around 69.4 kW at 11:00 and a diurnal peak heat loss of around 55.3 kW at 20:00. All the other building fabric elements follow a similar pattern and have their peak heat gain and heat loss around the same times during the summer design day (day 179).

7.4.7 Heat Gain and Loss Analysis Summary

In winter, the mosques generally experience heat gain through conduction from mid-morning to late afternoon, followed by a period of nocturnal heat loss. For instance, in Mosque 1, the roof reaches a diurnal peak heat gain of approximately 6.7 kW at 09:00 and a peak heat loss of around 6.9 kW at 18:00. This pattern of diurnal heat gain and nocturnal heat loss is triggered when the internal surface temperature (ST) exceeds the external ST. Mosque 6's roof has a diurnal peak heat gain of around 89.8 kW at 12:00 and a diurnal peak heat loss of 39.4 kW at 05:00. It is noticed that contemporary mosques (M1, M2, M3) have a relatively lower heat gain and heat loss relative to their floor area when compared with traditional mosques (M4, M5, and M6) due to the high time constant of clay walls and roofs that reach can reach up to 80 hours (while external concrete walls can have about 8.5 hours time constant when insulated or 3.5 hours when uninsulated).

In summer, the mosques experience a more intense cycle of heat gain and loss. For example, in Mosque 3, the roof reaches a diurnal peak heat gain of 26.2 kW at 12:00 and a peak heat loss of 11.5 kW at 01:00. Similar to the winter scenario, the mosques undergo a period of nocturnal heat loss after daytime thermal gain, prompted by the internal ST exceeding the external ST. Similarly to the winter scenario, the traditional mosques experienced higher heat gains and heat losses due to their higher time constants, which extended up to 80 hours.

7.5 Loads Breakdown

This section outlines the breakdown of the highest loads for each case study. Definitions of the parameters presented are as per the TAS EDSL software theory manual, which may differ from those found in reference books and other software (EDSL, 2020):

- Solar gain is “the sum of the surface solar gains for all the surfaces facing into the zone.”
- Lighting gain is “the power input from lights (sum of radiant and convective portions).”
- Occupancy gain is “the sensible power input from occupants (sum of radiant and convective portions).”
- Equipment gain is “the sensible power input from equipment (sum of radiant and convective portions).”
- Infiltration/ventilation heat gain (Inf/Vent Gain) represents “the heat gained (or if negative lost) by the zone due to the exchange of air between the zone and the external environment.”
- Building heat transfer represents the heat entering the zone through the internal building components, and heat released into the zone which had been temporarily stored in the air.

7.5.1 Hudhayfah Bin Al Yaman Mosque (M1)

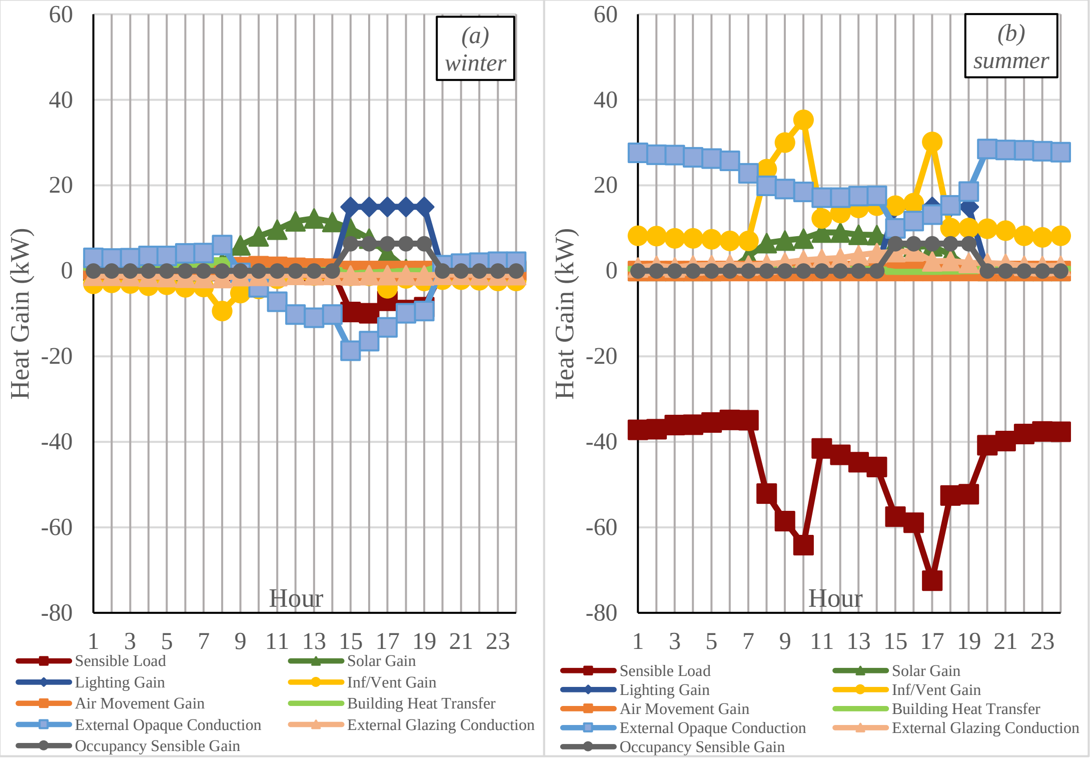


Figure 7.19: Computer Simulation Load Breakdown for Mosque 1 during (a) winter and (b) summer.

In winter, M1 stayed within the comfort zone during winter as per Figure 7.1 (a) due to the internal conditions (most notably the lighting gain, the occupancy sensible gain, and the solar gain) keeping the internal DBT within the thermal comfort range and slightly more than the external DBT, which ranged between 18.7 and 24.5 °C during the winter design day.

In summer, the high external DBT (reaching up to 38.4 °C) and the internal conditions had to be counteracted with a high sensible heat loss (air conditioning) reaching up to 72.5 kW at 17:00. The high sensible heat loss and high external DBT resulted in high external opaque conduction (reaching 28.5 kW at 20:00) and infiltration gain (reaching 35.3 kW at 10:00).

7.5.2 Abu Hamza Al Shari Mosque (M2)

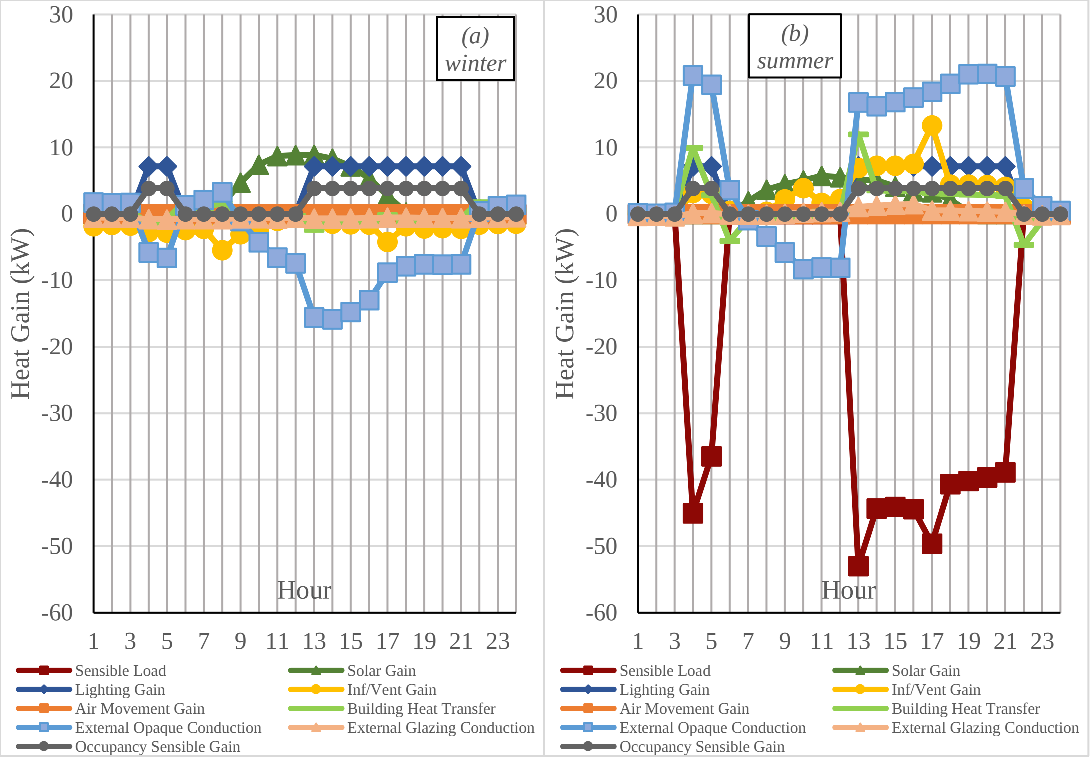


Figure 7.20: Computer Simulation Load Breakdown for Mosque 2 during (a) winter and (b) summer.

In winter, M2 stayed within the comfort zone during winter as per Figure 7.2 (a) due to the internal conditions (most notably the lighting gain, the occupancy sensible gain, and the solar gain as shown in Figure 7.20 (a) keeping the internal DBT within the thermal comfort range.

In summer, the high external DBT (reaching up to 36.2 °C) and the internal conditions had to be counteracted with a high sensible heat loss (air conditioning) reaching up to 53 kW at 13:00. The high sensible heat loss and high external DBT resulted in high external opaque conduction (reaching 28.5 kW at 20:00) and infiltration gain (reaching 35.3 kW at 10:00).

7.5.3 Othman bin Afan Mosque (M3)

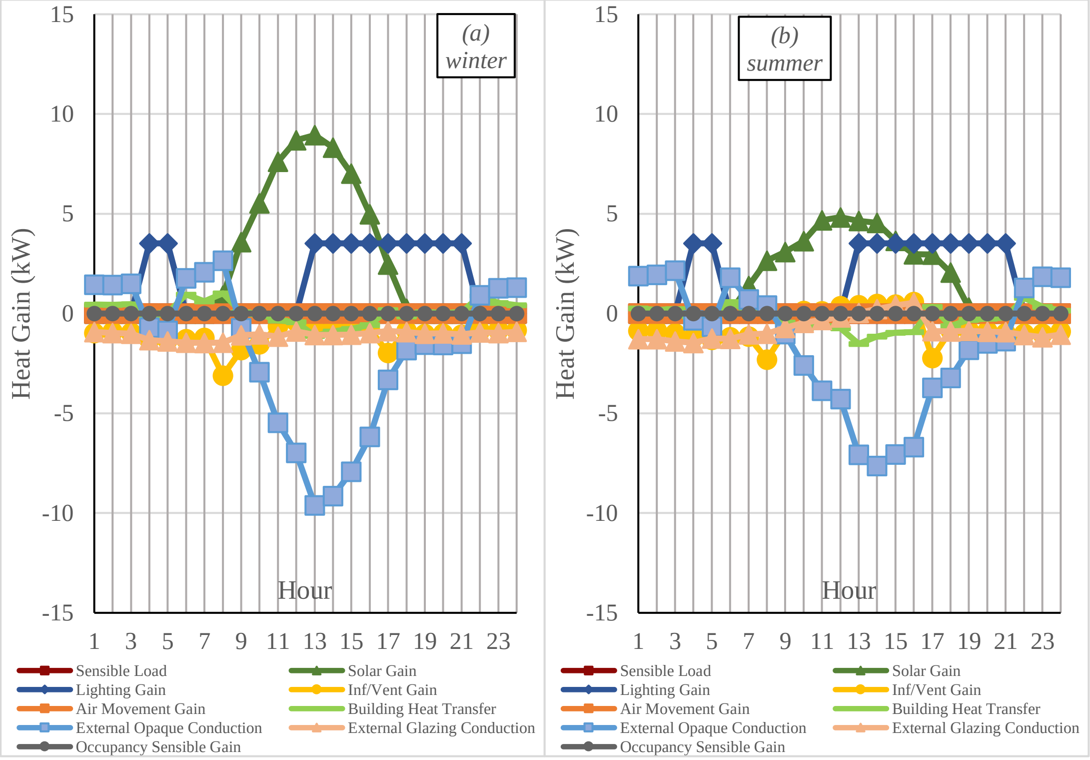


Figure 7.21: Computer Simulation Load Breakdown for Mosque 3 during (a) winter and (b) summer.

In winter, M3 stayed within the comfort zone during winter as per Figure 7.3 (a) due to the internal conditions (most notably the solar gain) keeping the internal DBT within the thermal comfort range. Although the mosque was unoccupied, the lighting remained switched on for a few hours each day.

In summer, the high external DBT (reaching up to 36.2 °C) and the internal conditions had to be counteracted with a high sensible heat loss (air conditioning) in order for M3 to reach the thermal comfort zone during the summer design day. However, the mosque was unoccupied and unconditioned due to COVID-19 restrictions, which made the internal DBT figures within the ballpark of the high external DBT figures (between 37 and 43 °C during the day).

7.5.4 Sa’al Mosque (M4)

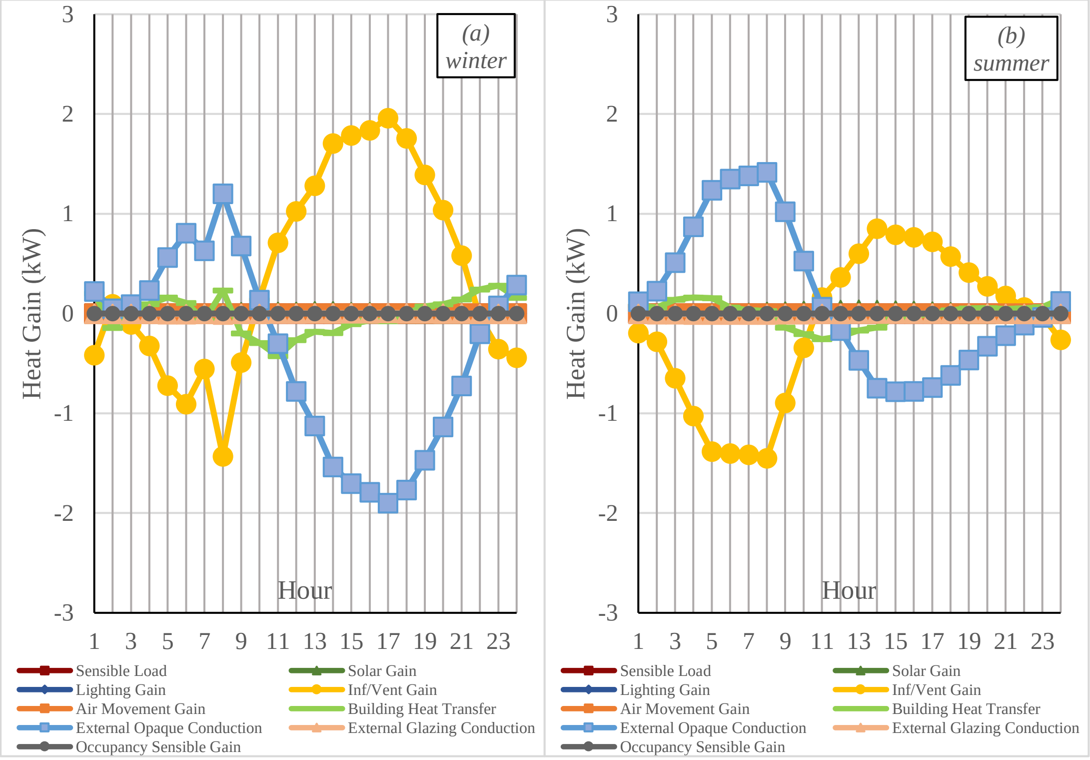


Figure 7.22: Computer Simulation Load Breakdown for Mosque 4 during (a) winter and (b) summer.

In winter, M4 was partly below the during winter as per Figure 7.4 (a) due to the lack of internal conditions in comparison with other mosques. It featured narrow windows measuring 0.14 metres in width and 0.55 metres in length, which limited solar gain. The mosque was unoccupied, so it did not have any lighting gains.

In summer, the loads breakdown was almost identical to winter as the mosque remained unoccupied and with limited internal conditions. The high external DBT (reaching up to 36.2 °C) and the internal conditions had to be counteracted with a high sensible heat loss (air conditioning) for M3 to reach the thermal comfort zone during the summer design day. However, the mosque was unoccupied and unconditioned due to covid-19 restrictions, causing the internal DBT figures to hover around 34 °C, significantly surpassing the maximum thermal comfort threshold of 30 °C.

7.5.5 Al Wafi Mosque (M5)

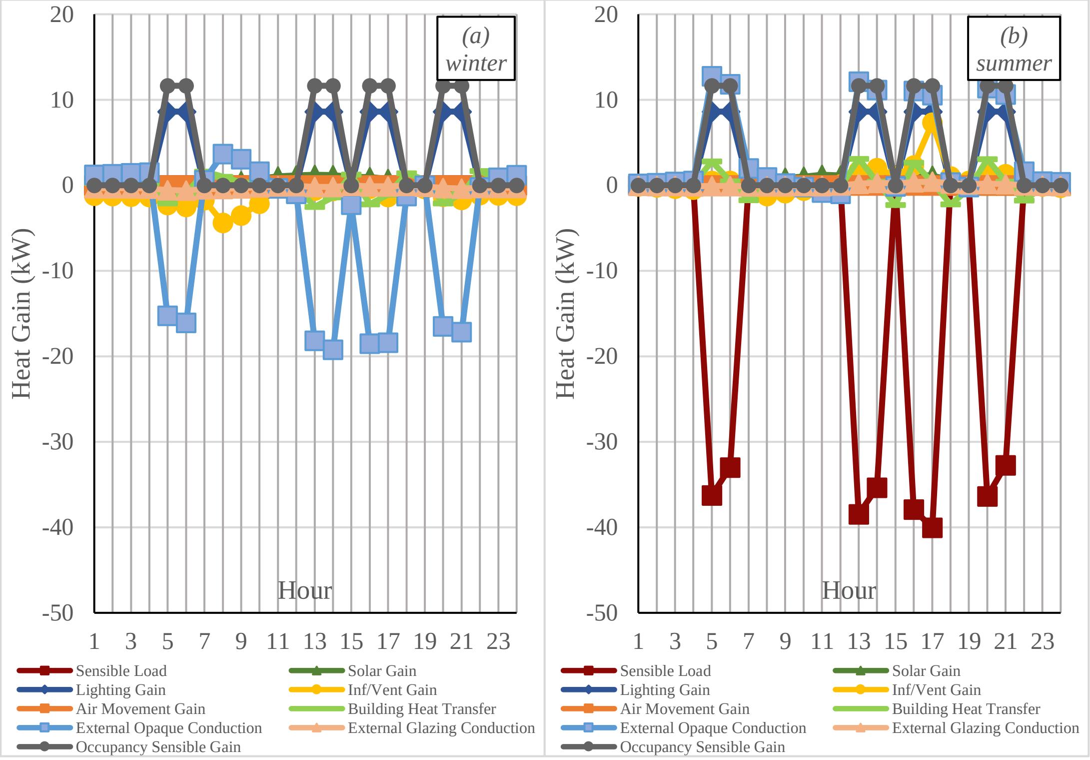


Figure 7.23: Computer Simulation Load Breakdown for Mosque 5 during (a) winter and (b) summer.

In winter, M5 stayed within the comfort zone during winter as per Figure 7.5 (a) due to the internal conditions (most notably the occupancy sensible gain and the lighting gain) keeping the internal DBT within the thermal comfort range.

In summer, the loads breakdown was similar to winter except for the sensible load spikes during occupancy periods. The high external DBT (reaching up to 45 °C) and the internal conditions had to be counteracted with a high sensible heat loss (air conditioning) for M5 to reach the thermal comfort zone during the summer design day. The sensible heat loss reached a maximum of 40 kW at 17:00.

7.5.6 Aal Hamoodah Mosque (M6)

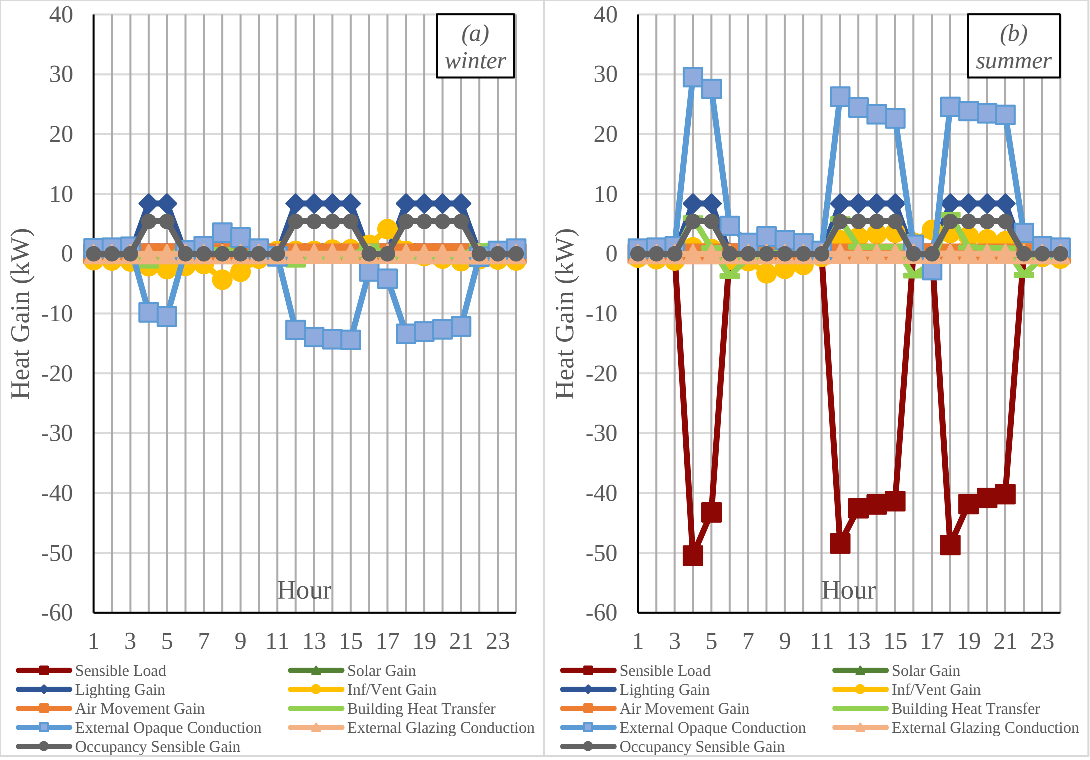


Figure 7.24: Computer Simulation Load Breakdown for Mosque 6 during (a) winter and (b) summer.

In winter, M6 stayed within the comfort zone during winter as per Figure 7.6 (a) due to the internal conditions (most notably the occupancy sensible gain and the lighting gain) keeping the internal DBT within the thermal comfort range.

In summer, the loads breakdown was similar to the winter design day loads breakdown except for the sensible load spikes during occupancy periods. The high external DBT (reaching up to 52.9 °C) and the internal conditions had to be counteracted with a high sensible heat loss (air conditioning) for M5 to reach the thermal comfort zone during the summer design day. The sensible heat loss reached a maximum of 50.4 kW at 04:00.

7.5.7 Loads Breakdown Comparison

The load breakdowns for each mosque of the six mosques during winter and summer were analysed using computer simulations. In winter, the mosques generally maintained thermal comfort due to internal conditions like lighting gain, occupancy sensible gain, and solar gain. In summer, challenges arose due to high external temperatures and internal conditions, leading to the need for significant sensible heat loss (air conditioning) to achieve thermal comfort. The contemporary mosques (M1, M2, M3) are characterised by notably larger windows, leading to increased solar gains. Conversely, the traditional mosques (M3, M4, M5) are distinguished by comparatively smaller windows, resulting in lower solar gains. Additionally, COVID-19 restrictions left M3 and M4 unoccupied and unconditioned, resulting in internal DBTs surpassing comfort limits.

7.6 Conclusion

Despite different architectural design and materials, all mosques studied show similar thermal conditions during winter, while in summer varied thermal responses suggest opportunities for design optimisation.

The computer simulation of the winter day shows all mosques have a similar pattern for both DBT and RH. There is a difference of up to 3 °C the mosques which accounted for the different building fabric, design, and internal conditions. All the mosques are within the comfort zone. Relative humidity is between 37.3% and 67.7% and is also within the comfort zone.

The computer simulation of the summer day shows that the mosques react differently to DBT during the naturally ventilated periods as shown. The air-conditioned period stays flat at 23 °C. This flat period is the same for all mosques and it does seem artificial, which can be as one of the drawbacks of a computer simulation. In a real world, temperature sensors will not be perfect and there will be swings of temperature throughout the space.

When the air conditioning is turned off at 5:00, each mosque reacts differently. The external temperature reaches a maximum of 47 °C at 16:00. M5 reaches a lowest high temperature of 31.8 °C while M2 reaches a highest high temperature of 35.7 °C just before the air conditioning is switched on again at 12:00. This could be due to the difference between the traditional and contemporary mosques building envelopes. Clay walls of M4, M5 and M6 have higher time constants (reaching up to 80 hours) than concrete walls (reaching up to 8.5 hours).

The heat gain and loss analysis indicated that the roofs, floors, and walls are among the top three heat gaining building elements via conduction in the six mosques. These building elements can be potential areas for improvements, which was explored further in the next chapter (Chapter 8. Suggested Improvements). The loads breakdown for the mosques showed that solar gain is one of the most noticeable differences between contemporary (M1, M2, and M3) and traditional (M4, M5, and M6) mosques. Traditional mosque buildings are subjected to less solar gain due to their much smaller glazing area. This is an area where contemporary mosques can improve by lowering thermal conductivity, reducing glazing area, or changing the glazing type. This is also explored further in the next chapter (Chapter 8. Suggested Improvements).

Chapter 8. CASE STUDY BUILDINGS THERMAL IMPROVEMENTS

8.1 Introduction

This chapter applies the lessons acquired from the literature review and results chapters to improve the six mosques' thermal performance. It begins with a comparison between the two previous chapters, Chapters 6 and 7, to compare between the field measurement and computer simulation results. Using these conclusions along with the literature review, suggested improvements are selected and applied to improve the thermal performance of the six mosque buildings. It was learned from various studies and publications that building envelope insulation, building material, fenestration and thermostat set point can be areas for improvement for buildings (Silva and Ghisi, 2020), mosques (Azmi and Ibrahim, 2020), and buildings in hot arid regions (Alaboud and Gadi, 2019). This was verified by the results presented in Chapters 6 and 7.

The suggested improvements are presented in five categories: Walls, Roofs, Windows, Internal Conditions, and Passive Cooling Techniques. There are fourteen different suggested improvements which are presented in Table 8.2. Each suggested improvement is assessed from three perspectives: thermal performance, thermal comfort, and energy efficiency. The analysis of the Resultant Temperature (RT) demonstrates thermal performance, the analysis of the Predicted Mean Vote (PMV) demonstrates thermal comfort, and the analysis of the Cooling Load (CL) demonstrates energy efficiency. The chapter concludes with three different combinations of the suggested improvements, each of which can be regarded as an example of an overall potential improvement for each building.

8.2 Comparison between field measurement and computer simulation results

As all mosques are naturally ventilated during winter, and their windows can be opened to control ventilation, no improvements are needed for the winter period except for M5. M5’s high occupancy heat gain leads to it occasionally overheating slightly above the upper limit of thermal comfort.

During summer, DBT field measurement results are different than DBT computer simulation results. One of the factors that affected the accuracy of the computer simulation was the unpredictable air conditioning schedule, which varied between the different mosques. For instance, M1 had packaged air conditioning units, which were turned on most of the time even when not occupied, for maintenance purposes. On the other hand, M2 and M6 air conditioning turns on for fajr prayer from around 4:00 to 5:00 and then turned on again around 11:00 until 21:00 as assumed in the computer simulations schedule. M5 turned on and off four times before and after each prayer, and during the last two prayers of the day, Maghrib and Isha, the air conditioning was left on continuously. M3 and M4 mosques were not occupied during field measurement for reasons related to the coronavirus pandemic. M3 air conditioning was turned on at random intervals to maintain the air conditioning system.

The computer simulations' results also revealed that the three traditional mosques retained heat more than the three contemporary mosques during the summer period. This is due to their higher heat capacity and time constant walls, which are relatively thick clay walls in all three traditional mosques.

The relative humidity results during summer are different between the field measurements and computer simulations. In both cases though, the internal relative humidity is affected by external relative humidity as it takes a similar pattern. The external RH used in the computer simulation is fluctuating between 18% and 75% during the day, while the measured external RH is relatively constant throughout the day for each mosque.

Table 8.1: Case studies' DBT and RH within the comfort zone as per Muscat bioclimatic chart according to the season, methodology, and air conditioning mode.

Are the cases studies within the thermal comfort zone?												
	Winter				**Summer**							
	Field Measurement		Computer Simulation		Field Measurement				Computer Simulation			
	Natural Ventilation				Air Conditioning		Natural Ventilation		Air Conditioning		Natural Ventilation	
	DBT	RH	DBT	RH	DBT	RH	DBT	RH	DBT	RH	DBT	RH
M1	Y	Y	Y	Y	Y	Y	N/A	N/A	Y	N	N	Y
M2	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y
M3	Y	Y	Y	Y	N/A	N/A	N	N	Y	N	N	Y
M4	Y	Y	Y	Y	N/A	N/A	N	N	Y	N	N	Y
M5	Y	Y	N	Y	N	Y	N	Y	Y	N	N	Y
M6	Y	Y	Y	Y	N	Y	N	Y	Y	N	N	Y

Table 8.1 shows under which case each mosque achieves the comfort zone (as per Muscat bioclimatic chart in Figure 2.3) and according to the season, research methodology, and air conditioning mode. It is evident that all mosques achieve the comfort zone during winter except for M5 due to higher occupancy gains.

During summer, M1’s AC is turned on most of the time throughout the day, hence the natural ventilation mode is not applicable in this case during field measurement. M3 and M4 were not used during the field measurement period due to COVID-19 government regulations.

As per summer field measurement results, M1 is within comfort zone as it is air conditioned throughout the day. M2’s AC is turned on intermittently during prayers only. It manages to stay within the comfort zone during both air conditioning and natural ventilation modes. The remaining four mosques, M3, M4, M5, and M6, all are not within the thermal comfort.

Computer simulation results show that all mosques do not achieve thermal comfort when they are naturally ventilated, but they do under the air conditioning mode.

The data analysis of both the computer simulation and the field measurement showed that all mosques operate within the comfort zone during the winter design day except for M5. M5’s high occupancy heat gain leads to it occasionally overheating slightly above the upper limit of thermal comfort.

During summer design day, there was a discrepancy between the field measurement and computer simulation results. Field measurement showed that all mosques are mostly above the maximum comfort zone in an air-conditioned mode except for M1. Computer simulation results showed that all mosques are within the comfort zone under the air-conditioned mode. When the AC switches off, all mosque’s internal DBT increase drastically above 30 °C except for M5 that maintains a DBT below 30 °C overnight under the natural ventilation mode.

8.3 Suggested Improvements

The six mosque buildings were simulated as both air-conditioned and free-running with various improvements and comparing their performance to demonstrate their thermal performance, thermal comfort, and energy efficiency. During the field measurement, M1, M2, M5, and M6 were air conditioned, so they were presented as such during the Results Chapter. M3 and M4 were unconditioned and unoccupied during the field measurement, so they were presented as such during the Results Chapter. To demonstrate the potential cooling load reduction as an air-conditioned building and to demonstrate the decrease in indoor dry bulb temperature as a free-running building (and whether it achieves thermal comfort levels without air-conditioning with the suggested improvements), each building would be simulated three times for each improvement in this chapter. The first simulation run would be as a free-running building to present the resultant temperature, which is discussed in “Resultant Temperature” subsections. The second run would a PMV/PPD analysis on the free-running building, which is discussed in “Thermal Comfort” subsections. The third run would be as an air-conditioned building to demonstrate the cooling load savings, which is discussed in “Cooling Load Reduction” subsections. In each subsection, the performance of each improvement computer simulation is compared to that of the base simulation to demonstrate its improvement.

, while the U-values for the roofs range between 0.816 and 1.736 W/m^2.K.

A total of fourteen suggested improvements were selected for all six mosques as presented in Table 8.2. At least three simulation runs were conducted for each suggested improvement to each mosque to display the resultant temperature, PMV, and cooling load data. This means that this chapter presents the findings of 288 computer simulations, which are part of at least 1000 simulations conducted throughout the course of this research.

Table 8.2: The fourteen suggested improvements showing the improved building element and a brief description for each improvement.

Improvement model	Improved building element	Description	Section
W1	Walls	Walls’ thermal conductivity is reduced by 50%	8.4
W2	Walls	Walls are changed from concrete to clay	8.4
W3	Walls	Walls are changed from clay to concrete	8.4
R1	Roof	Roofs’ thermal conductivity is reduced by 50%	8.5
R2	Roof	Roofs are changed from concrete to clay	8.5
R3	Roof	Roofs are changed from clay to concrete	8.5
F1	Fenestration	Windows’ glazing area is reduced by 50%	8.6
F2	Fenestration	Windows’ thermal conductivity is reduced by 50%	8.6
F3	Fenestration	Night purge (11:00 PM to 02:00 AM)	8.8
IC1	Internal Condition	Add two degrees Celsius to the cooling thermostat setpoint	8.7
IC2	Internal Condition	Lower infiltration rate	8.7
IC3	Internal Condition	Higher efficiency lighting	8.7
T1	Passive Cooling Technique	Khalwah	8.8
T2	Passive Cooling Technique	Increased vegetation around the buildings	8.8

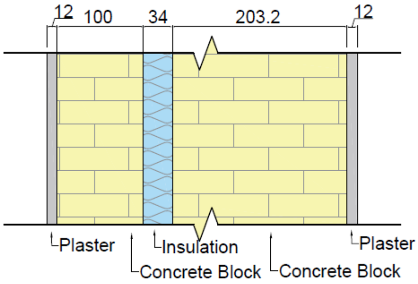
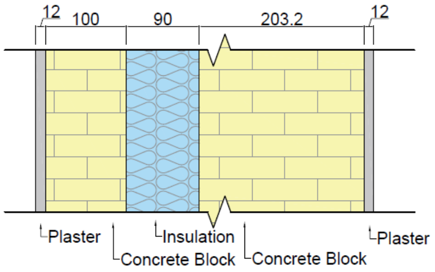
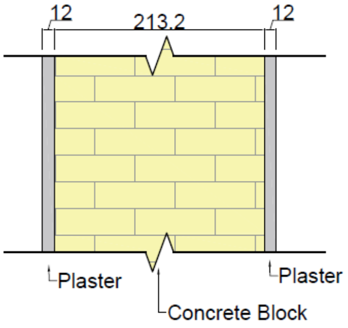
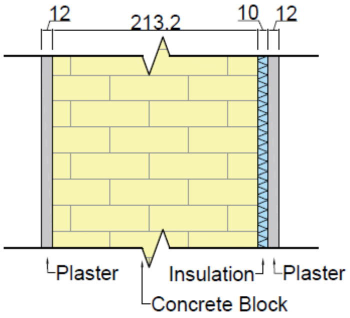
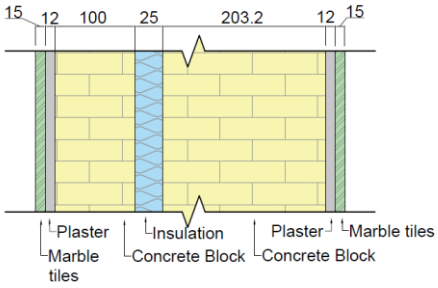
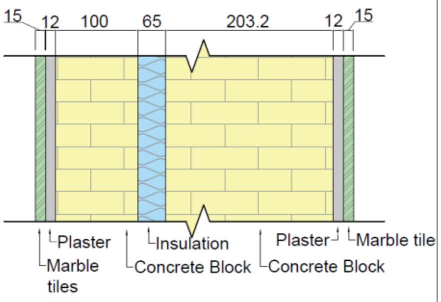
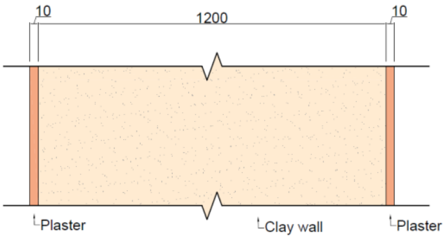
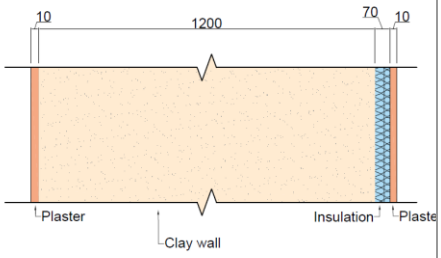
8.4 The Suggested Improvements to the Walls

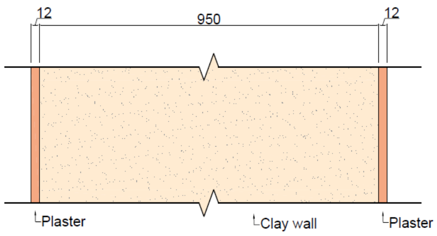
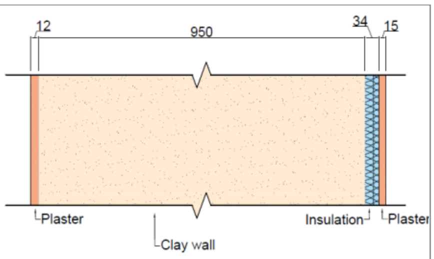
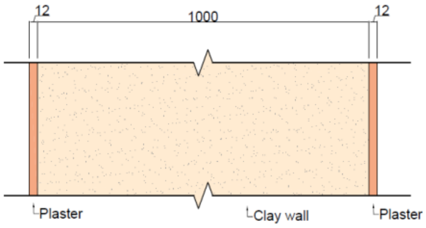
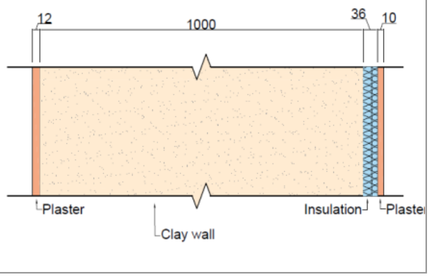
The first suggested improved building element are the walls. Building Heat Transfer and Building Conduction Opaque loads were among the highest through the walls as per section 7.4 Heat Gain and Loss Analysis and section 7.5 Loads Breakdown. Reduction of thermal conductivity would help reduce opaque conduction load. Changing from concrete to mud wall would increase the thermal mass and it is especially helpful for areas with more than 10 °C of diurnal temperature change. The first wall suggested improvement (W1) is to reduce the thermal conductivity by 50%. The second wall suggested improvement (W2) is to replace concrete walls with clay walls since one of the goals of this research is to compare between vernacular and contemporary mosque buildings (Only applicable to M1, M2 and M3). The third wall suggest improvement is do the opposite of the second suggested improvement, which is to replace clay walls with concrete walls and see the impact that would have on vernacular mosque buildings (M4, M5, and M6).

8.4.1 W1 Walls with half the U-value

The first improvement evaluated on the building is reducing all the external walls' U-value by 50%. An exercise was conducted to determine the optimal suggested improvement that would be suitable across the board. U-values of the walls for the six mosques range between 0.543 and 2.427 W/m^2.K. The first thought is to assign the optimal U-value for non-residential buildings. There is no national standard in Oman that specifies thermal transmittance requirements for buildings; however, the most relevant standard can be considered is the Saudi Code. The maximum u-value for non-residential walls should be 0.312 W/m^2.K as per the Saudi Energy Conservation Code – Commercial (SBC 601) (Saudi Building Code National Committee, 2018). Reducing the U-value of M1 wall from 0.543 W/m^2.K to 0.272 W/m^2.K would be a 50% reduction and would make the u-value slightly below the Saudi code requirement. Further reduction would incur further costs, and lower reduction would not meet the standard; hence, a 50% reduction was chosen across the board. The table below shows the base and improved walls constructions and U-value for each of the six mosques (Table 8.3).

Table 8.3: W1 suggested improvement detail for all six mosques showing the wall's cross section and U-value for each case study. Dimensions shown are in millimetres.

Mosque	Base wall	B1 wall
M1	U-value = 0.543 W/m^2.K  	U-value = 0.272 W/m^2.K 
M2	2.427 W/m^2.K  	U-value = 1.231 W/m^2.K 
M3	0.67 W/m^2.K  	0.323 W/m^2.K 
M4	0.595 W/m^2.K  	0.292 W/m^2.K 
M5	0.722 W/m^2.K	0.364 W/m^2.K

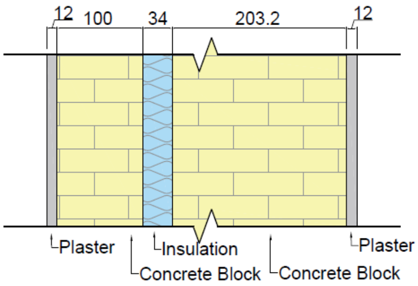
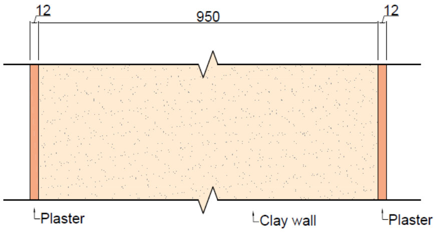
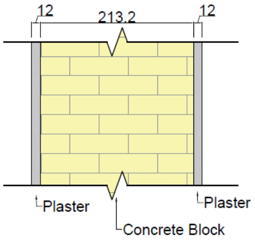
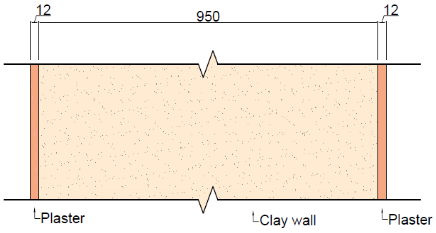
		
M6	0.698 W/m^2.K 	0.348 W/m^2.K 

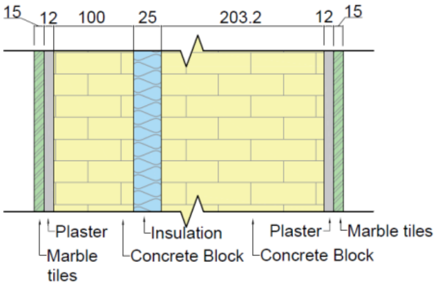
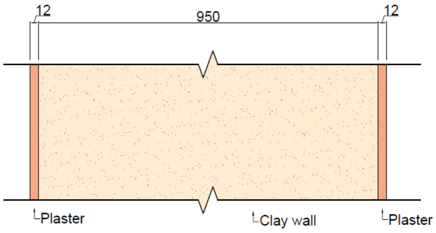
To achieve a 50% reduction in U-value, either the insulation thickness was increased, or an insulation layer was added to the wall.

8.4.2 W2 Walls changed from concrete to clay

The second improvement assessed on the building was changing all the external walls either from concrete to clay or from clay to concrete. This is to see how traditional buildings behave if they were built with concrete, and how contemporary buildings behave if built with clay. The table below shows the base and improved walls constructions and U-value for Mosques 1, 2 and 3 (Table 8.4).

Table 8.4: W2 suggested improvement detail for Mosques 1, 2, and 3 showing the wall's cross section and U-value for each case study detail. Dimensions shown are in millimetres.

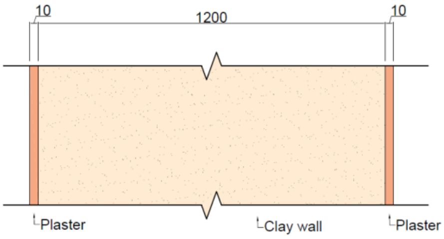
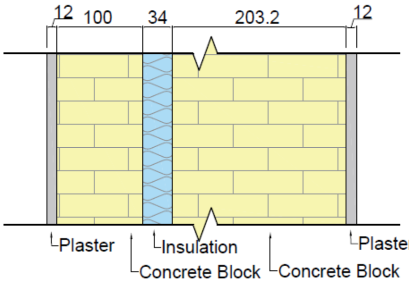
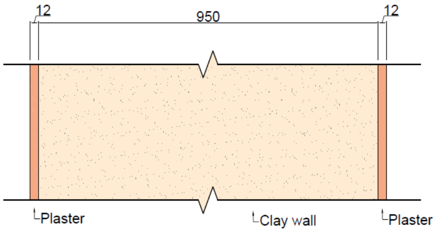
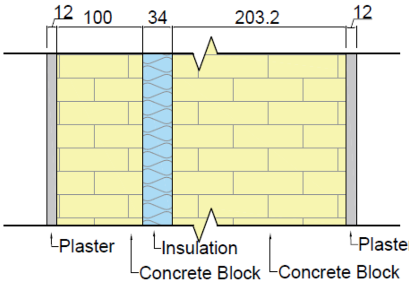
Mosque	Base U-value	B1 U-value
M1	U-value = 0.543 W/m^2.K 	0.722 W/m^2.K 
M2	2.427 W/m^2.K 	0.722 W/m^2.K 

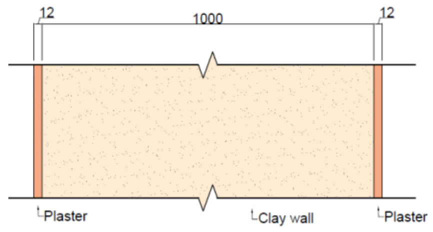
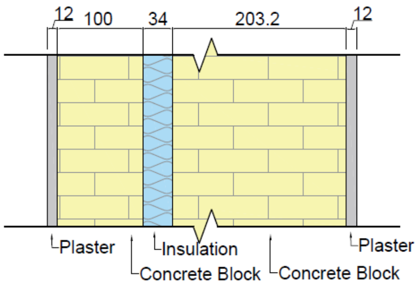
M3	0.67 W/m^2.K  	0.722 W/m^2.K 

8.4.3 W3 Walls changed from clay to concrete

The second improvement assessed on the building was changing all the external walls either from concrete to clay or from clay to concrete (Table 8.5). This is to see how traditional buildings behave if they were built with concrete, and how contemporary buildings behave if built with clay. The table below shows the base and improved walls constructions and U-value for Mosques 4, 5, and 6.

Table 8.5: W3 suggested improvement detail for Mosques 4, 5, and 6 showing the wall's cross section and U-value for each case study detail. Dimensions shown are in millimetres.

Mosque	Base U-value	B1 U-value
M4	0.595 W/m^2.K  	0.543 W/m^2.K 
M5	0.722 W/m^2.K  	0.543 W/m^2.K 
M6	0.698 W/m^2.K	0.543 W/m^2.K

8.4.4 Resultant Temperature using the Suggested Walls

The Resultant Temperature (RT) was analysed for the suggested walls in both summer day (day 179) and winter day (day 20) for all six mosques. Figures 8.1 to 8.6 show RT for the baseline, B1 wall and B2 wall for all six mosques in summer day and winter day.

The thermal analysis of mosques presented in section 7.4 Heat Gain and Loss Analysis found that heat gain of all building elements in all mosques occur mostly between 09:00 and 16:00, whereas heat loss occurs throughout the remaining hours of the day. As can be seen in Figures 8.1 to 8.6, the internal resultant temperature is within the comfort zone for all mosques, except for M5 which is only partly within the comfort zone. The main issue is during summer where all the mosques are well above the comfort zone upper limit (30 °C).

Introducing building materials with a lower thermal conductivity is one technique to minimise heat gains during the day and to achieve thermal comfort during the summer; therefore, proposed improvements W1, W2, and W3 are implemented.

Figures 8.1 to 8.6 show how would the suggested improvements W1, W2, and W3 would impact the resultant temperature of all six mosques during the summer day and winter day. W1 (50% reduction in thermal conductivity) is implemented to all six mosques. W2 (Concrete walls are replaced by clay walls) is implemented to M1, M2, and M3. W3 (Clay walls are replaced by concrete walls) is implemented to M4, M5, and M6.

8.4.4.1 Hudayfah Bin Al Yaman Mosque (M1)

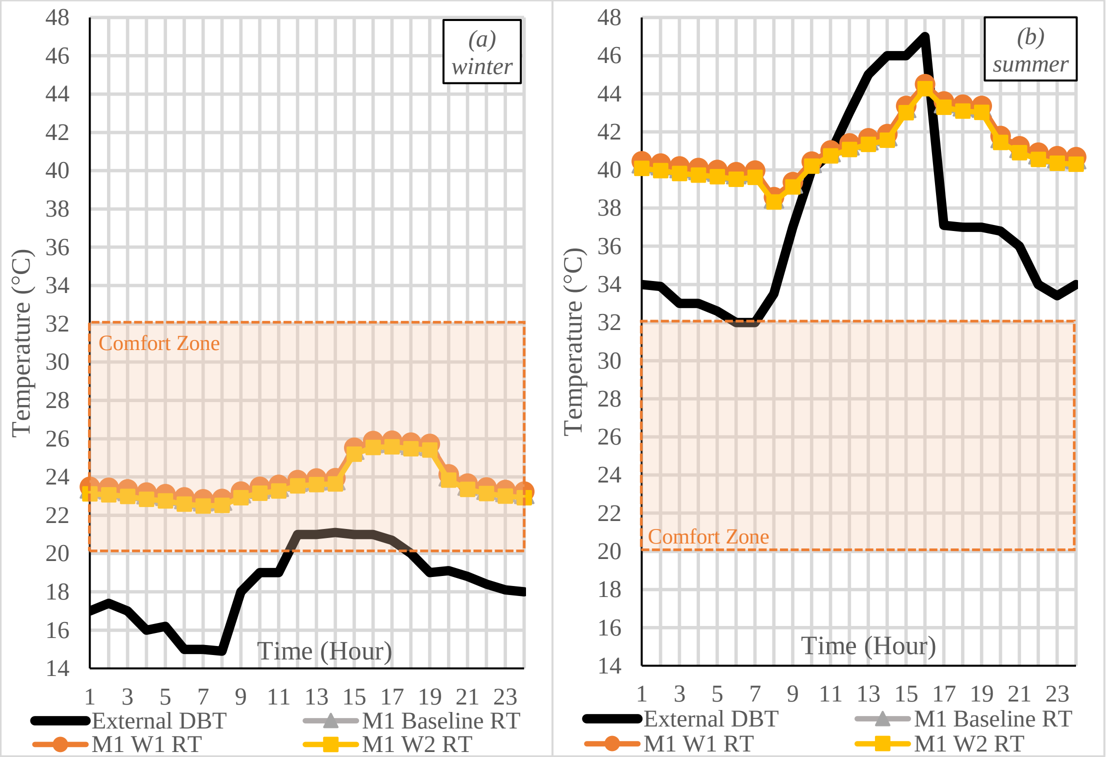


Figure 8.1: Resultant Temperatures (RT) for Mosque 1's baseline, W1, and W2 improvement models during winter (a) and summer (b)

In winter, W2 maintained the lowest RT during the entire winter day, peaking at 25.58 °C at 16:00, while the baseline was at 25.8 °C and W1 was at 25.9 °C at the same time (Figure 8.1a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature ranges from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, W2 maintained the lowest RT throughout the summer day, peaking at 44.27 °C at 16:00, while the baseline was at 44.44 °C, W1 was at 44.5 °C, and the external DBT was at 47 °C at the same time (Figure 8.1b). The M1 B2 achieved the lowest RT of 38.32 °C at 08:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.4.4.2 Abu Hamza Al Shari Mosque (M2)

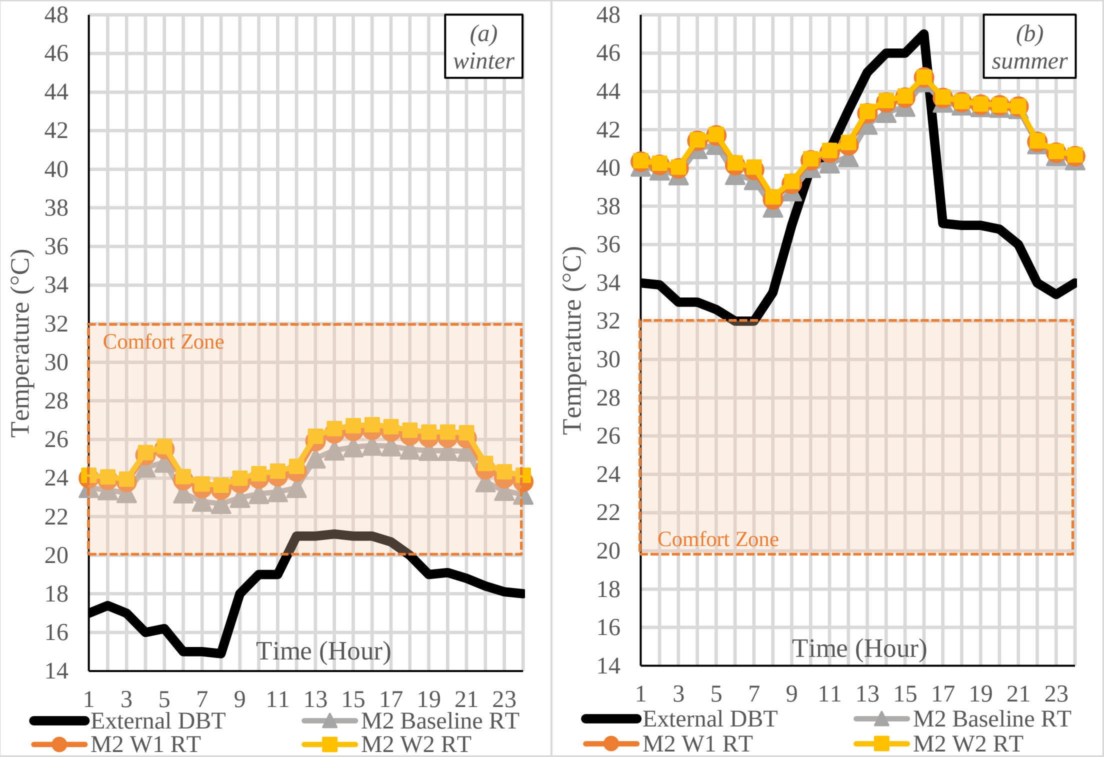


Figure 8.2: Resultant Temperatures (RT) for Mosque 2's baseline, W1, and W2 improvement models during winter (a) and summer (b)

In winter, the baseline maintained the lowest RT during the entire winter day, peaking at 25.69 °C at 16:00, while the W1 was at 26.49 °C and W2 was at 26.76 °C at the same time (Figure 8.2a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature range from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, the baseline maintained the lowest RT throughout the summer day, peaking at 44.49 °C at 16:00, while W1 was at 44.72 °C, W2 was at 44.75 °C, and the external DBT was at 47 °C at the same time (Figure 8.2b). The M2 baseline achieved the lowest RT of 37.94 °C at 08:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.4.4.3 Othman bin Afan Mosque (M3)

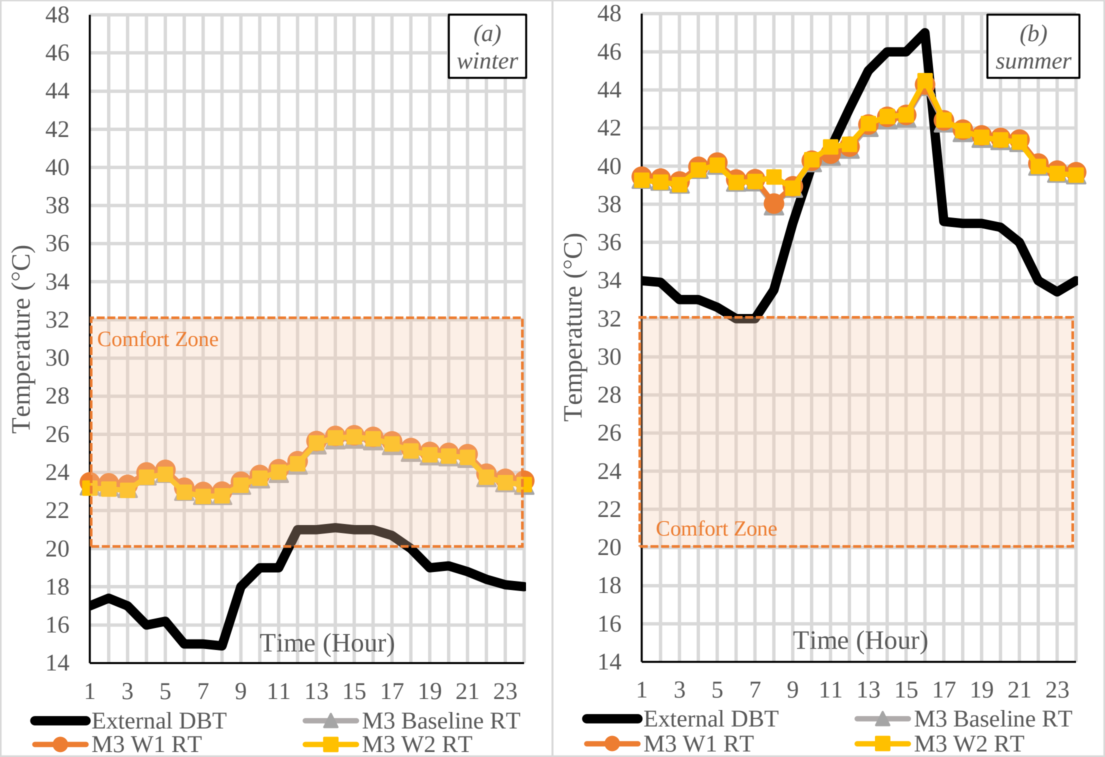


Figure 8.3: Resultant Temperatures (RT) for Mosque 3's baseline, W1, and W2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, W2 maintained the lowest RT during most of the winter day, peaking at 25.86 °C at 15:00, while the baseline was at 25.78 °C and W1 was at 25.95 °C at the same time (Figure 8.3a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature range from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, the M3 baseline, M3 W1, and 32 W2 were all in proximity throughout the day (Figure 8.3b). M3 W2 fluctuated the most having had the lowest diurnal RT at 38.85 at 09:00 (while baseline was at 38.88 and M3 B1 was at 38.95 C) and the highest diurnal RT at 44.49 °C at 16:00 (while the baseline was at 44.22 and M3 B1 was at 44.29). The lowest diurnal RT of 38.85 at 09:00 for M3 W2 is significantly higher than the thermal comfort upper limit of 30 °C.

8.4.4.4 Sa'al Mosque (M4)

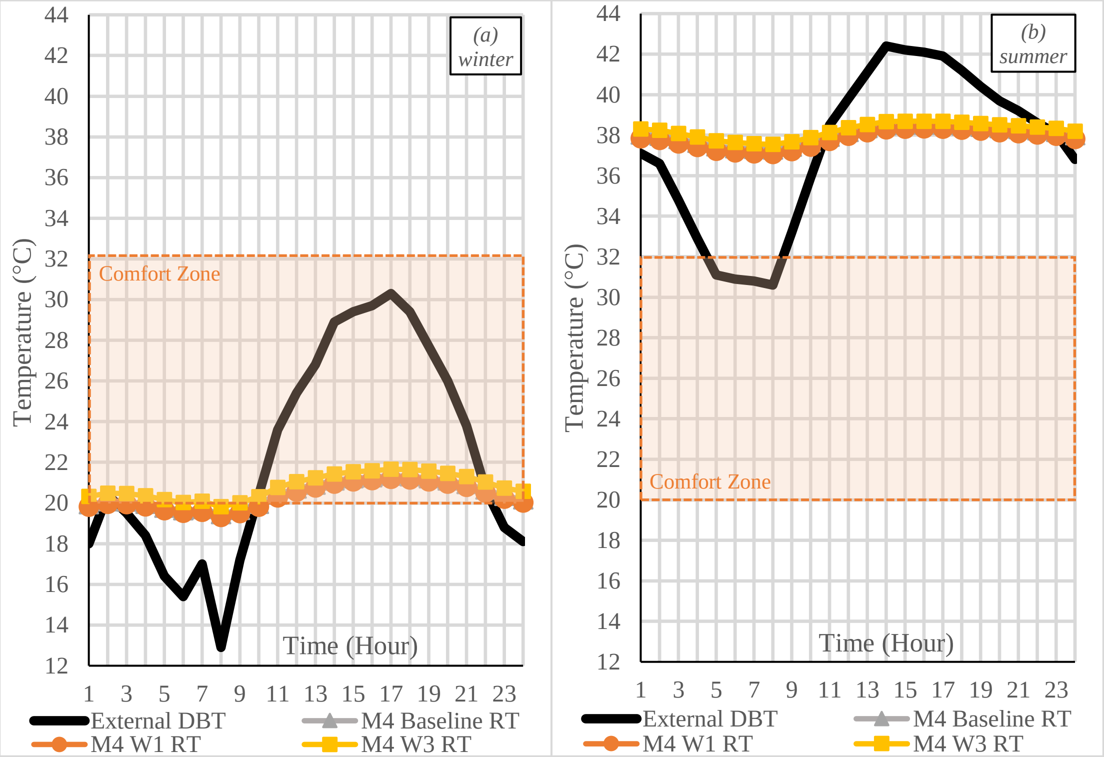


Figure 8.4: Resultant Temperatures (RT) for Mosque 4's baseline, W1, and W2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M4 W1 maintained the lowest RT during the entire winter day, peaking at 21.19 °C at 16:00, while the W2 was at 21.66 °C and baseline was at 21.34 °C at the same time (Figure 8.4a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature range from 12.9 °C to 30.3 °C. This could be attributed to the high thermal mass of the mosque that kept the RT consistent within a small range between 19.32 and 21.66.

In summer, M4 W1 maintained the lowest RT throughout the summer day, peaking at 38.32 °C at 17:00, while W2 was at 38.68 °C, baseline was at 38.53 °C, and the external DBT was at 42.1 °C at the same time (Figure 8.4b). The M4 W1 achieved the lowest RT of 37.07 °C at 08:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.4.4.5   Al Wafi Mosque (M5)

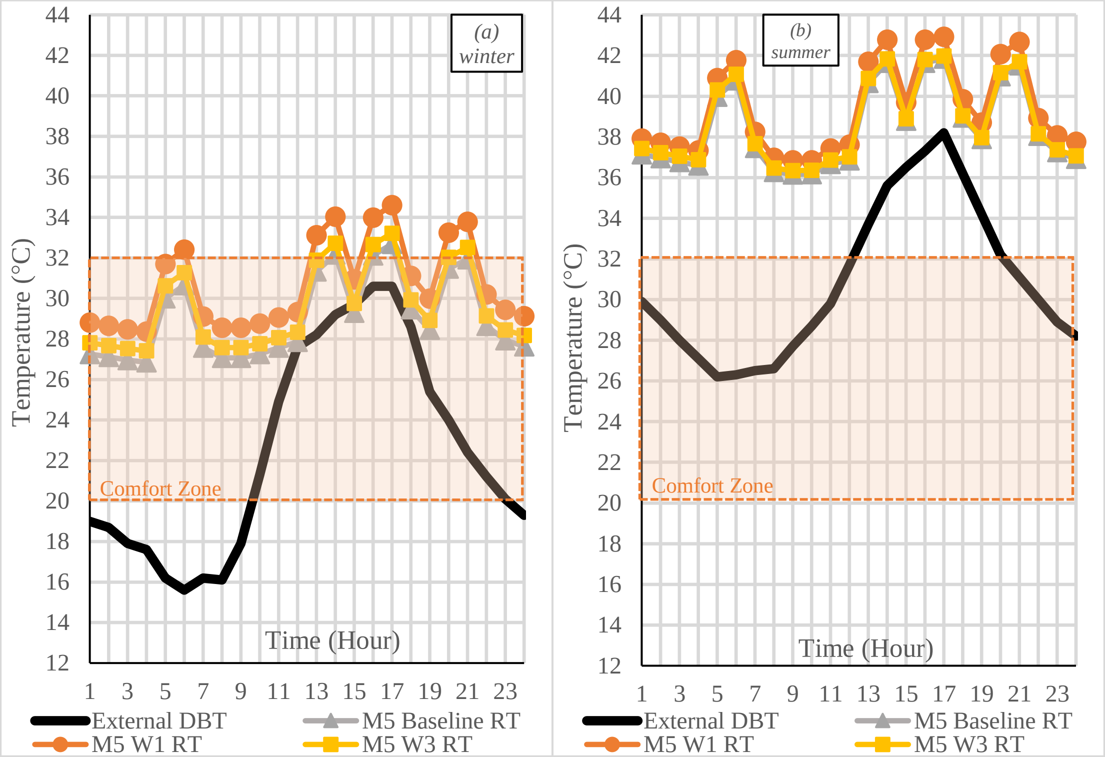


Figure 8.5: Resultant Temperatures (RT) for Mosque 5's baseline, W1, and W2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M5 baseline and M5 W2 maintained a lower than M5 W1 RT during the entire winter day, peaking at 32.17 and 32.72 °C at 14:00, while M5 W1 was at 34.04 °C at the same time (Figure 8.5a). M5 is the only mosque building out of the six mosques that did not achieve thermal comfort for the entire winter day. This could be attributed to the high occupancy gain during occupancy hours as depicted by the four peaks in the Figure 3 at 06:00, 14:00, 17:00, and 21:00.

In summer, M5 baseline maintained the lowest RT throughout the summer day, peaking at 41.85 °C at 17:00, while W1 was at 42.92 °C, W2 was at 41.98 °C, and the external DBT was at 38.2 °C at the same time (Figure 8.5b). The M5 baseline achieved the lowest RT of 36.16 °C at 09:00 which is significantly higher than the thermal comfort upper limit of 30 °C. Similar to winter, the high occupancy gain of M5 has significantly raised RT over the external DBT, pushing it well beyond the maximum limit of thermal comfort at 30 degrees Celsius.

8.4.4.6 Aal Hamoodah Mosque (M6)

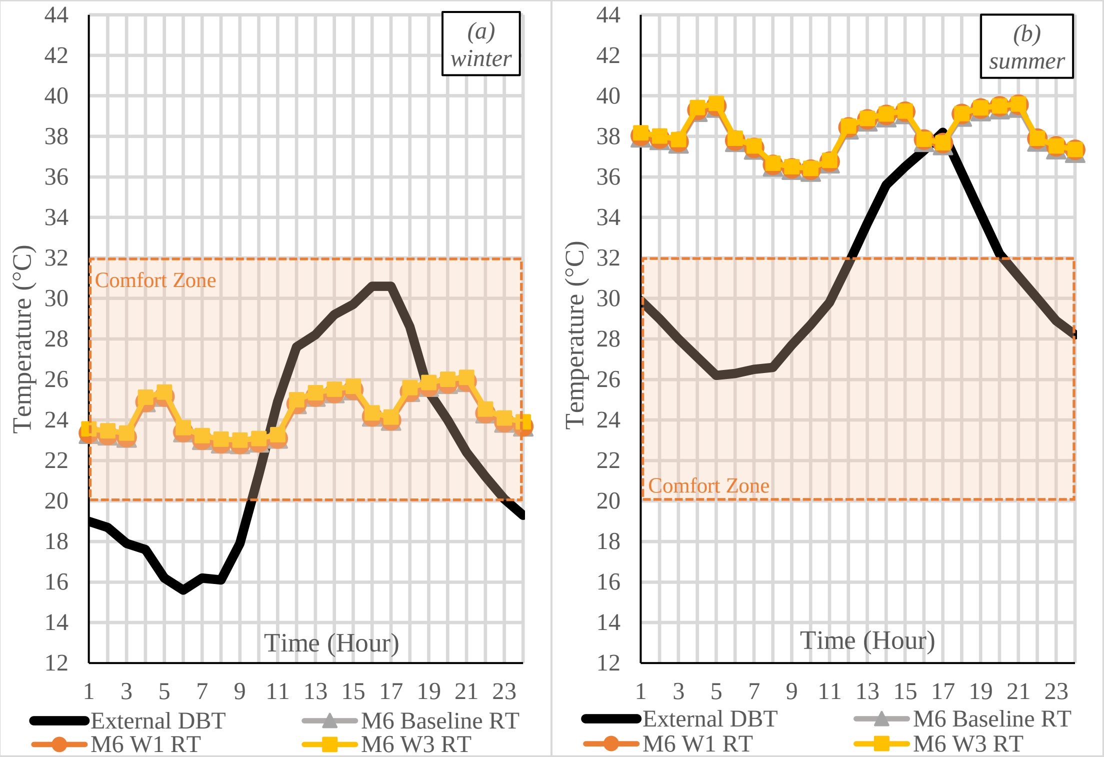


Figure 8.6: Resultant Temperatures (RT) for Mosque 6's baseline, W1, and W2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M6 baseline and M6 W1 were almost identical as they maintained lower RT during the entire winter day than M6 W2, peaking at 25.89 °C and 25.9 at 10:00, respectively, while M6 W2 was at 26.11 °C (Figure 8.6a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature range from 15.6 °C to 30.6 °C. This could be attributed to the high thermal mass of the mosque that kept the RT consistent within a small range between 22.81 and 26.11. The fluctuation that occurred during the five daily prayers is a result of the significant increase in occupancy during these times.

In summer, M6 baseline maintained the lowest RT during the entire winter day, peaking at 39.43 °C at both 05:00 and 21:00, while M6 W1 was at 39.57 °C and M6 W1 was at 39.63 °C (Figure 8.6b). The M6 baseline achieved the lowest RT of 36.27 °C at 10:00 which is significantly higher than the thermal comfort upper limit of 30 °C. Similar to winter, the high occupancy gain of M6 has significantly raised RT over the external DBT, pushing it well beyond the maximum limit of thermal comfort at 30 degrees Celsius.

8.4.5 Thermal Comfort using the Suggested Walls

Table 8.6: Percentage of annual occupied hours within the comfort range (-1 < PMV < +1) for the baseline model and the walls suggested improvements' models.

Model	M1	M2	M3	M4	M5	M6
Baseline	15.5%	14.3%	16.1%	40.4%	0.2%	25.6%
W1	14.7%	12.2%	15.0%	40.2%	0.1%	25.2%
W2	15.6%	10.9%	16.1%			
W3				39.2%	0.2%	25.1%

This section explores how the thermal comfort in each of the six mosques would be impacted by the various wall improvement techniques. The PMV and PPD analyses of each of the improvements in all six mosques were performed using the EDSL TAS programme. Table 8.6 shows the percentage of occupied hours that has a PMV ranging from -1 to +1. It is noted that all the occupied hours during summer fall outside of the -1 < PMV < +1 range, hence the values shown in the table are true as annual figures as well as winter figures. The buildings are assumed to be free-running.

W1 (higher insulation wall) appears to have decreased the percentage of hours within the comfort range. The results show a decrease in the percentage of hours within the -1 < PMV < +1 range for all mosques.

For M1, M2, and M3, W2 (concrete to clay) was applied. The results show an increase in the percentage of hours within the comfort range for M1 from 15.5% to 15.6% with W2. W2 has decreased the percentage of hours within the comfort range from 14.3% to 10.9%, while it did not change the percentage of hours within the comfort range for M3, so it stayed at 16.1%.

For M4, M5, and M6, W3 (clay to concrete) was applied. The results show a decrease in the percentage of hours within the comfort range for M4 and M6 from 40.4% to 39.2%, and from 25.2% to 25.1%, respectively. For M5, the percentage of hours within the comfort range remains unchanged at 0.2%.

While a higher insulation wall would better insulate against heat gain during the day, it would also prevent heat loss during the night. The W1 results suggest a the difference it made in heat gain is greater than heat loss than the base model.

8.4.6 Cooling Load Reduction using the Suggested Walls

Table 8.7: Cooling load reductions of the walls suggested improvements' models. The cooling load reduction is expressed as a percentage change compared to a baseline scenario

Model	M1	M2	M3	M4	M5	M6
W1	-1.1%	-5.3%	-1.4%	-5.4%	-5.2%	-1.6%
W2	0.8%	-6.6%	-0.3%			
W3				-3.5%	-0.9%	-1.7%

W1, a higher insulation wall, has caused a decrease in cooling load in all six mosque buildings. The reduction ranges from -1.1% to -5.4%. W2, the replacement of concrete walls with clay walls, was applied to M1, M2, and M3. It increased the cooling load by 0.8% in M1 and reduced the cooling load for M2 and M3 by to 6.6% and 0.3%, respectively. W3, the replacement of clay walls with concrete walls, has reduced the cooling load in M4, M5, and M6 by 3.5%, 0.9%, and 1.7% respectively.

The significant result for W2 was M2's cooling load reduction of 6.6%. This happened because M2 has uninsulated external concrete walls. Switching to higher thermal resistance clay walls have naturally reduced the cooling demand.

The significant results for W3 are M4's and M6's cooling load reduction of 3.5% and 1.7%, respectively. Given the intermittent usage of the mosque, the clay walls have the advantage of high thermal mass and high time constant which leads to consistent internal DBT throughout the day. The disadvantage of clay walls is that the heat loss process of the thick clay walls consumes more energy.

8.5 The Suggested Improvements to the Roofs

8.5.1 Description of the Suggested Roofs

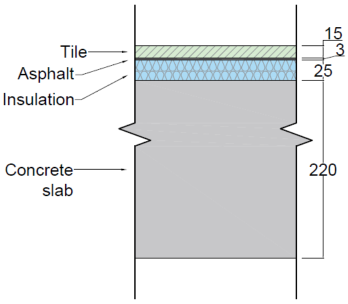
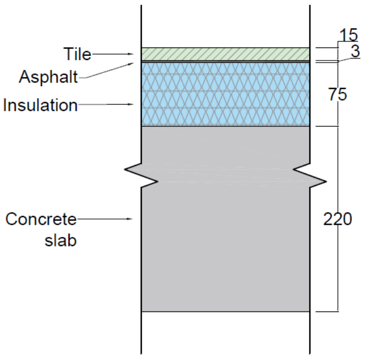
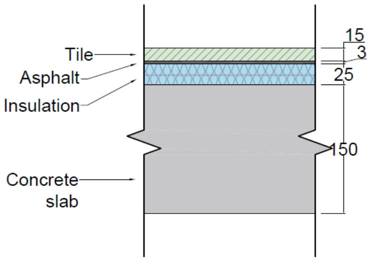
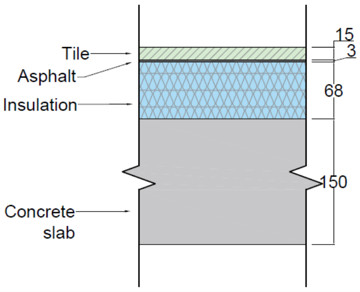
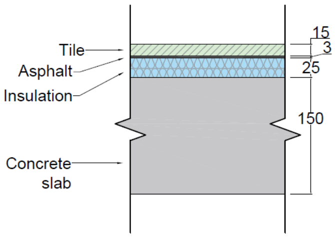
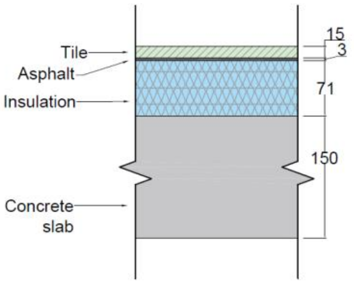
The second suggested improved building element are the roofs. Building Heat Transfer and Building Conduction Opaque loads were among the highest through the roofs. Reduction of thermal conductivity would help reduce opaque conduction load. Changing from concrete to mud wall would increase the thermal mass and it is especially helpful for areas with more than 10 °C of diurnal temperature change. From the heat loss/gain section, roofs were one of the highest heat gaining and losing building elements in all case studies. The first roof suggested improvement (R1) is to reduce the thermal conductivity by 50%. The second roof suggested improvement (R2) is to replace concrete roofs with clay roofs since one of the goals of this research is to compare between vernacular and contemporary mosque buildings (Only applicable to

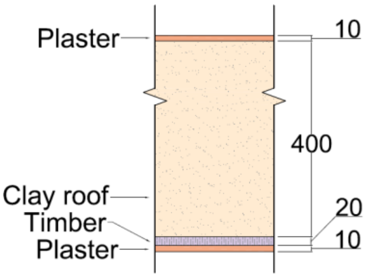
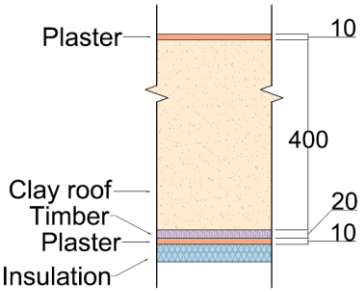
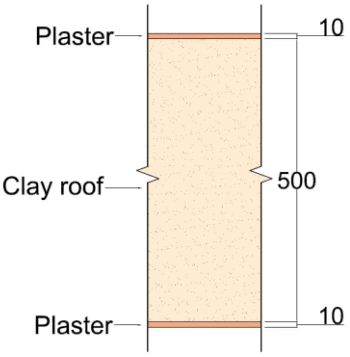
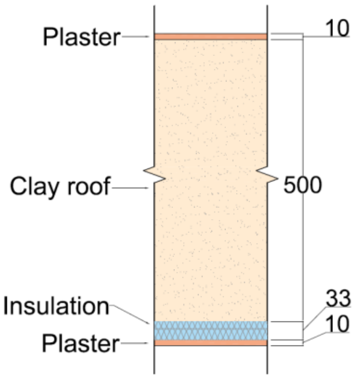
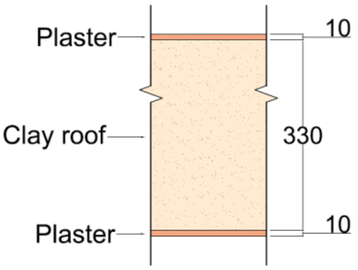
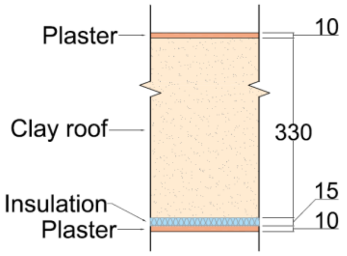
M1, M2 and M3). The third wall suggest improvement is do the opposite of the second suggested improvement, which is to replace clay roofs with concrete roofs and see the impact that would have on vernacular mosque buildings (M4, M5, and M6).

8.5.2 R1 Roofs with half the U-value

Similar to the walls, a 50% reduction to the U-value of roofs was modelled and simulated. The first improvement tested on the building roofs was halving their thermal conductivity. Table 8.8 shows the base U-value along with the improved U-value for each of the six mosques. To achieve a 50% reduction in U-value, either the insulation thickness was increased, or an insulation layer was added to the wall construction.

Table 8.8: R1 suggested improvement details for all six mosques showing the roofs' cross sections and U-value for each case study. Dimensions shown are in millimetres.

Mosque	Baseline model U-value and cross section	R1 U-value and cross section
M1	0.816 W/m².K  	0.399 W/m².K 
M2	0.86 W/m².K  	0.447 W/m².K 
M3	0.86 W/m².K  	0.432 W/m².K 
M4	1.198 W/m².K	0.491 W/m².K

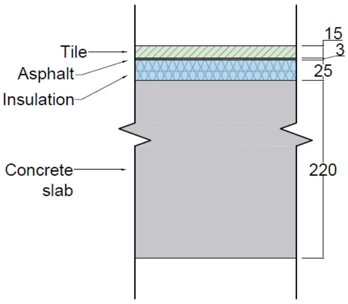
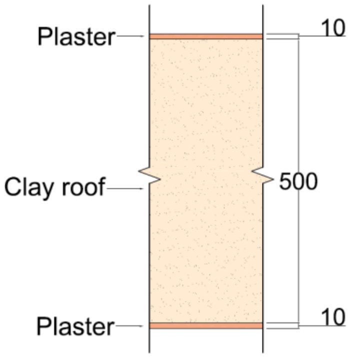
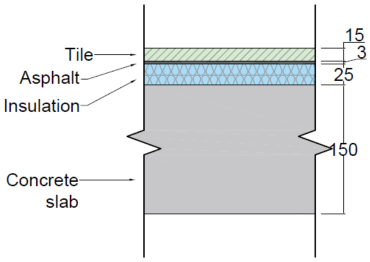
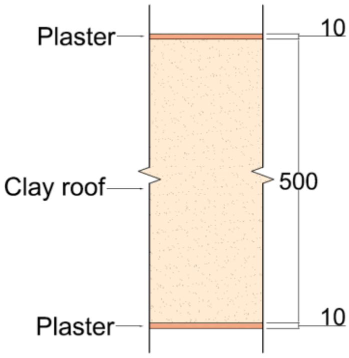
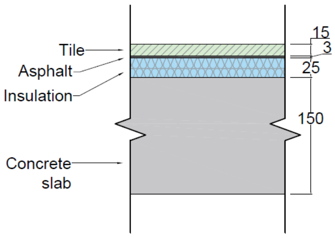
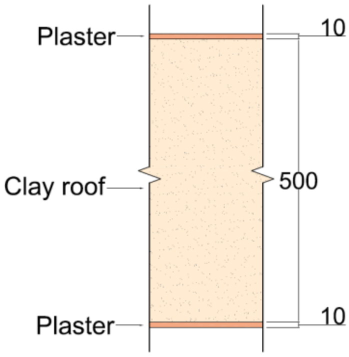
		
M5	1.25 W/m²·K 	0.604 W/m²·K 
M6	1.736 W/m²·K 	0.829 W/m²·K 

8.5.3 R2 Roofs changed from concrete to clay

The second improvement tested on the buildings' roofs was changing all the external walls from concrete to clay. This is to see how contemporary buildings behave if built with clay.

Table 8.9 shows the base U-value along with the improved U-value for each of the six mosques.

Table 8.9: R2 suggested improvement details for Mosques 1, 2, and 3 showing the roofs cross sections and U-value for each case study. Dimensions shown are in millimetres.

Mosque	Base U-value	B1 U-value
M1	0.816 W/m².K 	1.25 W/m².K 
M2	0.86 W/m².K 	1.25 W/m².K 
M3	0.86 W/m².K 	1.25 W/m².K 

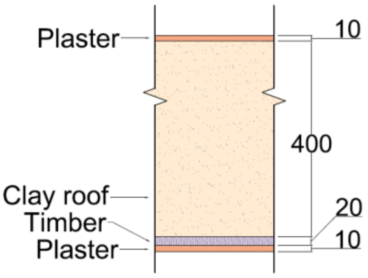
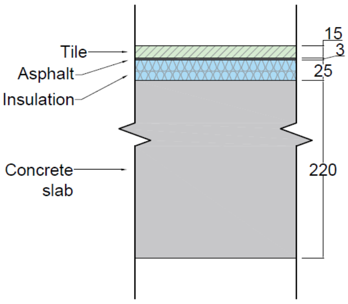
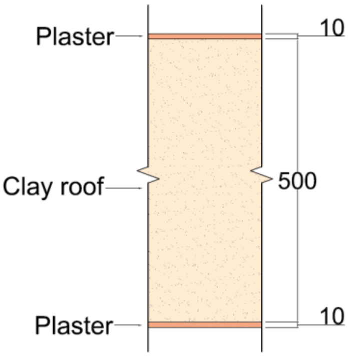
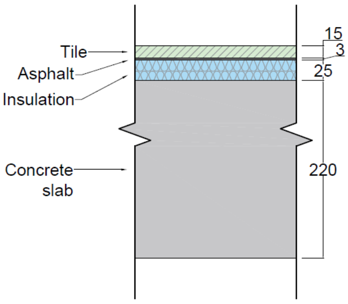
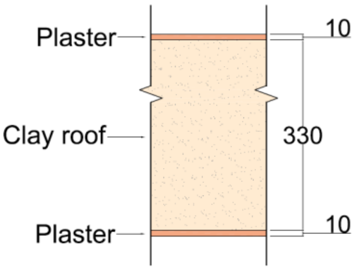
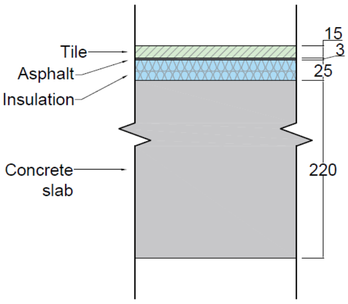
Changing the type of the roof material from concrete to clay or vice-versa yielded savings in the cooling load if the change is to a lower U-value. M1, M2, and M3 roofs already have relatively low U-values of 0.816 W/m^2.K, 0.86 W/m^2.K, and 0.86 W/m^2.K, respectively, which were all increased to 1.25 W/m^2.K.

8.5.4 R3 Roofs changed from clay to concrete

The third improvement tested on the buildings' roofs was changing all the external walls from clay to concrete. This is to see how traditional buildings behave if built with clay.

Table 8.10 shows the base U-value along with the improved U-value for each of the six mosques.

Table 8.10: R3 suggested improvement details for Mosques 4, 5, and 6 showing the roofs cross sections and U-value for each case study. Dimensions shown are in millimetres.

Mosque	Base U-value	B1 U-value
M4	1.198 W/m².K  	0.816 W/m².K 
M5	1.25 W/m².K  	0.816 W/m².K 
M6	1.736 W/m².K  	0.816 W/m².K 

8.5.5 Resultant Temperature using the Suggested Roofs

The resultant temperature (RT) was analysed for the suggested roofs in both summer day (day 179) and winter day (day 20) for all six mosques. Figures show RT for the baseline, R1, R2, and R3 walls for all six mosques in summer day and winter day.

Introducing building materials with a lower thermal conductivity is one technique to minimise heat gains during the day and to achieve thermal comfort during the summer; therefore, proposed improvements R1, R2, and R3 are implemented.

Figures 1 to 12 show how would the suggested improvements R1, R2, and R3 would impact the resultant temperature of all six mosques during the summer day and winter day. R1 roof (50% reduction in thermal conductivity) is implemented to all six mosques. R2 (Concrete walls are replaced by clay walls) is implemented to M1, M2, and M3. R3 (Clay walls are replaced by concrete walls) is implemented to M4, M5, and M6.

8.5.5.1 *Hudayfah Bin Al Yaman Mosque (M1)*

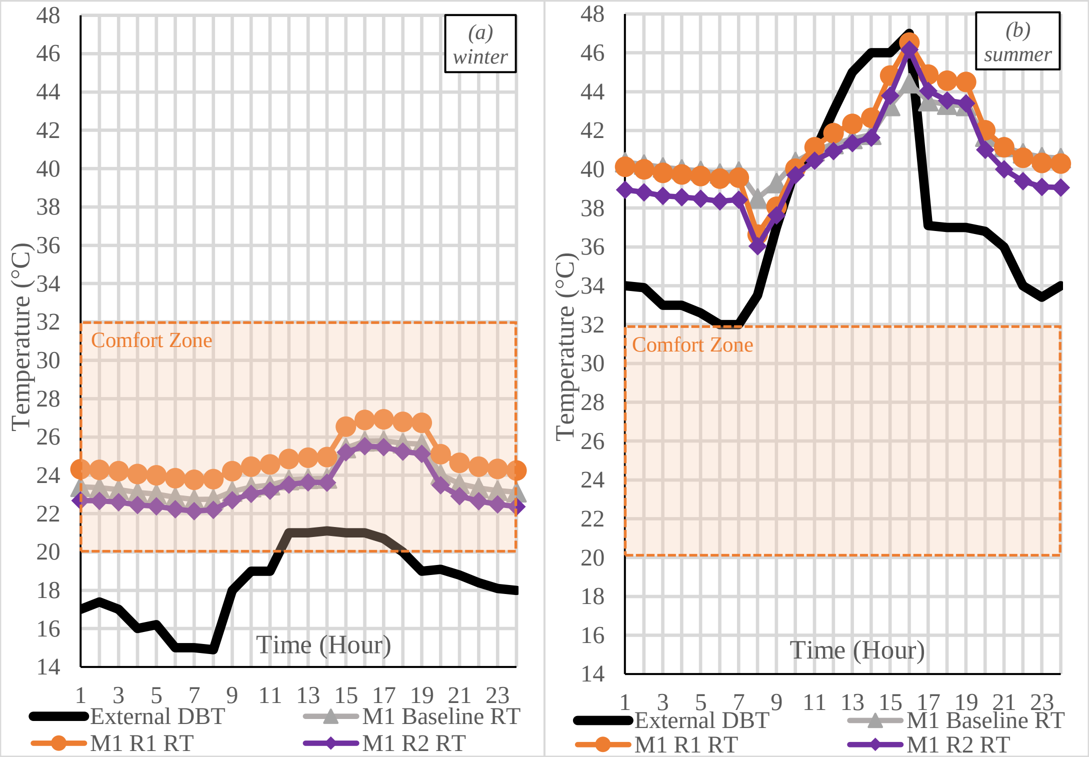


Figure 8.7: Resultant Temperatures (RT) for Mosque 1's baseline, R1, and R2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, R2 maintained the lowest RT during the entire winter day, peaking at 25.52 °C at 15:00, while the baseline was at 25.77 °C and W1 was at 26.9 °C at the same time (Figure 8.7a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature ranges from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, R2 maintained the lowest RT throughout most of the summer day, peaking at 46.16 °C at 16:00, while the baseline was at 44.44 °C, W1 was at 46.53 °C, and the external DBT was at 47 °C at the same time (Figure 8.7b). M1 R1 achieved the lowest RT of 36.04 °C at 08:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.5.5.2 Abu Hamza Al Shari Mosque (M2)

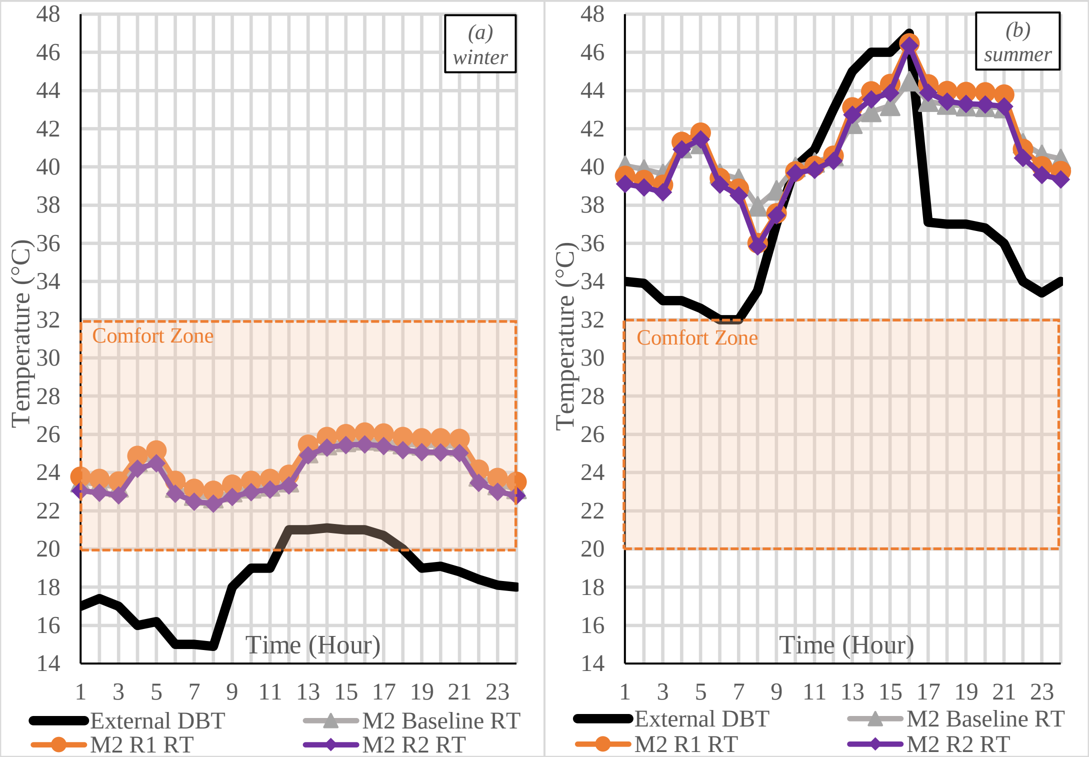


Figure 8.8: Resultant Temperatures (RT) for Mosque 2's baseline, R1, and R2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, R2 maintained the lowest RT during the entire winter day, peaking at 25.48 °C at 16:00, while the baseline was at 25.69 °C and R1 was at 26.09 °C at the same time (Figure 8.8a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature ranges from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, R2 maintained the lowest RT throughout most of the summer day, peaking at 46.47 °C at 16:00, while the baseline was at 44.49 °C, R1 was at 46.36 °C, and the external DBT was at 47 °C at the same time (Figure 8.8b). M1 R1 achieved the lowest R1 of 36.02 °C at 08:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.5.5.3 *Othman bin Afan Mosque (M3)*

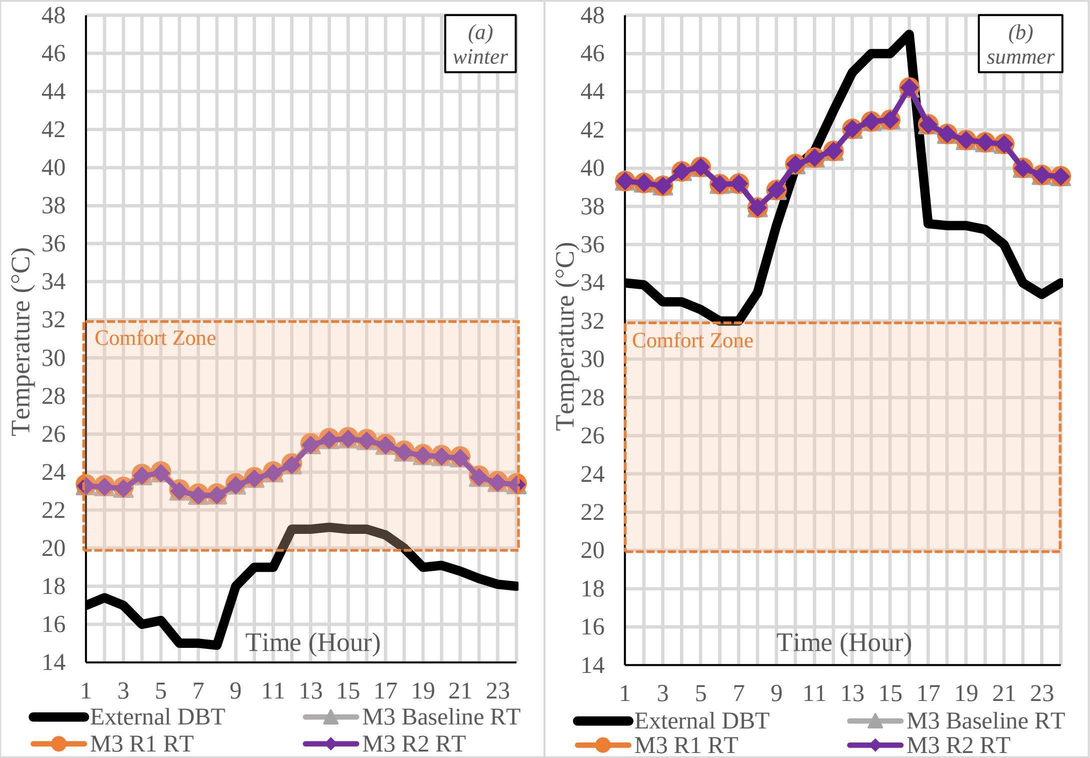


Figure 8.9: Resultant Temperatures (RT) for Mosque 3’s baseline, R1, and R2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, R2 maintained the lowest RT during the entire winter day, peaking at 25.74 °C at 15:00, while the baseline was at 25.78 °C and R1 was at 25.82 °C at the same time (Figure 8.9a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature ranges from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M3 Baseline, M3 R1, and M3 R2 stay almost identical throughout the summer day, peaking at 44.22 °C, 44.21 °C, and 44.21 °C respectively at 16:00, while the external DBT was at 47 °C at the same time (Figure 8.9b). M1 R1 and R2 achieved the lowest RT of 37.94 °C at 08:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.5.5.4 Sa'al Mosque (M4)

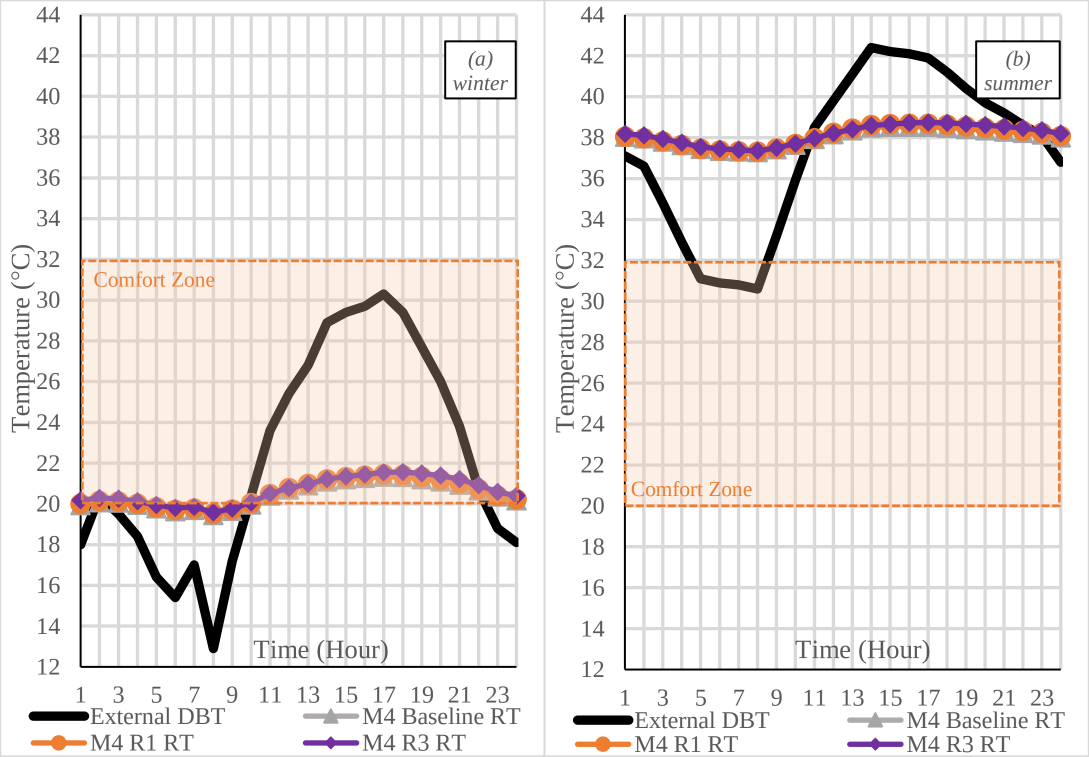


Figure 8.10: Resultant Temperatures (RT) for Mosque 4's baseline, R1, and R2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M4 Baseline maintained the lowest RT during the entire winter day, peaking at 21.34 °C at 17:00, while the M4 R1 was at 19.52 °C and M3 R3 was at 19.58 °C at the same time (Figure 8.10a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature ranges from 12.9 °C to 30.3 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M4 Baseline maintained the lowest RT during the entire winter day, peaking at 38.53 °C between 15:00 and 17:00, while the M4 R1 was at 38.67 °C and M3 R3 was at 38.74 °C at the same time (Figure 8.10b). M1 baseline achieved the lowest RT of 37.29 °C at 08:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.5.5.5 Al Wafi Mosque (M5)

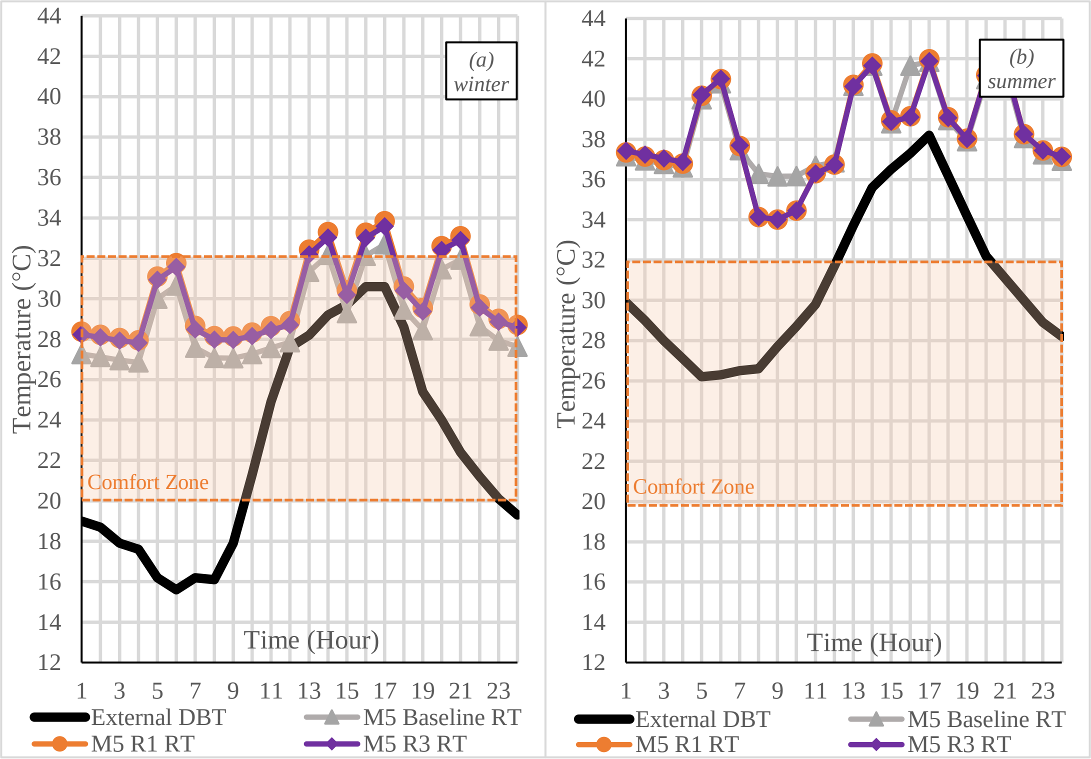


Figure 8.11: Resultant Temperatures (RT) for Mosque 5's baseline, R1, and R2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M5 baseline maintained the lowest RT during the entire winter day, peaking at 32.69 °C at 15:00, while M5 R1 was at 33.84 °C and M5 R3 was at 33.58 °C at the same time (Figure 8.11a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature ranges from 15.6 °C to 30.6 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M5 R1 and M5 R3 maintained a lower RT between 07:00 and 11:00. M5 Baseline was the lowest for the rest of the day. The RT peak of the day for M5 baseline, M5 R1, and M5 R3 was 41.85, 41.97 and 41.88, respectively. while the external DBT was at 38.2 °C at the same time (Figure 8.11b). M1 R1 and R3 achieved the lowest RT of 34.01 °C at 09:00 which is higher than the thermal comfort upper limit of 30 °C.

8.5.5.6 Aal Hamoodah Mosque (M6)

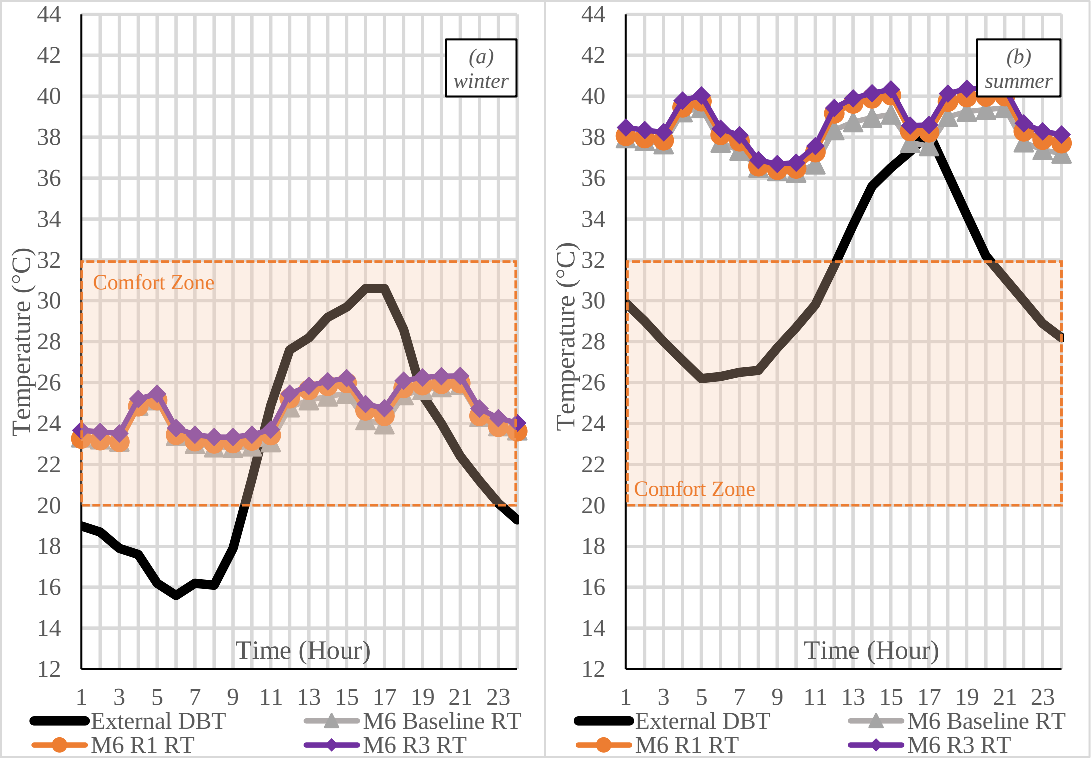


Figure 8.12: Resultant Temperatures (RT) for Mosque 6's baseline, R1, and R2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M6 Baseline maintained the lowest RT during most of the winter day, peaking at 25.89 °C at 21:00, while M5 R1 was at 25.97 °C and M5 R3 was at 26.33 °C at the same time (Figure 8.12a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature ranges from 15.6 °C to 30.6 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M6 Baseline maintained the lowest RT during the summer design day, peaking at 39.43 °C at 21:00, while M5 R1 was at 40.05 °C and M5 R3 was at 40.39 °C at the same time (Figure 8.12b). M6 Baseline had the lowest RT of the summer design day of 36.27 °C at 10:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.5.6 Thermal Comfort using the Suggested Roofs

Table 8.11: Percentage of annual occupied hours within the comfort range (-1 < PMV < +1) for the baseline model and the roofs suggested improvements' models

Model	M1	M2	M3	M4	M5	M6
Baseline	15.5%	14.3%	16.1%	40.4%	0.2%	25.6%
R1	9.9%	13.0%	15.3%	38.4%	0.1%	22.6%
R2	20.6%	17.0%	17.5%			
R3				39.4%	0.1%	21.9%

This section explores how the thermal comfort in each of the free-running six mosques would be impacted by the various roof improvement techniques. The PMV and PPD analyses of each of the improvements in all six mosques were performed using the EDSL TAS programme. Table 8.11 shows the percentage of occupied hours that has a PMV ranging from -1 to +1. It is noted that all the occupied hours during summer fall outside of the -1 < PMV < +1 range, hence the values shown in the table are true as annual figures as well as winter figures. The buildings are assumed to be free-running.

R1 (higher insulation roof) appears to have decreased the percentage of hours within the comfort range. The results show an decrease in the percentage of hours within the -1 < PMV < +1 range for all mosques.

For M1, M2, and M3, R2 (concrete to clay) was applied. The results show an increase in the percentage of hours within the comfort range for all three mosque buildings, M1, M2, and M3. The increase was from 15.5% to 20.6%, from 14.3% to 17%, and from 16.1% to 17.5%, respectively.

For M4, M5, and M6, W3 (clay to concrete) was applied. The results show a decrease in the percentage of hours within the comfort range for all three mosques, M4, M5, and M6. It decreased it from 40.4% to 39.4%, from 0.2% to 0.1% and from 25.6% to 21.9%, respectively.

While a higher insulation roof would better insulate against heat gain during the day, it would also prevent heat loss during the night. The R1 results suggest a the difference it made in heat gain is greater than heat loss than the base model. R2 (concrete to clay) and R3 (clay to concrete) verifies the results' chapter conclusion that clay walls has better thermal performance in a free running building due to the higher thermal mass and time constant of the clay walls.

8.5.7 Cooling Load Reduction using the Suggested Roofs

Table 8.12: Cooling load reductions of the roofs suggested improvements' models.

Model	M1	M2	M3	M4	M5	M6
R1	-12.8%	-2.8%	-1.9%	-5.3%	-4.4%	-9.0%
R2	8.6%	0.6%	0.8%			
R3				-1.7%	-1.3%	-7.0%

Table 8.12 presents the cooling load reduction in all six buildings. The cooling load reduction is expressed as a percentage change compared to a baseline scenario.

R1, a higher insulation wall, has caused a decrease in cooling load in all six mosque buildings. The reduction ranges from 1.9% to 12.8%. W2, the replacement of concrete walls with clay walls, was applied to M1, M2, and M3. It increased the cooling load for all three mosques, M1, M2, M3 by 8.6%, 0.6% and 0.8%. W3, the replacement of clay walls with concrete walls, has reduced the cooling load in M4, M5, and M6 by 1.7%, 1.3%, and 7% respectively.

A higher insulation roof (R1) worked better for all mosque buildings as it insulates better against heat gain during the air conditioning period. R2 (concrete to clay) and R3 (clay to concrete) verifies the results' chapter conclusion that concrete walls have better thermal performance in an air-conditioned building due to the lower thermal mass and time constant of the concrete walls.

8.6 The Suggested Improvements to the Windows

8.6.1 F1 Windows with half the glazing-to-wall ratio

The first improvement tested on the building's windows was reducing the glazing-to-wall ratio for all windows to half. Glazing ratio need to be designed and considered with care as decreasing the glazing ratio can reduce solar heat gain, but it also reduces the amount of natural light entering the space. Since there are varying sizes of windows, a 50% reduction to the glazing ratio was implemented across the board. Table 8.13 shows the base and reduced window sizes for each of the six mosques.

Table 8.13: The baseline and F1 models' window sizes for all six mosques

Mosque	Base window sizes	F1 window sizes
M1	1.9 m x 2.54 m	1.9 m x 1.27 m
M2	2m x 2.7m 1.48m x 2.3m 1m x 1.8m 1.5m x 1m	2 m x 1.35 m 1.48 m x 1.15 m 1 m x 0.9 m 1.5 m x 0.5 m
M3	1.38m x 4m 1.29m x 1m 1.2m x 2.5m	0.69 m x 4 m 1.29 m x 0.5 m 1.2 m x 1.25 m

M4	0.14 m x 0.55 m	0.14 m x 0.275 m
M5	0.7 m x 1 m	0.7 m x 0.5 m
M6	0.4 m x 0.6 m	0.4 m x 0.3 m

8.6.2 F2 Windows with half the U-value

The second improvement tested on the buildings' windows was reducing the U-value for all the windows to half. This is basically upgrading the Single glazed window to a Double glazed window and the double glazed window to a triple glazed window as shown in Table 8.14. M1 and M2 windows were upgraded from double to triple glazing. M3, M4, M5 and M6 windows were upgraded from single to double glazing.

Table 8.14: The baseline and F2 models' U-values and window type for all six mosques

Mosque	Base U-value	F2 U-value
M1	3.105 W/m².K Double glazed window	1.488 W/m².K Triple glazed window
M2	3.105 W/m².K Double glazed window	1.488 W/m².K Triple glazed window
M3	5.775 W/m².K Single glazed window	3.105 W/m².K Double glazed window
M4	5.775 W/m².K Single glazed window	3.105 W/m².K Double glazed window
M5	5.775 W/m².K Single glazed window	3.105 W/m².K Double glazed window
M6	5.775 W/m².K Single glazed window	3.105 W/m².K Double glazed window

8.6.3 F3 Night Purge

The third suggested improvement to the buildings' windows is to introduce night purge from 11pm to 2am every summer night as shown in Table 8.15. The natural ventilation starts when the internal dry bulb temperature of Zone 1 reaches 21 °C and increases proportionally until 23 °C when the maximum ventilation value of 3 air changes per hour will apply.

Table 8.15: The baseline and F3 models' night purge settings for all six mosques

Mosque	Base model ventilation	F3 model ventilation
M1	No night purge	11pm to 2am every summer night
M2	No night purge	11pm to 2am every summer night
M3	No night purge	11pm to 2am every summer night
M4	No night purge	11pm to 2am every summer night
M5	No night purge	11pm to 2am every summer night
M6	No night purge	11pm to 2am every summer night

8.6.4 Resultant Temperature using the Suggested Windows

8.6.4.1 Hudayfah Bin Al Yaman Mosque (M1)

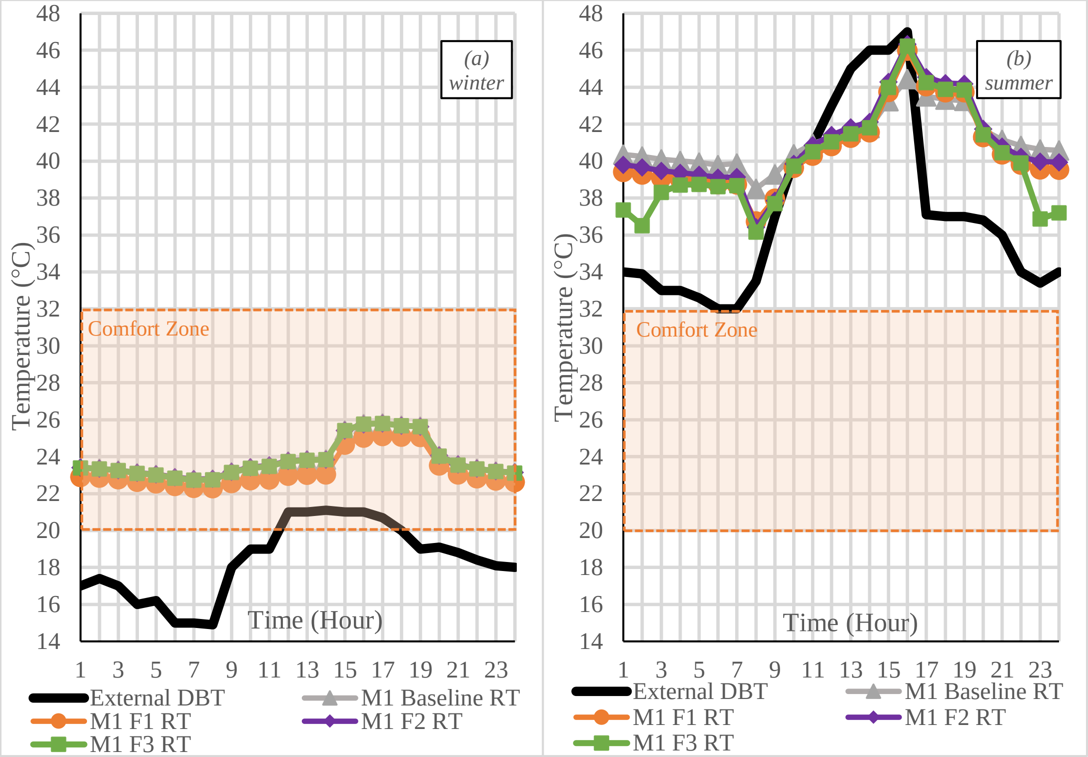


Figure 8.13: Resultant Temperatures (RT) for Mosque 1's baseline, F1, F2, and F3 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, F1 maintained the lowest RT during the entire winter day, peaking at 25.13 °C at 17:00, while the M1 Baseline, M1 F2, and M1 F3 were all at 25.8 °C at the same time (Figure 8.13a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature ranges from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, F3 maintained the lowest RT throughout most of the summer day, peaking at 46.24 °C at 16:00, while the baseline was at 44.44 °C, F1 was at 46.53 °C, F2 was at 46.34 °C, and the external DBT was at 47 °C at the same time (Figure 8.13b). M1 F3 achieved the lowest RT during the summer design day of 36.16 °C at 08:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.6.4.2 Abu Hamza Al Shari Mosque (M2)

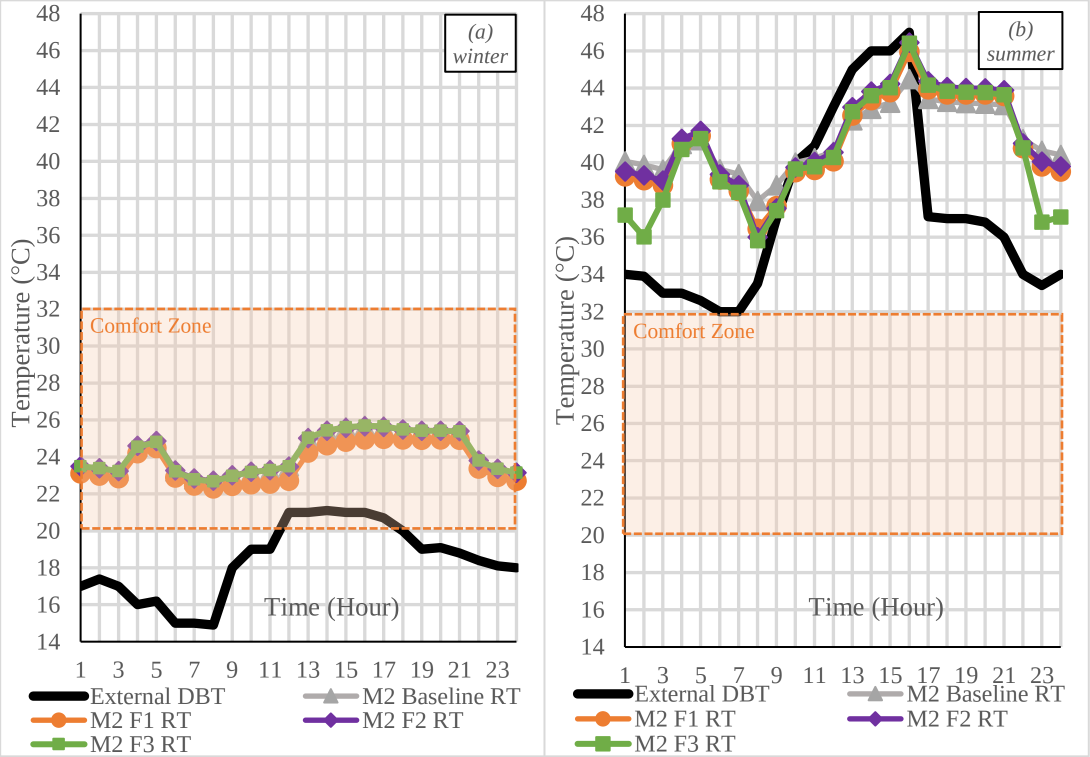


Figure 8.14: Resultant Temperatures (RT) for Mosque 2's baseline, F1, F2, and F3 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M2 F1 had the lowest RT of 22.29 °C during the entire winter day, peaking at 24.98 °C at 17:00, while the M1 Baseline was at 25.69 °C, M1 F2 was at 25.65, and M1 F3 was at 25.69 at the same time (Figure 8.14a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature ranges from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M2 F3 had the lowest RT of 35.81 °C during the summer day, peaking at 46.41 °C at 16:00, while the M2 Baseline was at 44.49 °C, F1 was at 45.95 °C, F2 was at 46.45 °C, and the external DBT was at 47 °C at the same time (Figure 8.14b). M1 F3 achieved the lowest RT during the summer design day of 35.81 °C at 08:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.6.4.3 Othman bin Afan Mosque (M3)

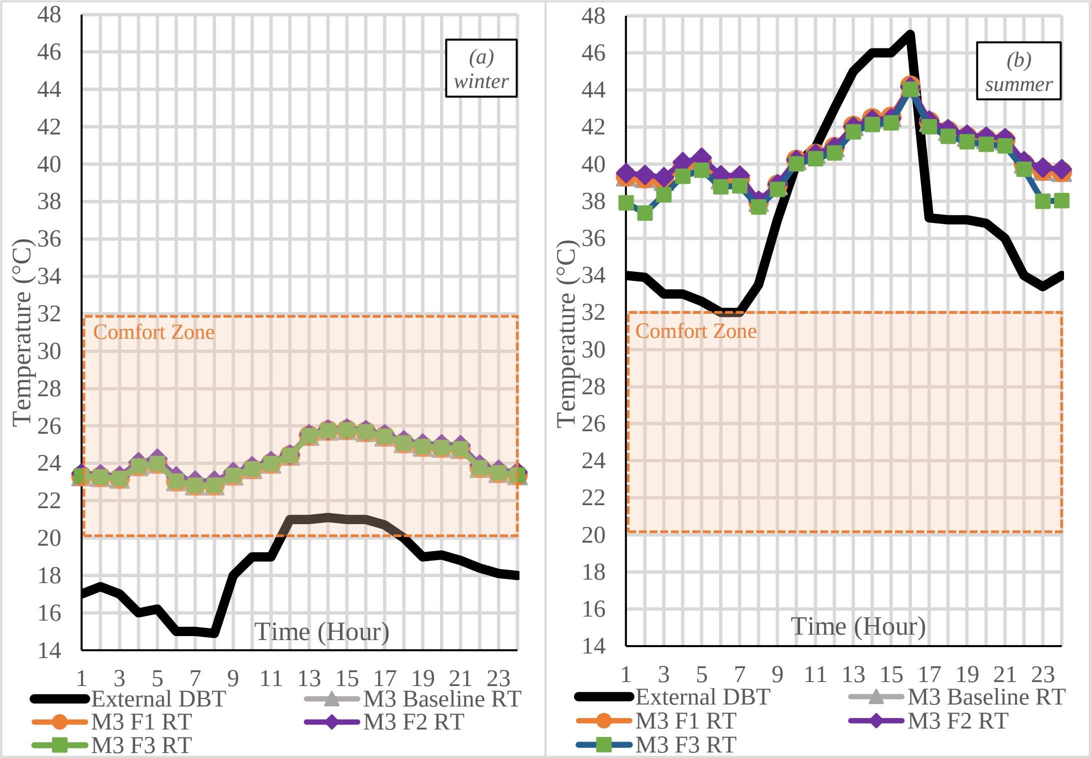


Figure 8.15: Resultant Temperatures (RT) for Mosque 3's baseline, F1, F2, and F3 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M3 Baseline, M3 F1, and M3 F3 share the lowest RT of 22.82 °C during the entire winter day, peaking at 25.78 °C at 15:00, while the M3 F2 was not far off at 25.85 °C at the same time (Figure 8.15a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature ranges from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M3 F3 had the lowest RT of 37.36 °C during the summer day, peaking at 44.03 °C at 16:00, while the M3 Baseline was at 44.22 °C, F1 was at 44.22 °C, F2 was at 44.15 °C, and the external DBT was at 47 °C at the same time (Figure 8.15b). M1 F3 achieved the lowest RT during the summer design day of 37.36 °C at 08:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.6.4.4 *Sa'al Mosque (M4)*

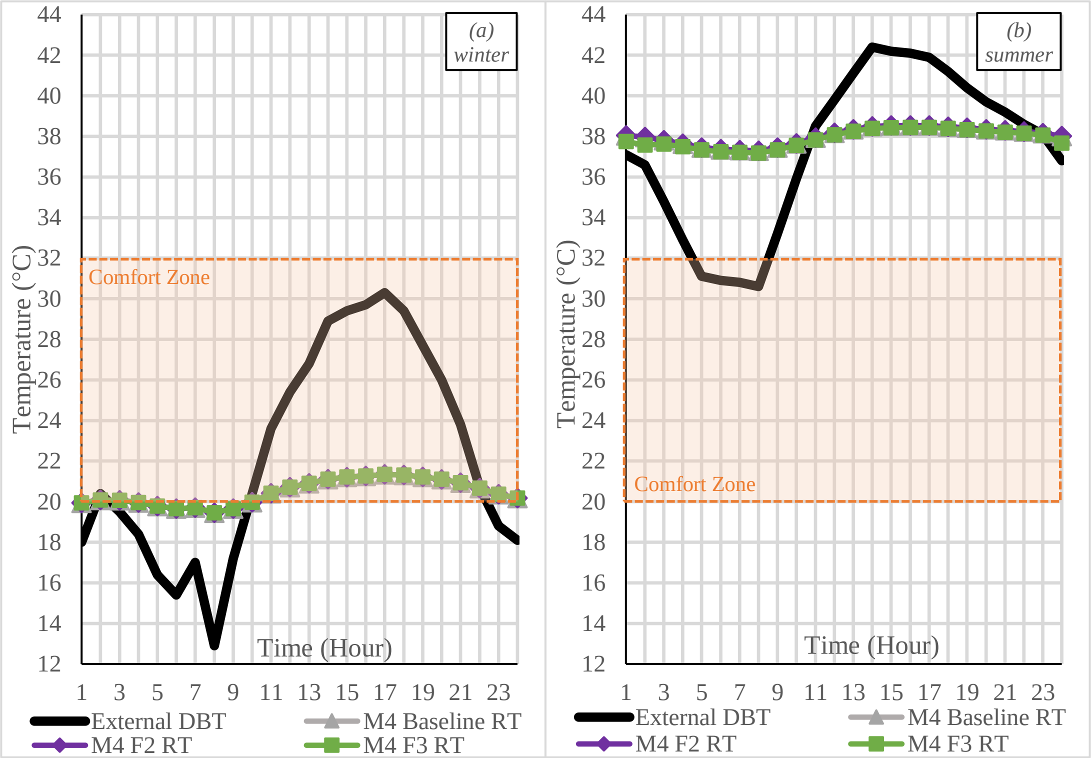


Figure 8.16: Resultant Temperatures (RT) for Mosque 4's baseline, F1, F2, and F3 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M4 Baseline, M4 F2, and M4 F3 all share the same RT throughout the entire winter day. The low for all three scenarios is 19.46 °C and the high is 21.34 °C. (Figure 8.16a). It shows that thermal comfort is achieved in all three cases during occupancy although the external dry bulb temperature ranges from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M3 F3 had the lowest RT of 37.18 °C during the summer day, peaking at 38.44 °C at 16:00, while the M3 Baseline was at 38.53 °C, F2 was at 38.53 °C, and the external DBT was at 42.1 °C at the same time (Figure 8.16b). M1 F3 achieved the lowest RT during the summer design day of 37.18 °C at 08:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.6.4.5 *Al Wafi Mosque (M5)*

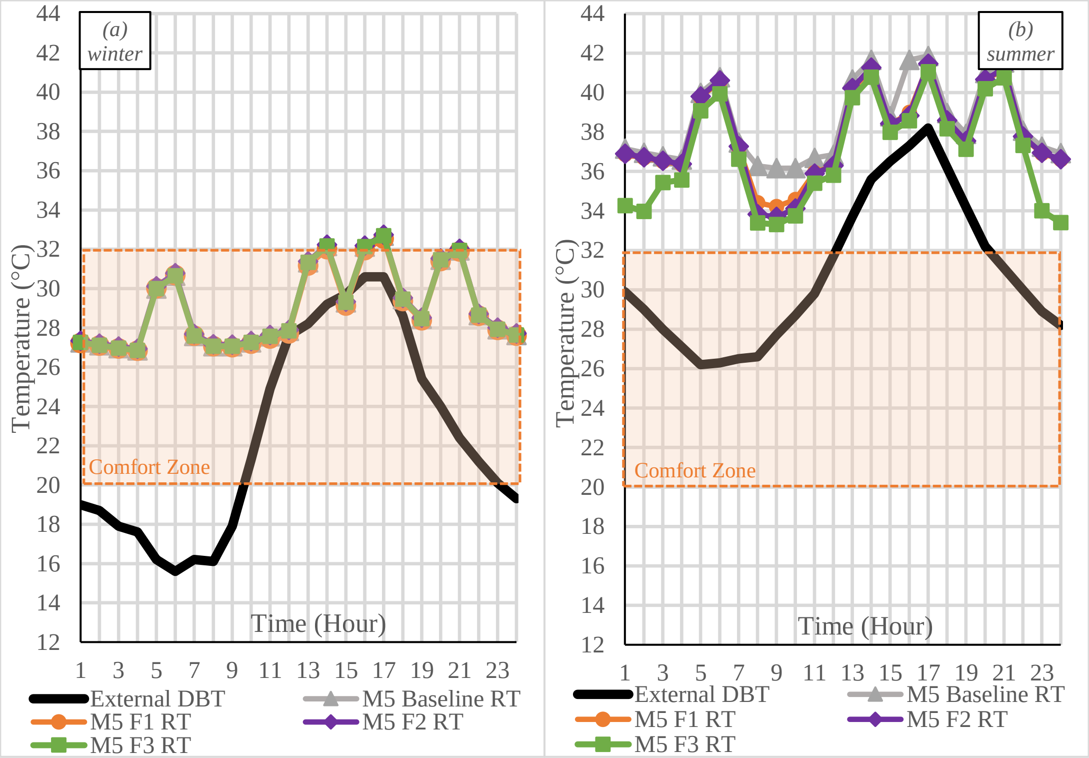


Figure 8.17: Resultant Temperatures (RT) for Mosque 5's baseline, F1, F2, and F3 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M5 F1 maintained the lowest RT of 26.84 2 °C during most of the winter day, peaking at 32.54 °C at 17:00, while the M5 Baseline was at 32.69, M5 F2 was at 32.74 °C, M5 F3 was at 32.69, and the external DBT was at 30.6 °C at the same time (Figure 8.17a). It shows that thermal comfort is not achieved in all three cases throughout the day although the external dry bulb temperature ranges from 15.6 °C to 30.6 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M5 F3 had the lowest RT of 33.31 °C during the summer day, peaking at 41.05 °C at 17:00, while the M5 Baseline was at 36.84 °C, M5 F1 was at 34.21 °C, M5 F2 was at 33.69 °C, and the external DBT was at 38.2 °C at the same time (Figure 8.17b). M5 F3 achieved the lowest RT during the summer design day of 33.31 °C at 09:00 which is higher than the thermal comfort upper limit of 30 °C.

8.6.4.6 Aal Hamoodah Mosque (M6)

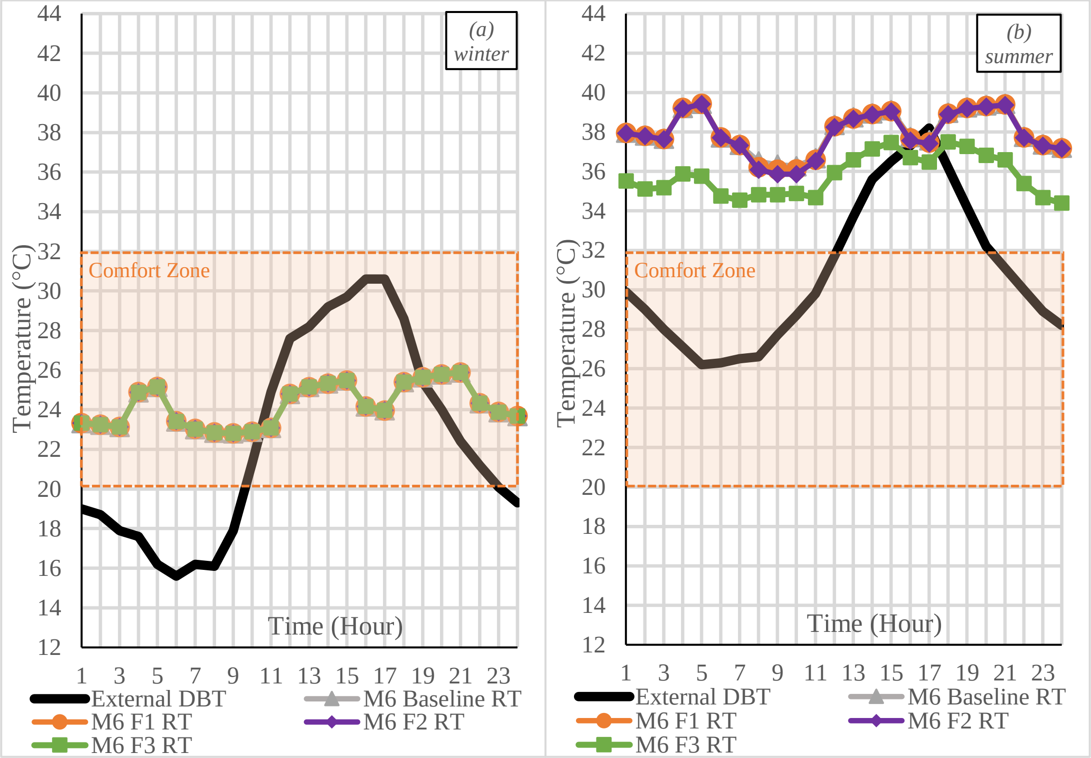


Figure 8.18: Resultant Temperatures (RT) for Mosque 6's baseline, F1, F2, and F3 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M6 Baseline, M6 F1, M6 F2, and M6 F3 all share the same RT throughout the entire winter day. The low for all three scenarios is 22.81 °C and the high is 25.89 °C. (Figure 8.18a). It shows that thermal comfort is achieved in all three cases during occupancy although the external dry bulb temperature ranges from 15.6 °C to 30.6 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M5 F3 had the lowest RT of 34.39 °C during the summer day, peaking at 37.49 °C at 18:00, while the M5 Baseline was at 39.43 °C, M5 F1 was at 39.43 °C, M5 F2 was at 39.41 °C, and the external DBT was at 38.2 °C at the same time (Figure 8.18b). M5 F3 achieved the lowest RT during the summer design day of 34.39 °C at 00:00 which is higher than the thermal comfort upper limit of 30 °C.

8.6.5 Thermal Comfort using the Suggested Windows

Table 8.16: Percentage of annual occupied hours within the comfort range (-1 < PMV < +1) for the baseline model and the windows suggested improvements' models

Model	M1	M2	M3	M4	M5	M6
Baseline	15.5%	14.3%	16.1%	40.4%	0.2%	25.6%
F1	20.2%	17.4%	16.1%	40.5%	0.2%	25.6%
F2	15.3%	14.4%	15.5%	40.7%	0.2%	25.6%
F3	15.5%	14.3%	16.2%	39.8%	0.2%	25.6%

This section explores how the thermal comfort in each of the six mosques would be impacted by the various fenestration improvement techniques. The PMV and PPD analyses of each of the improvements in all six mosques were performed using the EDSL TAS programme. Table 8.16 shows the percentage of occupied hours that has a PMV ranging from -1 to +1. It is noted that all the occupied hours during summer fall outside of the -1 < PMV < +1 range, hence the values shown in the table are true as annual figures as well as winter figures. The buildings are assumed to be free-running.

F1 (reduced glazing to wall ratio by 50%) increased the percentage of hours within the comfort range for M1, M2, and M4, while it remained unchanged for M3, M5, and M6. The increase was most significant in both M1 and M2. This is due to the large windows of M1 and M2, which meant that a 50% decrease in glazing to wall ratio would better insulate the building against heat gains.

F2 (reduced glazing conductivity by 50%) decreased for M1 and M3, increased the percentage of hours within the comfort range for M2 and M4, and it remained unchanged for M5 and M6. F2 did not have a significant impact on thermal comfort in all mosques.

F3 (night purge) increased the percentage of hours within the comfort range for M3, decreased it for M4, and it remained unchanged for M1, M2, M5, and M6. F3 did not have a significant impact on thermal comfort in all mosques.

8.6.6 Cooling Load Reduction using the Suggested Windows

Table 8.17: Cooling load reductions of the windows suggested improvements' models

Model	M1	M2	M3	M4	M5	M6
F1	-6.6%	-3.5%	0.0%	-0.1%	-1.9%	-0.2%
F2	-2.6%	-1.4%	-2.3%	0.0%	-0.7%	-0.1%
F3	-5.5%	-2.2%	-2.3%	-0.2%	26.4%	46.0%

Table 8.17 presents the cooling load reduction in all six buildings. The cooling load reduction is expressed as a percentage change compared to a baseline scenario.

F1 (reduced glazing to wall ratio by 50%) has caused a decrease in cooling load in all mosque buildings except for M3, which remained unchanged. The reduction ranges from 0.1% to 6.6%. The most significant cooling load reductions here are in M1, M2, and M5, which have large windows. Lower glazing to wall ratio meant lower heat gains in the these mosques. Because the remaining mosques had single glazing and/or smaller windows, a 50% reduction in glazing to wall ratio did not result in significant cooling load savings.

F2 (reduced glazing conductivity) has caused a decrease in cooling load in all mosque buildings except for M4, which remained unchanged. The reduction ranges from 0.1% to 2.6%. The most significant cooling load reductions here are in M1, M2, and M3. These mosque buildings have large windows, which meant any reduction in heat conductivity would translate to greater reductions in heat gains.

F3 (night purge) has reduced the cooling load in M1, M2, M3, and M4 by 5.5%, 2.2%, and 2.3%, and 0.2% respectively. It increased the cooling load by 26.4% and 46% for M5 and M6, respectively. Due to the lower external DBT around 30 °C on the summer design day at midnight for M5 and M6, night purge contributed to heat gain more than heat loss. For M4, the external DBT was around 37 °C on the summer design day at midnight. For M1, M2, and M3, the external DBT was around 34 °C in the summer design day at midnight.

8.7 Suggested Improvements to the Internal Conditions

8.7.1 IC1 Increase the cooling thermostat setpoint by 2 °C

The first suggestion for improving the internal conditions is to increase the cooling thermostat setpoint by two degrees Celsius, as outlined in Table 8.18. Testing was conducted with varying increases of 1, 2, and 3 degrees Celsius, resulting in reduced cooling loads across all six case studies. The results demonstrated a reduction in cooling loads across all six case studies, with the magnitude of the reduction proportional to the increase in setpoint. Ultimately, an increase of 2 degrees Celsius was deemed to be the most suitable and practical approach to present in this research.

Table 8.18: The baseline and IC1 models cooling thermostat setpoints.

Mosque	**Base cooling thermostat set point (°C)**	**IC1 cooling thermostat setpoint (°C)**
M1	20	22
M2	23	25
M3	23	25
M4	23	25
M5	23	25
M6	23	25

8.7.2 IC2 lower infiltration rate

The second suggestion for improving the internal condition is to lower the infiltration rate from 0.5 ACH to 0.1 ACH for each building as shown in Table 8.19. It is assumed that achieving 0.1 ACH is possible by installing better insulated window frames and door frames.

Table 8.19: The baseline and IC2 models infiltration rates.

Mosque	**Base infiltration rate (ACH)**	**IC2 infiltration rate (ACH)**
M1	0.5	0.1
M2	0.5	0.1
M3	0.5	0.1
M4	0.5	0.1
M5	0.5	0.1
M6	0.5	0.1

8.7.3 IC3 High efficiency lighting

The third suggestion for improving the internal condition is to use higher efficiency LED lighting systems inside the buildings (Table 8.20). The current lighting heat gain was assumed to be 16.5 W/m^2 for all six case studies. If the suggested higher efficiency LED lighting is the Sylvia GLS shape 806Lm, it would have a lighting heat gain of 4.34 W/m^2 (*ToLEDo GLS | Sylvania Lighting Solutions*, 2023). This suggested improvement does not apply to Mosque 4, as the base model of Mosque 4 was considered unoccupied and unlit.

Table 8.20: The baseline and IC3 models lighting heat gains

Mosque	Base lighting heat gain (W/m^2)	IC3 lighting heat gain (W/m^2)
M1	16.5	4.34
M2	16.5	4.34
M3	16.5	4.34
M4	0	N/A
M5	16.5	4.34
M6	16.5	4.34

8.7.4 Resultant Temperature using the Suggested Internal Conditions

8.7.4.1 Hudayfah Bin Al Yaman Mosque (M1)

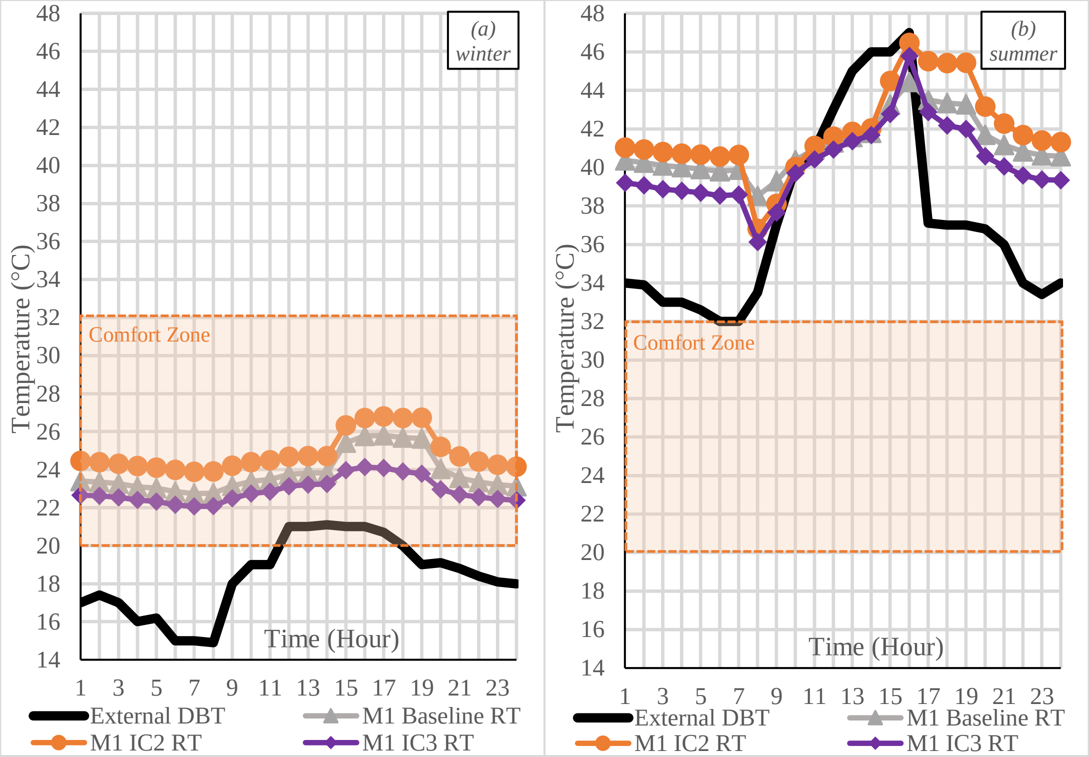


Figure 8.19: Resultant Temperatures (RT) for Mosque 1's baseline, W1, and W2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M1 IC3 maintained the lowest RT of 22.06 during most of the winter design day, peaking at 24.13 °C at 16:00, while the M1 Baseline was at 25.8 °C, M1 IC2 was at 26.795 °C, and the external DBT was at 21 °C at the same time (Figure 8.19a). It shows that thermal comfort is achieved in all five cases throughout the day although the external dry bulb temperature ranges from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M1 IC3 maintained the lowest RT of 36.12 °C throughout the summer design day, peaking at 45.78 °C at 16:00, while M1 Baseline was at 44.44 °C, M1 IC2 was at 46.46 °C, and the external DBT was at 47 °C at the same time (Figure 8.19b). M1b P1 achieved the lowest RT during the summer design day of 36.12 °C at 08:00 which is higher than the thermal comfort upper limit of 30 °C.

8.7.4.2 Abu Hamza Al Shari Mosque (M2)

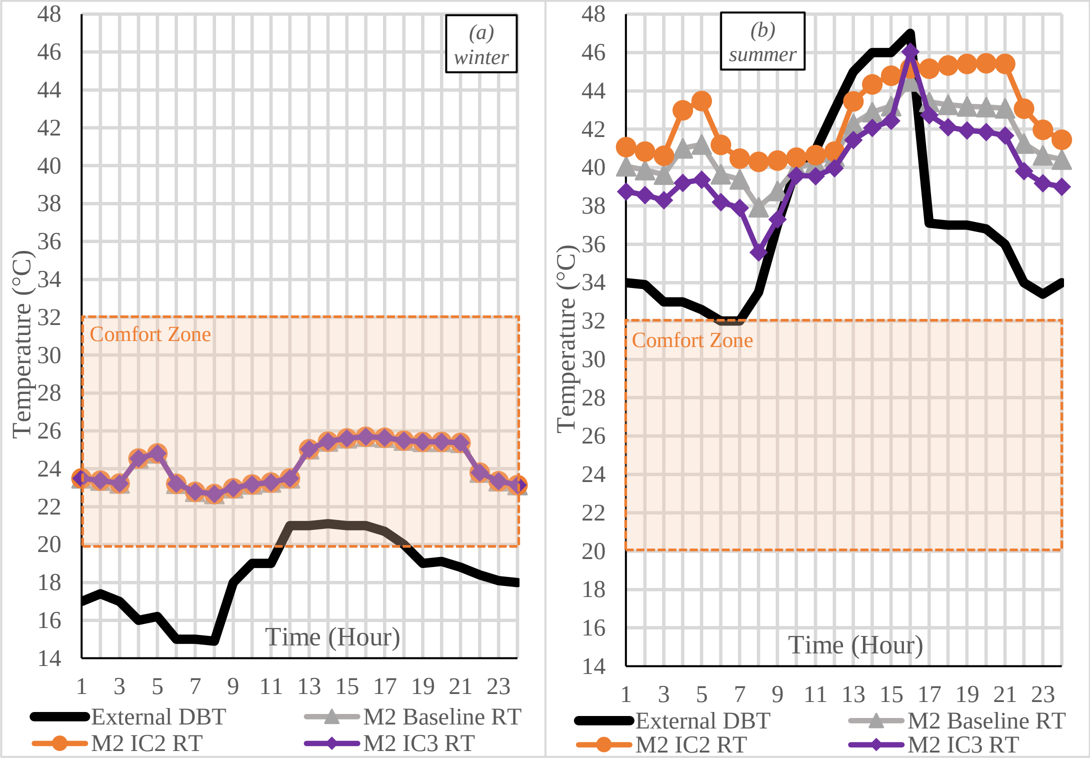


Figure 8.20: Resultant Temperatures (RT) for Mosque 2's baseline, W1, and W2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M2 Baseline, M2 IC2, and M2 IC3 all share the same lowest RT of 22.67 °C during the entire winter day, and also share the peak diurnal RT of 25.69 °C at 16:00 (Figure 8.20a). It also shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature ranges from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M2 IC3 had the lowest RT of 35.59 °C during the summer design day, peaking at 46.05 °C at 16:00, while the M2 Baseline was at 44.49 °C, M2 IC2 was at 45.44 °C, and the external DBT was at 47 °C at the same time (Figure 8.20b). M1 IC3 achieved the lowest RT during the summer design day of 35.59 °C at 08:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.7.4.3 Othman bin Afan Mosque (M3)

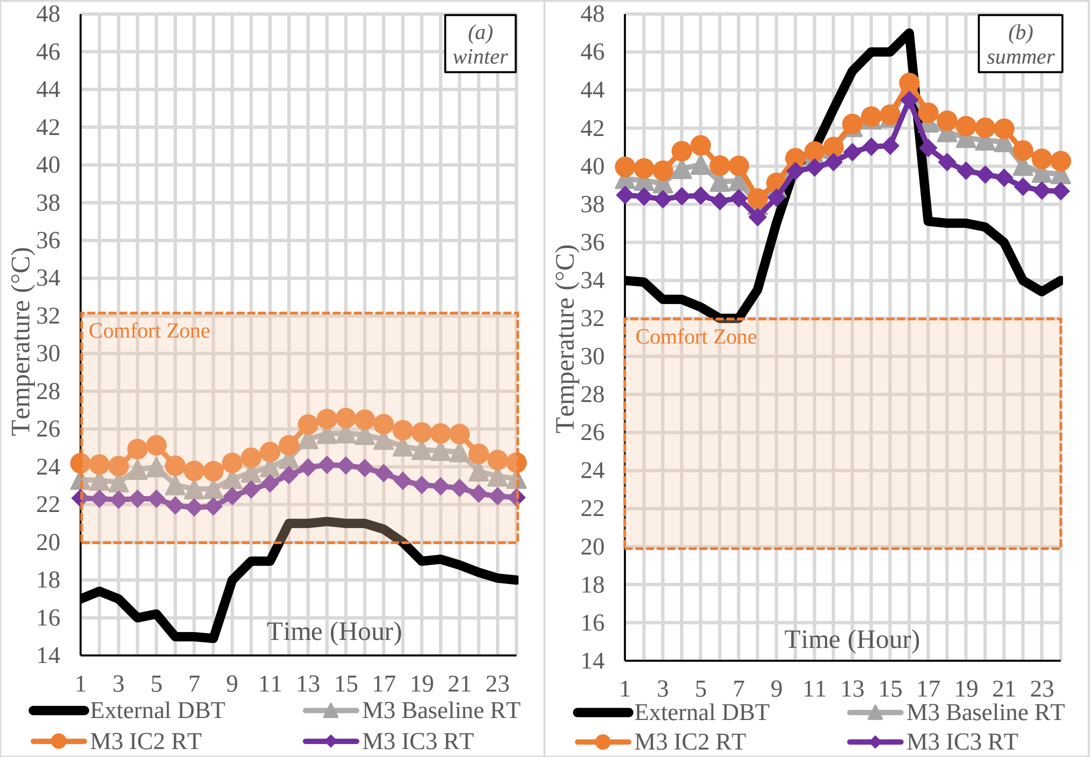


Figure 8.21 Resultant Temperatures (RT) for Mosque 3's baseline, W1, and W2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b).

In winter, M3 IC3 had the lowest RT of 21.84 °C during the entire winter day, peaking at 24.1 °C at 15:00, while the M3 Baseline was at 25.78, M3 IC2 was at 26.58, and the external DBT was at 21 at the same time (Figure 8.21a). It shows that thermal comfort is achieved in all five cases throughout the day although the external dry bulb temperature ranges from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M3 IC3 had the lowest RT of 35.59 °C during the entire summer design day, peaking at 46.05 °C at 16:00, while the M3 Baseline was at 44.49 °C, M3 IC2 was at 45.44 °C, and the external DBT was at 47 °C at the same time (Figure 8.21b). M3 O4 achieved the lowest RT during the summer design day of 35.59 °C at 08:00 which is higher than the thermal comfort upper limit of 30 °C.

8.7.4.4 Sa’al Mosque (M4)

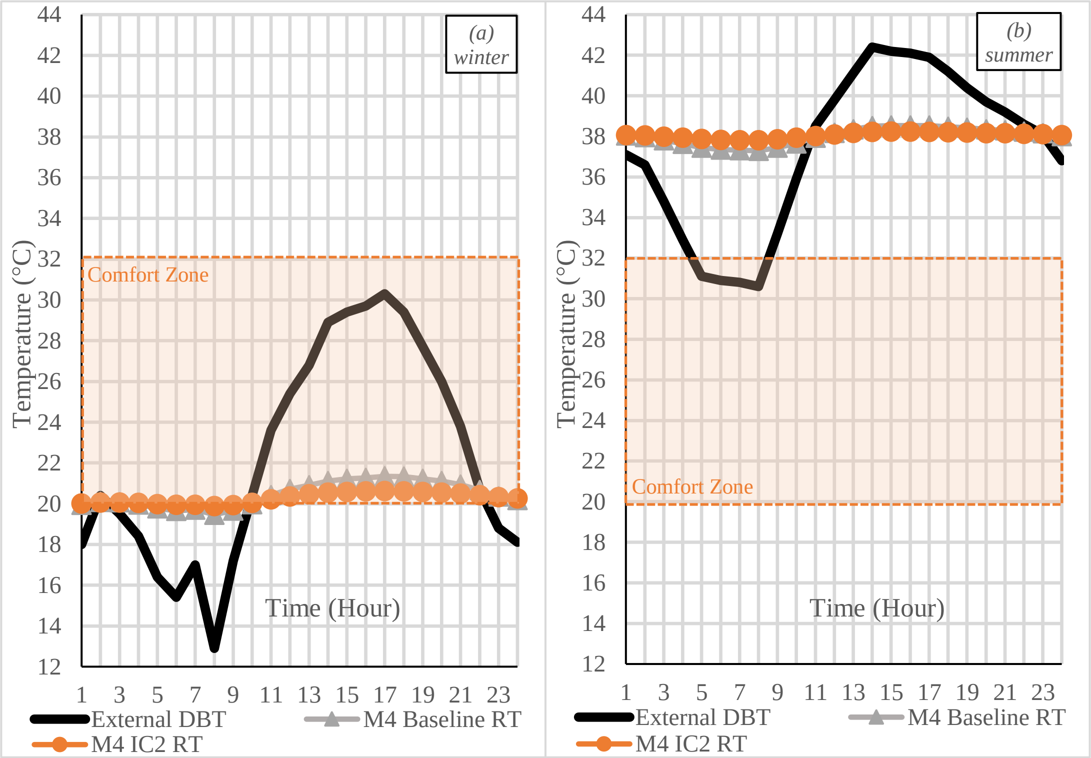


Figure 8.22: Resultant Temperatures (RT) for Mosque 4’s baseline, W1, and W2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b).

In winter, M4 Baseline had lower RT than M4 IC2 during the early morning until 11:00. After than M4 IC2 had lower RT than M4 Baseline (Figure 8.22a). It shows that thermal comfort is achieved in all three cases during occupancy although the external dry bulb temperature ranges from 12.9 °C to 30.3 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M4 Baseline had lower RT than M4 IC2 during the early morning until 11:00. After than M4 IC2 had lower RT than M4 Baseline (Figure 8.22b). M4 Baseline achieved the lowest RT during the summer design day of 37.94 °C at 08:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.7.4.5 Al Wafi Mosque (M5)

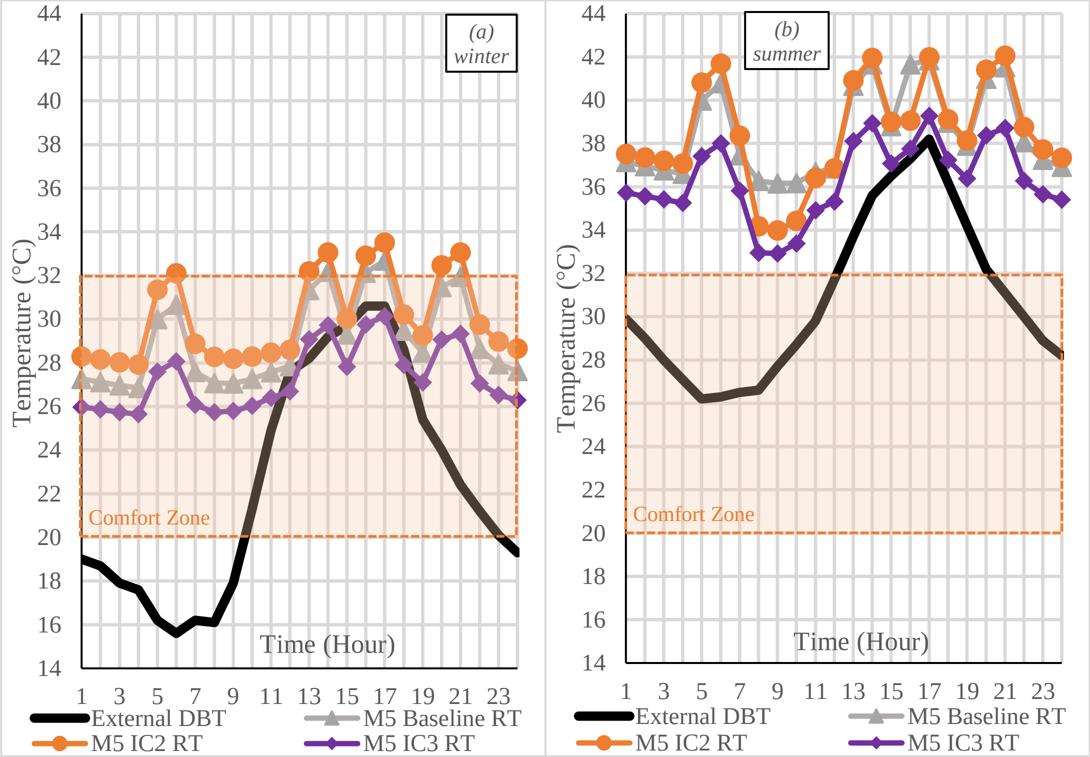


Figure 8.23: Resultant Temperatures (RT) for Mosque 5's baseline, W1, and W2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M5 IC3 maintained the lowest RT of 25.64 2 °C during most of the winter design day, peaking at 30.14 °C at 17:00, while the M5 Baseline was at 32.69, M5 IC2 was at 33.51 °C, and the external DBT was at 30.6 °C at the same time (Figure 8.23a). It shows that thermal comfort is not achieved in all three cases throughout the day although the external dry bulb temperature ranges from 15.6 °C to 30.6 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M5 IC3 had the lowest RT of 32.92 °C during the summer day, peaking at 39.27 °C at 17:00, while the M5 Baseline was at 41.85 °C, M5 IC2 was at 41.98 °C, and the external DBT was at 38.2 °C at the same time (Figure 8.23b). M5 F3 achieved the lowest RT during the summer design day of 32.92 °C at 09:00 which is higher than the thermal comfort upper limit of 30 °C.

8.7.4.6 Aal Hamoodah Mosque (M6)

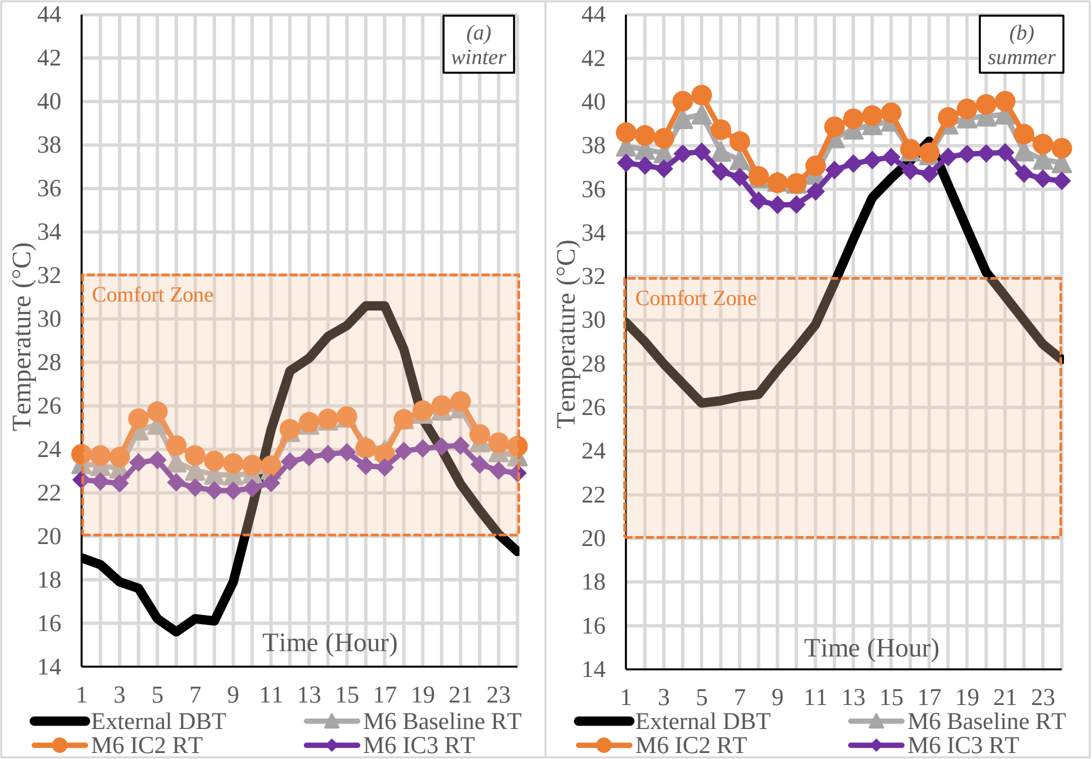


Figure 8.24: Resultant Temperatures (RT) for Mosque 6’s baseline, W1, and W2 improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M6 IC3 maintained the lowest RT of 22.1 °C during most of the winter design day, peaking at 24.18 °C at 21:00, while the M6 Baseline was at 25.89, M6 IC2 was at 26.2 °C, and the external DBT was at 30.6 °C at the same time (Figure 8.24a). It shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature ranges from 15.6 °C to 30.6 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M6 IC3 had the lowest RT of 35.28 °C during the summer design day, peaking at 37.72 °C at 05:00, while the M5 Baseline was at 39.43 °C, M5 IC2 was at 40.31 °C, and the external DBT was at 26.2 °C at the same time (Figure 8.24b). M6 IC3 achieved the lowest RT during the summer design day of 35.28 °C at 09:00 which is higher than the thermal comfort upper limit of 30 °C.

8.7.5 Thermal Comfort using the Suggested Internal Conditions

Table 8.21: Percentage of annual occupied hours within the comfort range (-1 < PMV < +1) for the baseline model and the internal conditions suggested improvements' models.

Model	M1	M2	M3	M4	M5	M6
Baseline	15.5%	14.3%	16.1%	40.4%	0.2%	25.6%
IC2	10.1%	14.3%	11.1%	39.6%	0.0%	22.5%
IC3	24.7%	14.3%	23.3%	20.3%	0.6%	30.7%

This section explores how the thermal comfort in each of the six mosques would be impacted by the other improvement techniques no discussed in the previous sections. The PMV and PPD analyses of each of the improvements in all six mosques were performed using the EDSL TAS programme. Table 8.21 shows the percentage of occupied hours that has a PMV ranging from -1 to +1. It is noted that all the occupied hours during summer fall outside of the -1 < PMV < +1 range, hence the values shown in the table are true as annual figures as well as winter figures. The O1 and O2 improvement models (increasing the cooling thermostat setpoint by 1 °C and 2 °C, respectively) are not shown in this table as they are only applicable to air-conditioned buildings, which are assumed to achieve the thermostat set point and achieving the thermal comfort levels. The buildings are assumed to be free-running in this section.

IC2 (Lower infiltration rate) decreased the percentage of hours within the comfort range for all mosques except for M2, which remained unchanged. Less air permeability means less heat loss through infiltration, hence a decrease in thermal comfort.

IC3 (Higher efficiency lighting) increased the percentage of hours within the comfort range for M1, M3, M5, and M6, decreased for M4 and it remained unchanged for M5. A reduction in lighting gain could impact the thermal comfort if it has a sizable portion of all heat gains. This is reflected by how much each mosque building change in thermal comfort.

8.7.6 Cooling Load Reduction using the Suggested Internal Conditions

Table 8.22: Cooling load reductions of the internal conditions suggested improvements' models.

Model	M1	M2	M3	M4	M5	M6
IC1	-14.2%	-13.8%	-15.1%	-17.8%	-12.8%	-15.4%
IC2	-26.7%	-7.4%	-8.5%	-17.4%	-4.6%	-6.2%
IC3	-18.4%	-11.3%	-12.7%	0.0%	-13.2%	-11.6%

Table 8.22 presents the cooling load reduction in all six buildings. The cooling load reduction is expressed as a percentage change compared to a baseline scenario.

IC1 (thermostat increase by 2 °C) reduced the cooling load in all six mosques. The reduction ranges between 12.8% and 17.8%.

IC2 (lower infiltration rate) reduced the cooling load in all six mosques. The reduction ranges between 4.6% and 26.7%. This is because it made the building limited heat gain further by lowering the infiltration rate.

IC3 (higher efficiency lighting) decreased the cooling load in all mosque buildings except for M4, which remained unchanged. The reduction ranges from 11.3% to 18.4%. M4 was considered unoccupied, so it did not have lighting gain.

8.8 The Suggested Passive Cooling Techniques

8.8.1 T1 Khalwah (Underground chamber)

The first passive cooling technique is to introduce a Khalwah system to the building. It is a completely underground basement floor or chamber. Table 8.23 shows the areas of the main prayer hall compared to the introduced Khlawah areas in each mosque. The area of the Khalwah was chosen to have the same area as the main prayer hall if possible, depending on site conditions and what is deemed most suitable for each mosque. It usually has lower dry bulb temperature benefiting from the ground insulation and temperature. For more about Khalwah, refer to section 2.7.

Table 8.23: Zone 1 (main prayer hall) and Khalwah (underground prayer hall) areas for each T1 model.

Mosque	**Zone 1 area (m^2)**	**T1 Khalwah introduced basement area (m^2)**
M1	924	420
M2	445	115
M3	220	220
M4	295	295
M5	302	302
M6	538	280

8.8.2 T2 Increased vegetation around the buildings

The second passive cooling technique is to introduce more vegetation around the building. Vegetation was increased around each mosque building as perceived most reasonable for each case to cover the surrounding walls.

8.8.3 Resultant Temperature using the Suggested Passive Cooling Techniques

8.8.3.1 Hudayfah Bin Al Yaman Mosque (M1)

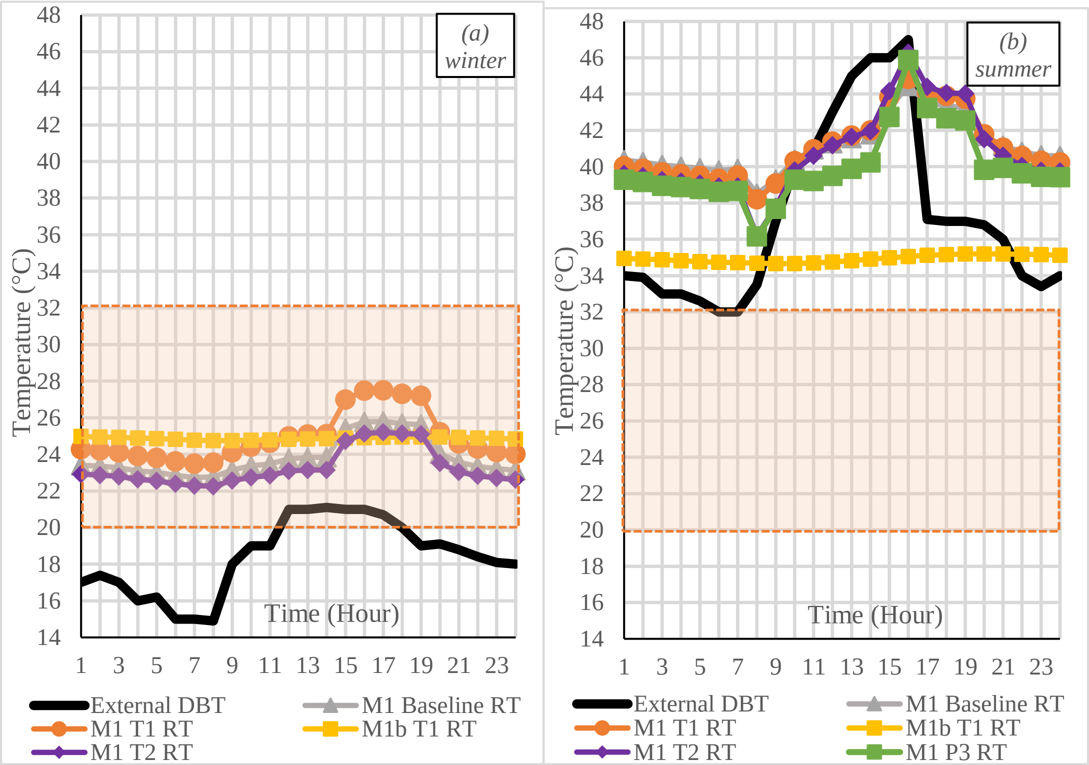


Figure 8.25: Resultant Temperatures (RT) for Mosque 1's baseline, T1, T2, Mosque 1 Khalwah (M1b T1) improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M1 T2 maintained the lowest RT of 22.26 during most of the winter day, peaking at 25.2 °C at 17:00, while the M1 Baseline was at 25.8 °C, M1 T1 was at 27.5 °C, and M1b P1 was at 24.98, and the external DBT was at 20.7 °C at the same time (Figure 8.25a). It shows that thermal comfort is achieved in all five cases throughout the day although the external dry bulb temperature ranges from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M1b T1 maintained the lowest RT of 34.66 °C throughout the summer design day, peaking at 35.2 °C at 16:00, while M1 Baseline was at 44.44 °C, M1 T1 was at 44.83 °C, M1 T2 was at 46.28 °C, and the external DBT was at 47 °C at the same time (Figure 8.25b). M1b T1 achieved the lowest RT during the summer design day of 34.66 °C at 08:00 which is higher than the thermal comfort upper limit of 30 °C.

8.8.3.2 Abu Hamza Al Shari Mosque (M2)

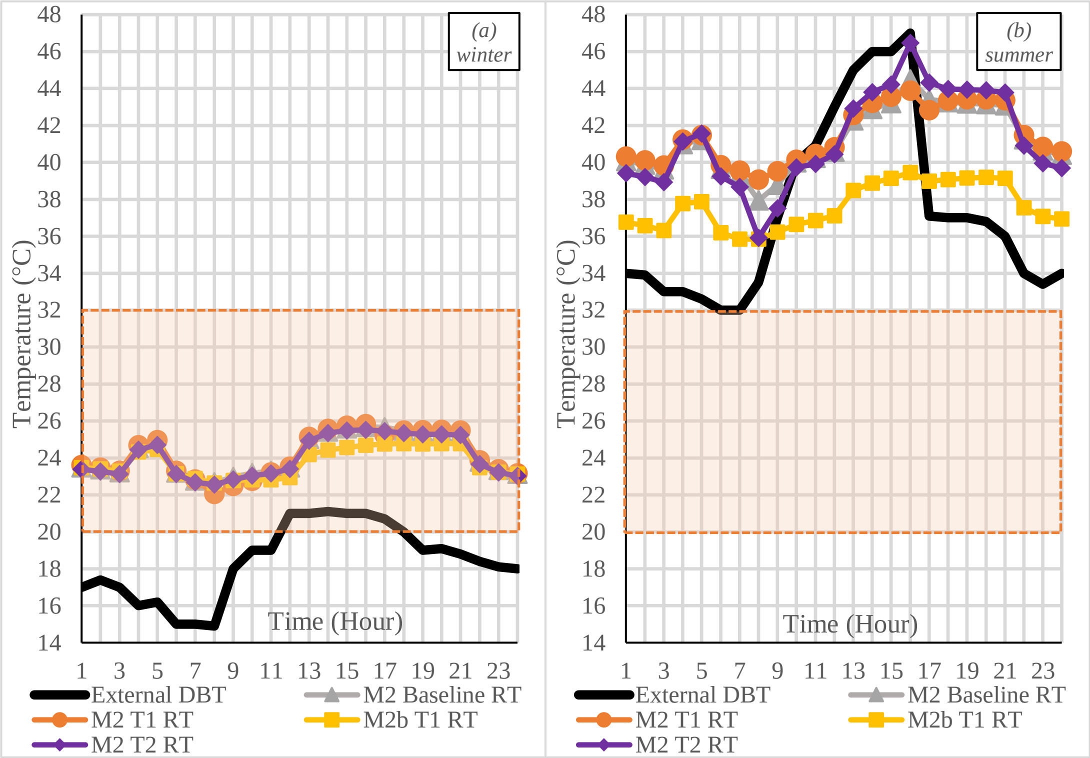


Figure 8.26: Resultant Temperatures (RT) for Mosque 2's baseline, T1, T2, Mosque 2 Khalwah (M1b T1) improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M2 T1 had the lowest RT of 22.06 °C during the entire winter day, peaking at 25.83 °C at 16:00, while the M1 Baseline was at 25.69 °C, M2b T1 was at 24.78, and M2 T2 was at 22.52 at the same time (Figure 8.26a). M2b maintained the lowest RT during occupancy hours. It also shows that thermal comfort is achieved in all three cases throughout the day although the external dry bulb temperature ranges from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M2b P1 had the lowest RT of 39.45 °C during the summer day while the M2 Baseline was at 44.49 °C, M2 P2 was at 46.46 °C, and the external DBT was at 47 °C at the same time (Figure 8.26b). M2b P1 achieved the lowest RT during the summer design day of 39.45 °C at 08:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.8.3.3 Othman bin Afan Mosque (M3)

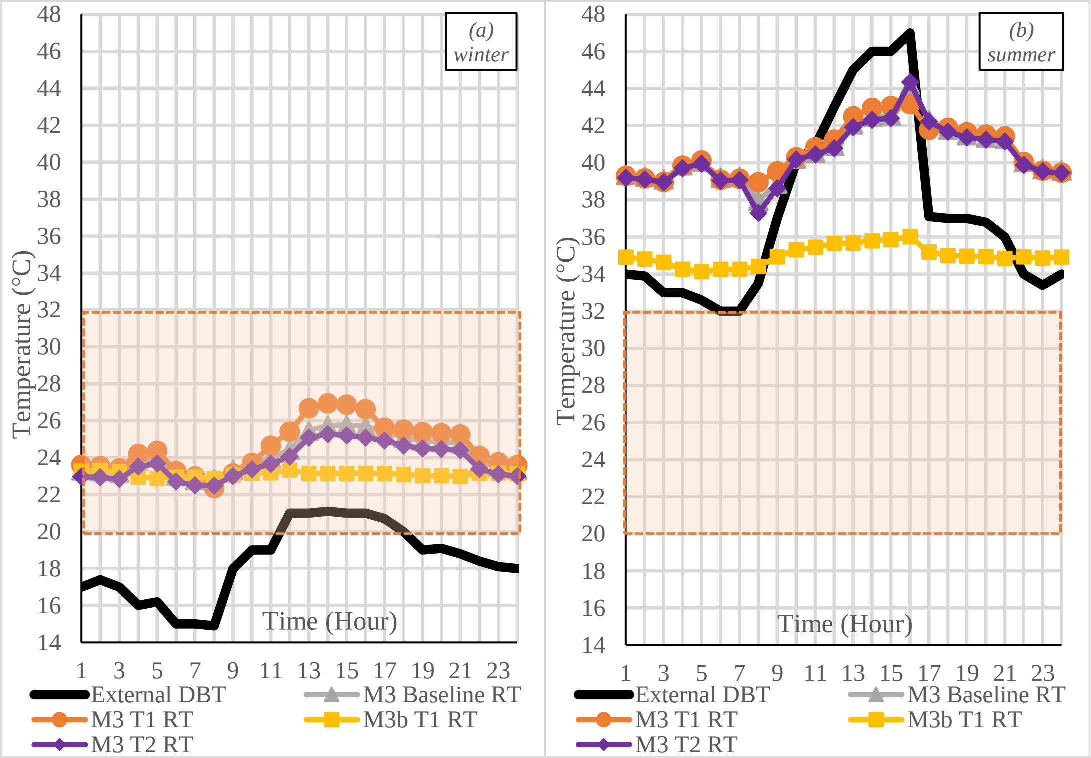


Figure 8.27: Resultant Temperatures (RT) for Mosque 3's baseline, T1, T2, Mosque 3 Khalwah (M1b T1) improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M3 Baseline had the lowest RT of 22.82 °C during the entire winter day, peaking at 25.78 °C at 15:00, while the M3 T1 was at 26.87, M3b T1 was at 23.14, M3 T2 was at 25.21 °C at the same time (Figure 8.27a). It is evident that maintained a significantly lower range throughout the day compared to the other scenarios and maintained the lowest RT during occupancy hours. It shows that thermal comfort is achieved in all five cases throughout the day although the external dry bulb temperature ranges from 14.9 °C to 21.1 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M3b T1 had the lowest RT of 34.13 °C during the entire summer design day, peaking at 36.01 °C at 16:00, while the M3 Baseline was at 44.22 °C, M3 T1 was at 43.16 °C, M3 T2 was at 44.35 °C, and the external DBT was at 47 °C at the same time (Figure 8.27b). M3b T1 achieved the lowest RT during the summer design day of 34.13 °C at 05:00 which is higher than the thermal comfort upper limit of 30 °C.

8.8.3.4 *Sa'al Mosque (M4)*

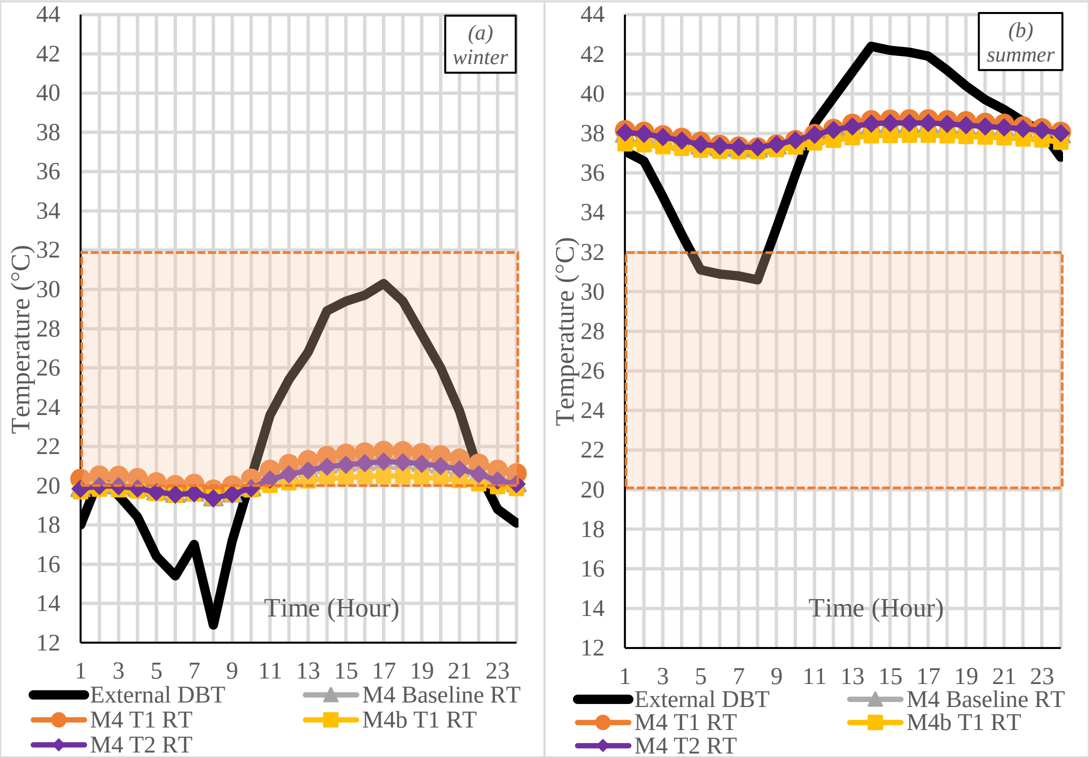


Figure 8.28: Resultant Temperatures (RT) for Mosque 4's baseline, T1, T2, Mosque 4 Khalwah (M1b T1) improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M4b T1 had the lowest RT during the winter design day of 19.42, peaking at 20.5 °C, while M4 Baseline was at 21.34, M4 T1 was at 21.76, M4 T2 was at 21.22, and the external DBT was at 30.3 °C at the same time (Figure 8.28a). It shows that thermal comfort is achieved in all three cases during occupancy although the external dry bulb temperature ranges from 12.9 °C to 21.34 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M4 T2 had the lowest RT of 37.65 °C during the summer design day, while the M4 Baseline was at 38.17 °C, M4 T1 was at 38.17 °C, M4b T1 was at 38.22 °C, and the external DBT was at 39.8 °C at the same time (Figure 8.28b). M4 T2 achieved the lowest RT during the summer design day of 37.65 °C at 05:00 which is significantly higher than the thermal comfort upper limit of 30 °C.

8.8.3.5 Al Wafi Mosque (M5)

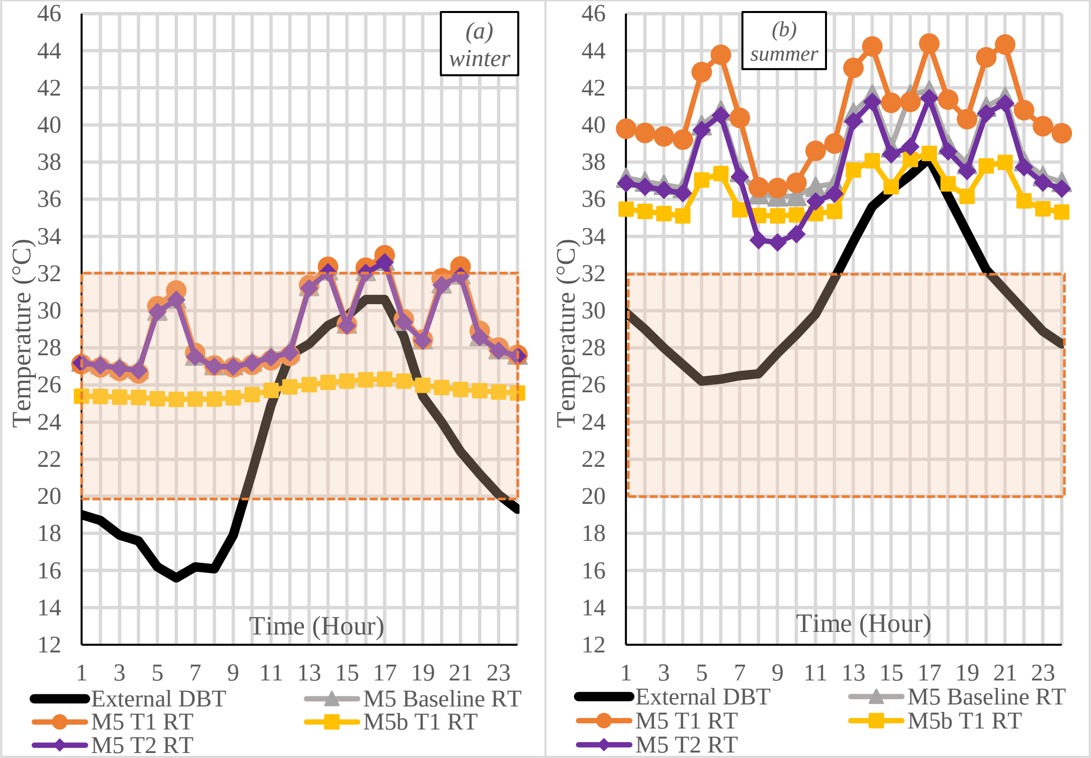


Figure 8.29: Resultant Temperatures (RT) for Mosque 5's baseline, T1, T2, Mosque 5 Khalwah (M1b T1) improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M5b T1 maintained the lowest RT of 25.22 °C during most of the winter day, peaking at 26.31 °C at 17:00, while the M5 Baseline was at 32.69, M5 T1 was at 32.98 °C, M5 T2 was at 32.6, and the external DBT was at 30.6 °C at the same time (Figure 8.29a). It shows that thermal comfort is not achieved in all three cases throughout the day although the external dry bulb temperature ranges from 15.6 °C to 30.6 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M5 T2 had the lowest RT of 33.37 °C during the summer design day, peaking at 40.4 °C at 17:00, while the M5 Baseline was at 41.85 °C, M5b T1 was at 44.38 °C, and the external DBT was at 38.2 °C at the same time (Figure 8.29b). Although M5 T2 had the lowest RT between 08:00 and 10:00 (which are unoccupied hours), M5b P1 had the lowest RT during the rest of the day by a margin of up to 6.36 °C. M5 T2 achieved the lowest RT during the summer design day of 33.37 °C at 09:00 which is higher than the thermal comfort upper limit of 30 °C.

8.8.3.6 Aal Hamoodah Mosque (M6)

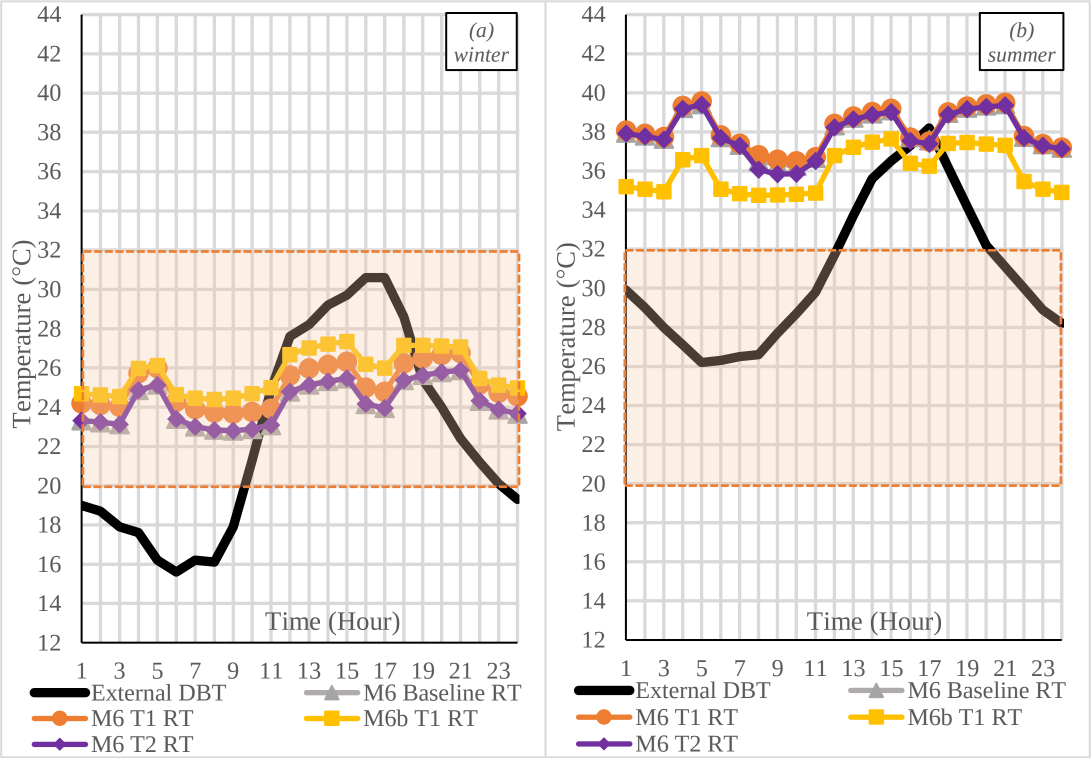


Figure 8.30: Resultant Temperatures (RT) for Mosque 6's baseline, T1, T2, Mosque 6 Khalwah (M1b T1) improvement models in addition to the External Dry Bulb Temperature (OT) during winter (a) and summer (b)

In winter, M6 T2 RT had the lowest RT of 22.8 °C during the entire winter day, peaking at 25.88 °C, while M6 Baseline was at 25.89, M6 P1 was at 26.76, M6b P1 was at 27.34, and the external DBT was at 22.4 °C at the same time (Figure 8.30a). It shows that thermal comfort is achieved in all three cases during occupancy although the external dry bulb temperature ranges from 15.6 °C to 30.6 °C. This could be attributed to both the internal and external heat gains throughout the day that kept the mosque internal resultant temperature consistently higher than the external DBT and within the comfort zone.

In summer, M6b T1 had the lowest RT of 34.75 °C during the summer day, peaking at 37.63 °C at 15:00, while the M5 Baseline was at 39.11 °C, M5 T1 was at 39.17 °C, M5 T2 was at 39.02 °C, and the external DBT was at 38.2 °C at the same time (Figure 8.30b). M6b T1 achieved the lowest RT during the summer design day of 34.75 °C at 08:00 which is higher than the thermal comfort upper limit of 30 °C.

8.8.4 Thermal Comfort using the Suggested Passive Cooling Techniques

Table 8.24: Percentage of annual occupied hours within the comfort range (-1 < PMV < +1) for the baseline model and the passive cooling techniques suggested improvements' models.

Model	M1	M2	M3	M4	M5	M6
Baseline	15.5%	14.3%	16.1%	40.4%	0.2%	25.6%
T1	16.3%	17.0%	49.6%	57.1%	1.8%	27.5%
T2	19.2%	14.8%	17.7%	41.0%	0.2%	25.7%

This section explores how the thermal comfort in each of the six mosques would be impacted by the various suggested passive cooling improvement techniques. The PMV and PPD analyses of each of the improvements in all six mosques were performed using the EDSL TAS programme. Table 8.24 shows the percentage of occupied hours that has a PMV ranging from -1 to +1. It is noted that all the occupied hours during summer fall outside of the -1 < PMV < +1 range, hence the values shown in the table are true as annual figures as well as winter figures. The buildings are assumed to be free-running.

T1 (Khalwah) increased the percentage of hours within the comfort range for all six mosque buildings. This shows that the Khlawah system provides a more thermally comfortable environments due to the decreased internal DBT in the basement.

T2 (increased vegetation around the buildings) increased the percentage of hours within the comfort range for M1, M2, M3, M4, and M6, while it remained unchanged for M5 at 0.2%. Vegetation was provided where possible. M5 was already surrounded by a substantial number of trees, so the increase in surrounding vegetation was not a significant improvement.

8.8.5 Cooling Load Reduction using the Suggested Passive Cooling Techniques

Table 8.25: Cooling load reductions of the passive cooling techniques suggested improvements' models.

Model	M1	M2	M3	M4	M5	M6
T1	-6.2%	0.9%	-1.0%	-0.8%	14.0%	-1.9%
T2	-15.3%	-0.3%	-0.6%	0.0%	0.0%	-0.2%

Table 8.25 presents the cooling load reduction in all six buildings. The cooling load reduction is expressed as a percentage change compared to a baseline scenario.

T1 (khalwah) has caused a decrease in cooling load in M1, M3, M4 and M6, while the cooling load increased for M2 and M5. M1 had a more cooling load reduction because the air conditioning system is assumed to be running 24 hours a day.

T2 (increased vegetation around the buildings) decreased the cooling load in all mosque buildings, except for M4 and M5 which remained unchanged. The reduction ranges from 0.2% to 15.3%. M1 had a more cooling load reduction because the air conditioning system is assumed to be running 24 hours a day.

8.9 Combinations

This research does not aim to provide the best possible combinations for all the six mosques. Such exercise is outside the scope of this research as it involves running through endless number of combinations to achieve the best possible thermal performance, thermal comfort, and cooling load. There are more than 16,000 possible combinations for 14 improvements for each mosque. This section, however, presents the potential largest reduction in each of the three parameters: resultant temperature, annual discomfort hours, and cooling load. This is based on the results of the suggested improvements chapter.

Table 8.26: The suggested improvement that has the maximum improvement in each category showing the percentage of improvement for each mosque building during summer only.

	M1		M2		M3		M4		M5		M6	
Walls												
RT*	W2	-2%	W1	3%	W2	1%	W1	-2%	W3	1%	W1	1%
Annual Discomfort Hours	W2	0%	W1	15%	W2	0%	W1	1%	W3	1%	W1	2%
CL	W1	-1%	W2	-7%	W1	-1%	W1	-5%	W1	-5%	W3	-2%
Roof												
RT*	R2	0%	R2	3%	R2	0%	R1	1%	R3	-2%	R1	9%
Annual Discomfort Hours	R2	-33%	R2	-19%	R2	-9%	R3	2%	R3	46%	R1	12%
CL	R1	-13%	R1	-3%	R1	-2%	R1	-5%	R1	-4%	R1	-9%
Windows												
RT*	F1	1%	F1	3%	F3	-2%	F3	-1%	F3	-11%	F3	-21%
Annual Discomfort Hours	F1	-30%	F1	-21%	F3	0%	F2	-1%	F1	-17%	F1	0%
CL	F1	-7%	F1	-4%	F2	-2%	F3	0%	F1	-2%	F1	0%
Internal Conditions												
RT*	IC3	-4%	IC3	-6%	IC3	-12%	IC3	-3%	IC3	-23%	IC3	-17%
Annual Discomfort Hours	IC3	-59%	O3	0%	IC3	-45%	IC2	2%	IC3	-183%	IC3	-20%
CL	IC2	-27%	IC1	-14%	IC1	-15%	IC1	-18%	IC3	-13%	IC1	-15%
PCT												
RT*	T1	-60%	T1	-32%	T1	-55%	P3	-11%	T1	-27%	T1	-18%
Annual Discomfort Hours	T2	-24%	T1	-19%	T1	-207%	T1	-41%	T1	-789%	T1	-8%
CL	T2	-15%	T2	-0.3%	T1	-1%	T1	-1%	T2	0%	T1	-2%

The improvements with the most reductions from the four building elements categories showed in Table 8.26 (Walls, Roofs, Windows, and Internal Conditions) were selected in each of the three combinations: Resultant Temperature, Annual Discomfort Hours, and Cooling Load. The resulting reductions in each of the category associated with each combination are shown in Table 8.27.

Table 8.27: Percentage of improvement for the three combinations within each respective category

	M1	M2	M3	M4	M5	M6
Combination 1: Resultant Temperature*	-12%	-11%	-14%	-6%	-24%	-18%
Combination 2: Annual Discomfort Hours	-15%	-8%	-13%	-3%	-5%	-13%
Combination 3: Cooling Load	-36%	-42%	-33%	-58%	-21%	-58%

The research discovered that across all six mosques, all three combinations—Resultant Temperature, Annual Discomfort Hours, and Cooling Load—had successfully achieved significant decreases in each of their respective categories. These results suggest that the suggested improvements have a good chance of improving the mosques thermal comfort conditions. It is important to note that the research did not aim to determine the optimal combinations, as there may be other more effective combinations that were not investigated in this research. The findings of this research, especially in areas with hot and dry climates, are encouraging and call for further investigation and development of solutions to improve the thermal comfort of mosques.

8.10 Conclusion

This research aims to investigate the thermal performance in buildings in Oman with a special focus on mosques as a case study. The research identified five categories of suggested improvements based on a comparison of the results presented in Chapters 6 and 7 and the literature review: Walls, Roofs, Windows, Internal Conditions, and Passive Cooling Techniques. The thermal performance, thermal comfort, and energy efficiency of these proposed improvements were evaluated using Resultant Temperature (RT), Predicted Mean Vote (PMV), and Cooling Load (CL) analyses, respectively.

The research applied three different combinations of the suggested improvements, namely Resultant Temperature, Annual Discomfort Hours, and Cooling Load, to evaluate their potential to improve thermal comfort conditions in the mosques under research. All six mosques demonstrated significant reductions in all three categories, demonstrating the effectiveness of the suggested improvements. Combination 1 resulted in reductions of up to 24% in the percentage improvement required to achieve the upper limit of thermal comfort (30 °C), Combination 2 led to reductions of up to 15% in annual discomfort hours, and Combination 3 resulted in cooling load reductions of up to 58%.

The findings of this research indicate that improvements in building envelope insulation, building material, fenestration, thermostat set points, and passive cooling techniques have the potential to significantly enhance the thermal comfort of mosque buildings in Oman and similar climates. Noting that the research did not investigate all possible improvement combinations and that other solutions may be more effective is essential. Nevertheless, the results presented here provide valuable insights into how to enhance the thermal performance of mosques and other buildings in comparable contexts. Future research should concentrate on identifying and evaluating alternative potential solutions and combinations.

Chapter 9. CONCLUSIONS

This chapter presents the key findings and outcomes of the research, which sought to identify strategies for enhancing the thermal performance of buildings in Oman, focusing on both traditional and contemporary mosques as case studies. This chapter can be viewed as a reflection on the research questions and objectives, highlighting the key insights and recommendations for future research.

9.1 Research Conclusions

The significance of mosques in Oman is evident in the country's history, where many historical mosques still stand today, serving as a testament to the country's rich cultural heritage. They house the five daily prayers and the Friday weekly prayers which are held in congregation. Mosques also serve as community centres holding social and educational events.

The internal environment and conditions of mosques in Oman are designed to provide thermal comfort to worshippers, particularly during the hot summer months when external dry bulb temperatures can exceed 40°C. Contemporary mosques that are built in the last fifty years in Oman were designed to rely on air conditioning systems to provide thermal comfort to worshippers. They are designed with concrete walls and roofs, which may or may not be insulated. Traditional mosques in Oman are typically designed with thick walls, small windows, and high ceiling openings. These design elements contribute to reducing solar gain, providing natural ventilation, and maintaining comfortable indoor temperatures.

Traditional buildings in Oman have a rich architectural heritage that can provide valuable insights into passive design strategies that can be implemented in contemporary buildings. Passive design strategies such as natural ventilation, shading, and the use of local materials can help reduce energy consumption and promote sustainable building practices. By incorporating these strategies into contemporary mosque buildings in Oman, designers can reduce the reliance on mechanical systems and increase the energy efficiency of these buildings.

The reintegration of Oman's vernacular architectural wisdom emerges as a crucial effort given the growing importance of sustainability and energy efficiency. Bridging the past and the present, this research pushes forward the adaptation of historical practices for modern applications, leading to a future that is rooted in tradition yet forward-looking in its approach.

9.2 Literature Review Conclusions

Mosques are built as houses of worship where the five daily prayers and the Friday weekly prayers are performed. It is also considered a centre for the community, a school, an institute, and an education centre. Islamic architecture is unique in that its very essence promotes sustainability. Mosques are by nature very basic in design and serve their intended function effectively. This is accomplished by "borrowing" materials from nature, such as water, earth, stone, and wood, to construct energy-efficient buildings. This construction would become harmonious with nature and cause no damage (Al-Qemaqchi, 2018). Mosques have had many techniques to achieve thermal comfort ever since they were first built such as courtyards (Yousef and Yousef, 2001), domed roof (Fathy, 1986), and underground chambers “Khalwah” (Saudi Commission for Tourism & National Heritage, 2018). A number of recent studies concur that research is required in the areas of building thermal performance of mosques (Shohan, 2015; Alabdullatief, 2020), passive and sustainable cooling techniques (Azmi, Arıcı and Baharun, 2021), and the development of energy-related design codes (Al-ajmi, 2010).

This research focuses on the thermal performance and thermal comfort aspects, which are both complex aspects, which are affected by many factors. Factors that affect a human thermal comfort can be related to the surrounding environment, the built environment, or the human body itself. Taking this into consideration, there are several variables that can be measured to study a thermal environment in given time and location. This can be done using field measurement using physical instruments. In addition to the field measurement methodology, a computer simulation can be conducted to study a building’s energy performance. Some of top energy building performance factors are related to the thermal control aspects such as insulation, fenestration, shading devices, and ventilation. This is important in this research as there will be a computer simulation conducted to study the building performance factors and their effects.

The Sultanate of Oman is the location of the case studies of this research. The geographical, geological, and climatic details of Oman have historically dictated a vernacular architectural style that is both sustainable and harmonious with the environment. The exploration of Oman's diverse landscapes, from the series of mountains to the expansive deserts and coastal areas, highlights the rich variety of influences that have shaped Oman’s built environments.

In a world coping with the urgent need to mitigate climate change and reduce energy consumption, the lessons derived from Oman's traditional architectural practices present a viable pathway. Oman’s hot climate, which ranks among the most extreme globally, further stresses the pressing necessity to adopt passive strategies to limit electricity usage. It becomes even more imperative for Oman to embrace local and sustainable construction methods to not only reduce energy consumption and building costs but also enhance thermal performance substantially.

The utilisation of locally available materials and the adoption of construction techniques optimised for thermal comfort stand as a testament to the wisdom embedded in Oman's architectural heritage. Moreover, the emphasis on passive cooling strategies, as highlighted in the works of renowned scholars such as Hassan Fathy, offers a blueprint for contemporary architects to encourage buildings that resonate deeply with the cultural and historical context of Oman while encouraging energy efficiency.

Most of the vernacular settlements and buildings have not survived the test of time unfortunately. Mosques are an exception as they were and are continuously used and renovated (Damluji, 1998). This was one of the reasons why mosques were chosen as the case study for this research.

9.3 Field Measurement Conclusions

The field measurement methodology involved collecting DBT, MRT, RH, and ST data, which were then analysed to determine the indoor thermal comfort of mosques during winter and summer design days. The data analysis revealed that all six mosques were within the comfort zone of the Muscat bioclimatic chart during the winter, with internal DBT ranging from 20.9 °C to 26.5 °C and internal RH being predominantly within the comfort range. During the summer, air-conditioned mosques (M1, M2, M5, and M6) were within the comfort zone, whereas unconditioned mosques (M3 and M4) fell completely outside the thermal comfort zone. M3 and M4 were closed due to COVID-19 regulations at the time. In addition, the data analysis revealed that the measured air velocity was not uncomfortable, and that the internal RH was directly proportional to the external RH at the time.

9.4 Computer Simulation Conclusions

The six mosques' computer simulation results for winter design day (day 20) and summer design day (day 179) were analysed. The results of the winter design day computer simulation reveal that all six mosques have a similar DBT and RH pattern. However, there is a difference of up to 3 °C between the temperatures, which can be attributed to the different construction, design, and internal conditions of the buildings. Despite this variation, it was determined that all mosques were within the comfort zone, with RH between 37.3% and 67.7%, which is also within the comfort zone.

In contrast, the results of the summer design day computer simulation reveal that mosques respond differently to DBT during naturally ventilated periods. The air-conditioned period in all mosques remains constant at 23 °C which does seem artificial. In the real world, temperature sensed will not be as fixed, and there will be fluctuation in DBT throughout the space.

During the summer design day, when the air conditioning is turned off at 5:00, each mosque reacts differently as the external DBT continues to rise to a maximum of 47 °C at 16:00. M5 reaches the lowest high temperature of 31.8 °C, while M2 reaches the highest high temperature of 35.7 °C just prior to the reactivation of the air conditioning at 12:00. This could be due to the difference between the traditional and contemporary mosques building envelopes. Clay walls of M4, M5 and M6 have higher time constants (reaching up to 80 hours) than concrete walls (reaching up to 8.5 hours).

The heat gain and loss analysis indicated that the roofs, floors, and walls are among the top three heat gaining building elements via conduction in the six mosques. These building elements can be potential areas for improvements. The loads breakdown for the mosques showed that solar gain is one of the most noticeable differences between contemporary (M1, M2, and M3) and traditional (M4, M5, and M6) mosques. Traditional mosque buildings are subjected to less solar gain due to their much smaller glazing area. This is an area where contemporary mosques can improve by lowering thermal conductivity, reducing glazing area, or changing the glazing type.

9.5 Suggested Improvements Conclusions

This research project focused on building envelope material, fenestration, thermostat set point, and ventilation. These three areas have the potential to be improved in hot regions as per this literature review and results discussed.

The objective of this research was to find ways improve the thermal performance of six mosques in Oman. The research identified five potential improvement categories, including walls, roofs, windows, internal conditions, and passive cooling methods. The thermal performance, thermal comfort, and energy efficiency of these suggested improvements were evaluated using Resultant Temperature (RT), Predicted Mean Vote (PMV), and Cooling Load (CL) analyses, respectively.

Overall, the suggested improvements showed promising results and are recommended for most of the case studies. All the suggested improvements have shown the potential to provide improvements in terms of cooling load and/or thermal comfort.

Three different combinations of the suggested improvements were evaluated for their potential to improve thermal comfort conditions in the mosques. All six mosques showed significant reductions in all three categories, demonstrating the effectiveness of the suggested improvements. Combination 1 reduced by up to 24% the percentage improvement required to achieve the upper limit of thermal comfort 30 °C, Combination 2 reduced by up to 15% the percentage of annual discomfort hours, and Combination 3 reduced by up to 58% the cooling load. These findings imply that improvements in building envelope, building material, fenestration, thermostat set points, and passive cooling techniques have the potential to significantly improve the thermal comfort of mosque buildings in Oman and climates similar to it.

It is essential to note, however, that this research did not examine all possible improvement combinations, and other solutions may be more effective. Despite this, the results presented here provide valuable insights into how to improve the thermal performance of mosques and other buildings in similar contexts.

9.6 Recommendations

Based on the field measurements, computer simulations, literature review, and general observations made during this research, a number of recommendations for enhancing the thermal performance of buildings in Oman can be made. These recommendations can help architects, engineers, policymakers, and stakeholders design, construct, and operate occupant-friendly, energy-efficient, and sustainable buildings.

- It is recommended to prioritise achieving energy efficacy than energy efficiency when constructing buildings. It is even more sustainable to forgo building altogether if possible.
- Although some of the suggested improvements may seem effective according to this research, it depends on each different use case. It is recommended to integrate the thermal modelling process within the building design for each use case to achieve higher energy efficiency, sustainability, and thermal comfort.
- For free running buildings, it is recommended to consider higher thermal mass building envelope such as thick clay walls. It is also recommended to use more efficient lighting, and plant outside vegetation for shading. It is also recommended to utilise passive cooling techniques such as underground chambers, *Khalwahs*.
- For air-conditioned buildings, it is recommended to consider higher thermal conductivity building envelope such as insulated concrete walls for air-conditioned buildings. It is recommended to lower the infiltration rate.
- It is recommended to provide incentives for the construction of energy and thermally efficient buildings. For instance, incentivising the adoption of the suggested improvements in this research to achieve greater energy efficiency and long-term energy savings in buildings.

9.7 Contribution to Knowledge of the Research

This research contributes to knowledge by addressing the research gap understanding thermal building performance in Oman’s hot climate, where air conditioning represents a significant portion of energy consumption. Three traditional mosques and three contemporary mosques were examined as case studies using field measurement and computer simulation methodologies. The research analysed fourteen suggested improvements for mosques offering improvements to resultant temperature, cooling load and thermal comfort. These suggested improvements were carefully combined into three distinct combinations, each of which represented the most effective enhancements tailored to the specific needs of individual mosques targeting three key parameters: Resultant Temperature (RT), Cooling Load (CL), and Predicted Mean Vote (PMV). The first combination was designed to enhance the Resultant Temperature (RT) parameter, leading to a 24% improvement compared to the baseline model. For the second combination, the most effective improvements were combined to address the Cooling Load (CL) parameter, yielding a 58% reduction in cooling load compared to the baseline model. Lastly, the third combination focused on optimising the Predicted Mean Vote (PMV) parameter, resulting in a reduction of up to 15% in annual discomfort hours. These suggested improvements have the potential to offer significant benefits for clients, architects, builders, and stakeholders in the region to provide a pathway to achieve both energy efficiency and thermal comfort in building designs.

9.8 Limitations

The scope of this research was limited to the thermal performance of mosque buildings in hot and arid climates, specifically in Oman. The research investigated the impact of vernacular architecture on thermal comfort and performance, as well as potential areas for reducing cooling loads, with a focus on traditional and contemporary mosque buildings. Other building types or architectural styles were excluded from this research.

The outbreak of the COVID-19 pandemic, which began during March 2020 had a significant impact on this research. The global health crisis imposed a set of constraints that altered both the methodology and data collection process. Due to strict health and safety regulations, access to mosques for on-site data collection was limited. Several quarantine periods, movement bans, social distancing, and lockdowns hindered the research timeline, delaying travel to various sites for data collection.

Because of the research's complexity and time constraints, it was not possible to cover all aspects of mosque buildings' thermal comfort and thermal performance using field measurement and computer simulation methodologies. Field measurements were restricted to a set of parameters including dry bulb temperature, relative humidity, surface temperature, globe temperature, and air velocity. The analysed outcomes of the computer simulations were also limited to dry bulb temperature, relative humidity, heat gains, heat losses, and load breakdown. Excluded aspects also include indoor air quality, energy consumption field measurement, and economic analysis of the suggested improvements.

Indoor Air Quality (IAQ) was excluded due to the research scope focusing on thermal performance of mosque buildings in hot climates, resulting in time and budget constraints. While the significance of including IAQ in the research was increased by the COVID-19 pandemic, the limited or absent occupancy in mosques during the field measurement period would have compromised the validity of the results for an IAQ study.

Field measurements were carried out in six mosques in three locations in Oman, which are Muscat, Nizwa, and Al Wafi. Consequently, the applicability of the findings may be limited to these buildings and locations. Dhofar, a governate in the south of Oman, is not included in this research because its monsoon season makes it climatically distinct from the studied cities.

9.9 Future Work

The research on the thermal performance of mosque buildings in Oman had several limitations that could be overcome by future research. There are a number of aspects that can be further explored that were excluded from this research such as the air quality, moisture content, acoustics, and mosques' space design. It is recommended to expand this research to cover other climates and building types. To expand on the findings, future research could investigate the use of Generic Optimisation software to explore endless combinations of building elements and the full range of factors influencing thermal performance. In addition, investigating the potential use of Computational Fluid Dynamics (CFD) simulation and advanced optimisation software could provide a deeper understanding of the dynamic interactions between airflow, heat transfer, and thermal performance in mosque buildings. Artificial Intelligence presents another valuable area of exploration that has great potential to offer useful tools for thermal modelling and computer simulation. Future research could also investigate the effect of occupant behaviour on thermal performance and identify methods for encouraging energy-efficient behaviour. Exploring the feasibility of integrating renewable energy systems into mosque structures could also be an interesting avenue for further research.

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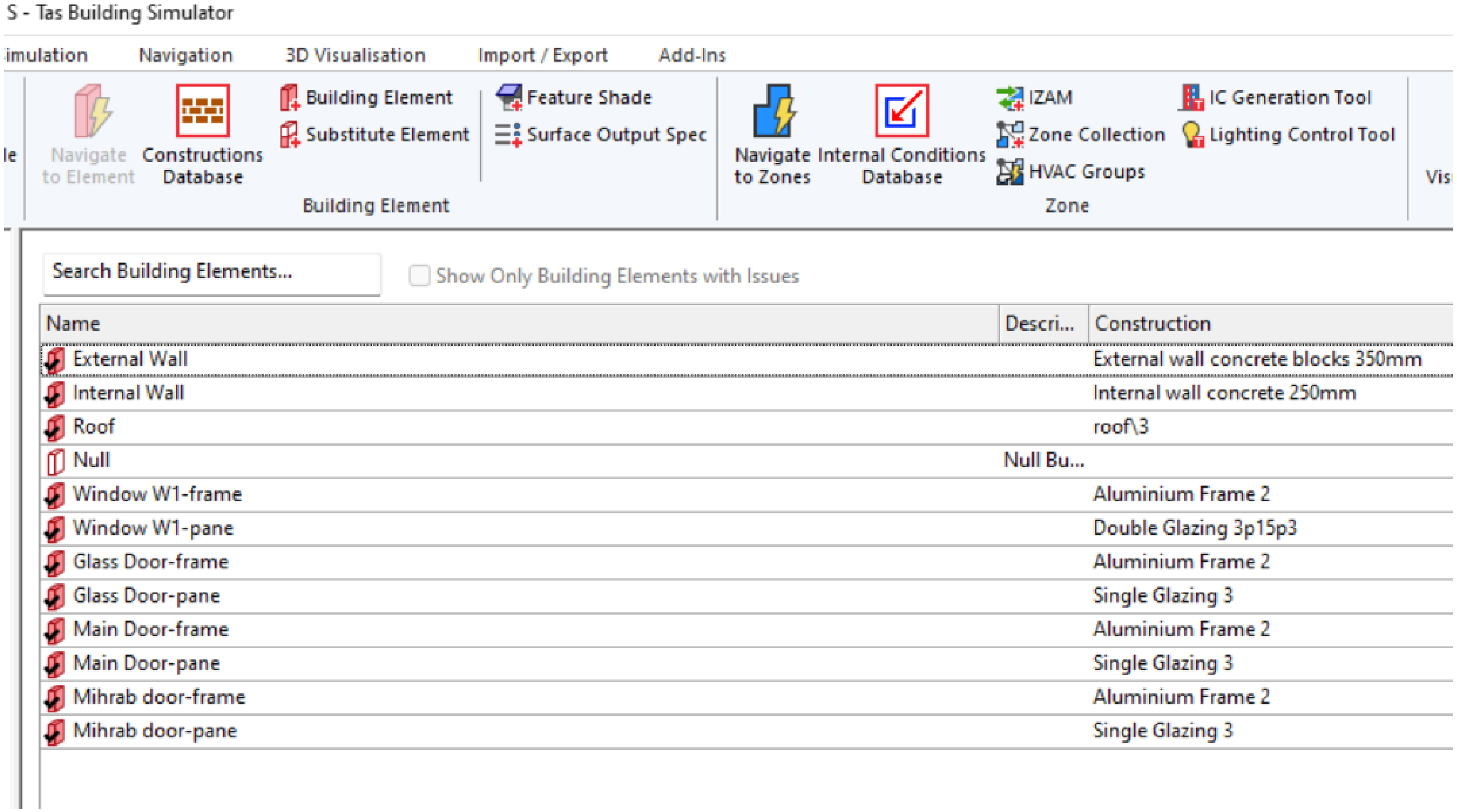
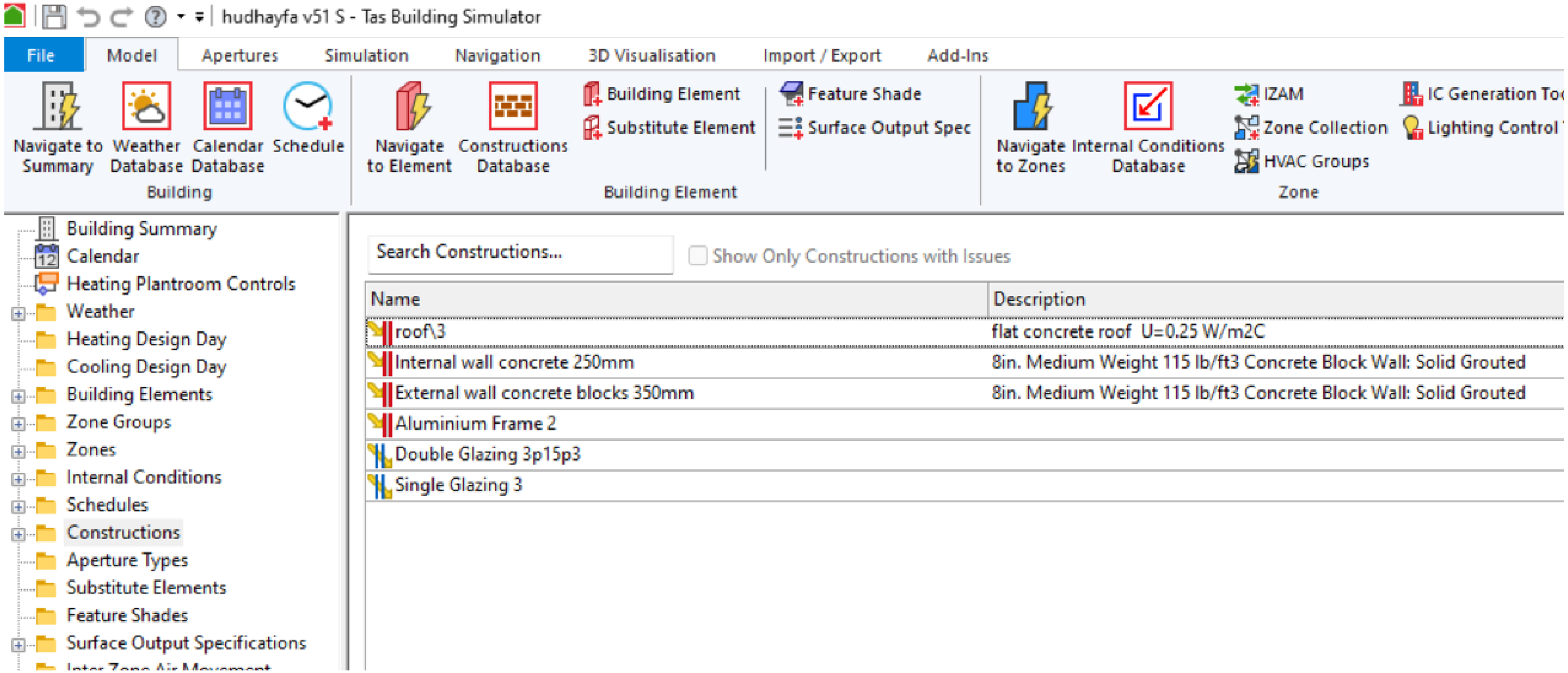
APPENDIX A: SCREENSHOTS OF MOSQUE 1 SIMULATION INPUTS AND OUTPUTS



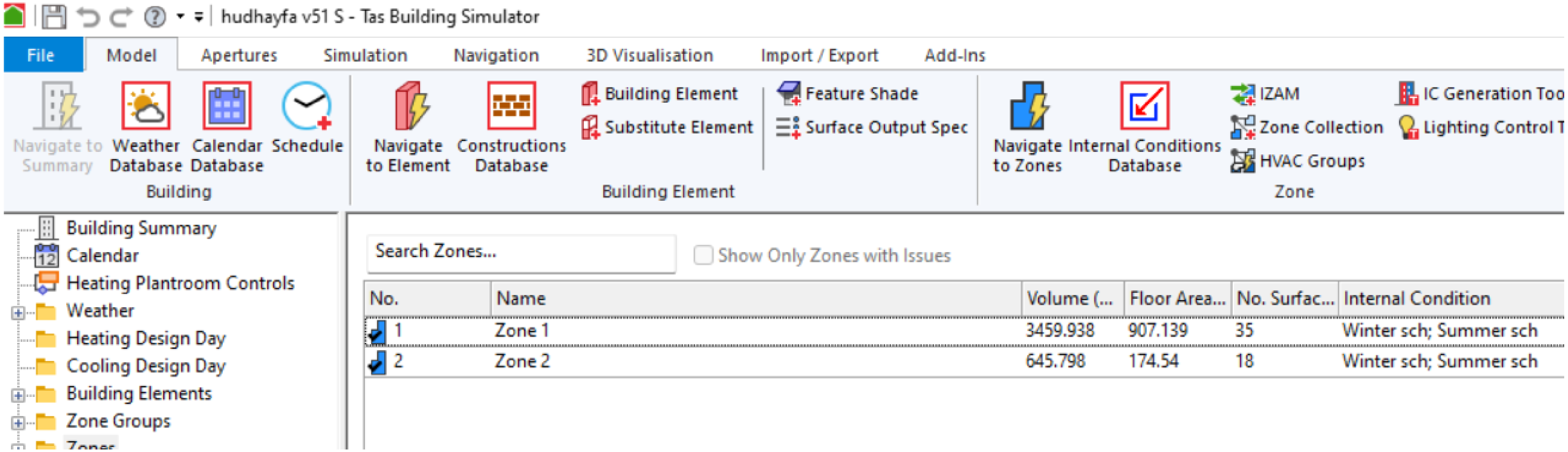
Name	Descri...	Construction
External Wall		External wall concrete blocks 350mm
Internal Wall		Internal wall concrete 250mm
Roof		roof\3
Null	Null Bu...	
Window W1-frame		Aluminium Frame 2
Window W1-pane		Double Glazing 3p15p3
Glass Door-frame		Aluminium Frame 2
Glass Door-pane		Single Glazing 3
Main Door-frame		Aluminium Frame 2
Main Door-pane		Single Glazing 3
Mihrab door-frame		Aluminium Frame 2
Mihrab door-pane		Single Glazing 3

Figure 10.1: Building elements assigned to each construction.



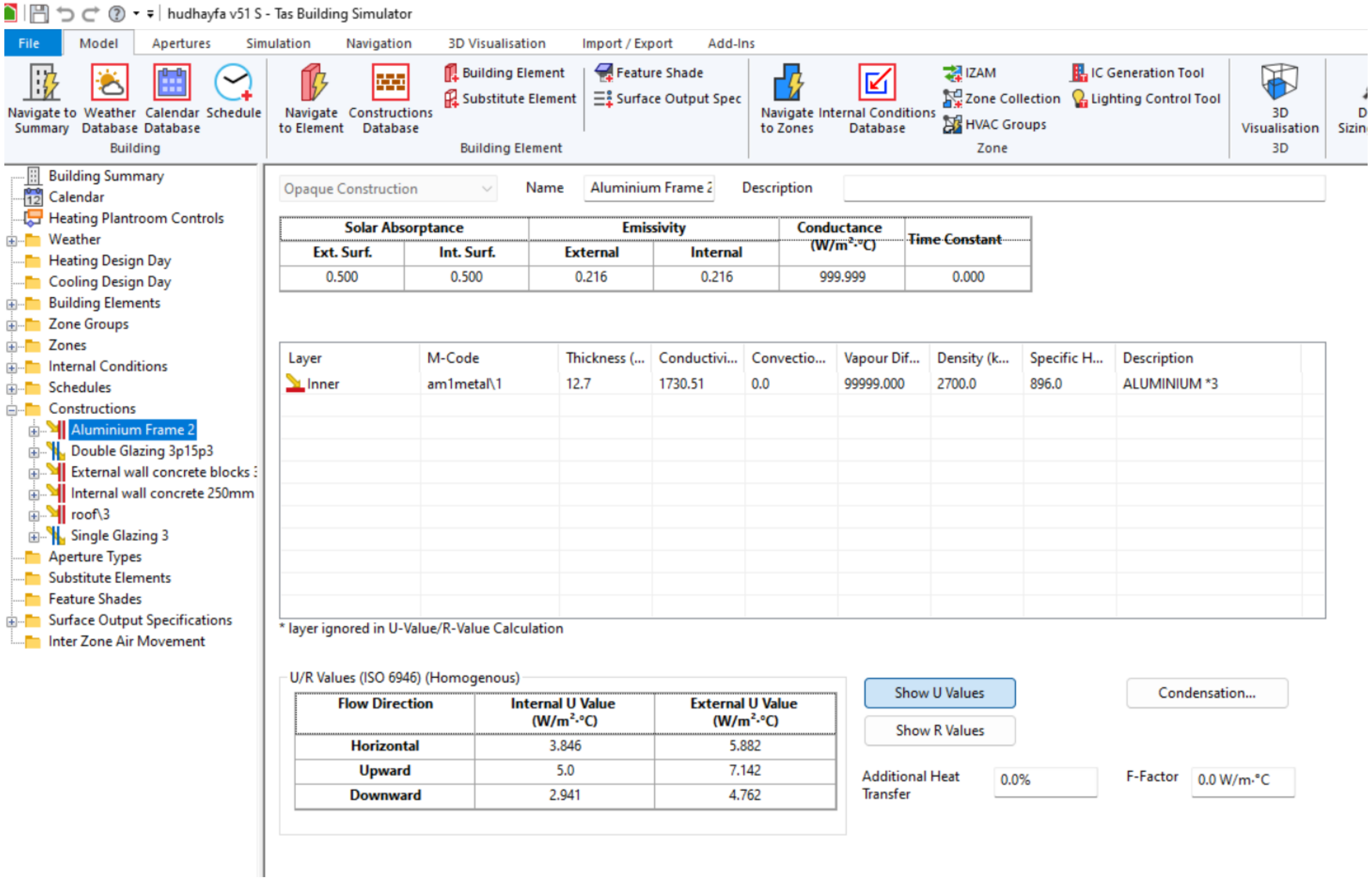
Name	Description
roof\3	flat concrete roof U=0.25 W/m2C
Internal wall concrete 250mm	8in. Medium Weight 115 lb/ft3 Concrete Block Wall: Solid Grouted
External wall concrete blocks 350mm	8in. Medium Weight 115 lb/ft3 Concrete Block Wall: Solid Grouted
Aluminium Frame 2	
Double Glazing 3p15p3	
Single Glazing 3	

Figure 10.2: Construction list



No.	Name	Volume (...	Floor Area...	No. Surfac...	Internal Condition
1	Zone 1	3459.938	907.139	35	Winter sch; Summer sch
2	Zone 2	645.798	174.54	18	Winter sch; Summer sch

Figure 10.3: The two zones. Each zone assigned with an internal condition, one for summer and the other for winter (outlined in the internal conditions Table)



Opaque Construction

Name: Aluminium Frame 2

Description:

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.500	0.500	0.216	0.216	999.999	0.000

Layer	M-Code	Thickness (...	Conductivi...	Convectio...	Vapour Dif...	Density (k...	Specific H...	Description
Inner	am1metal\1	12.7	1730.51	0.0	99999.000	2700.0	896.0	ALUMINIUM *3

* layer ignored in U-Value/R-Value Calculation

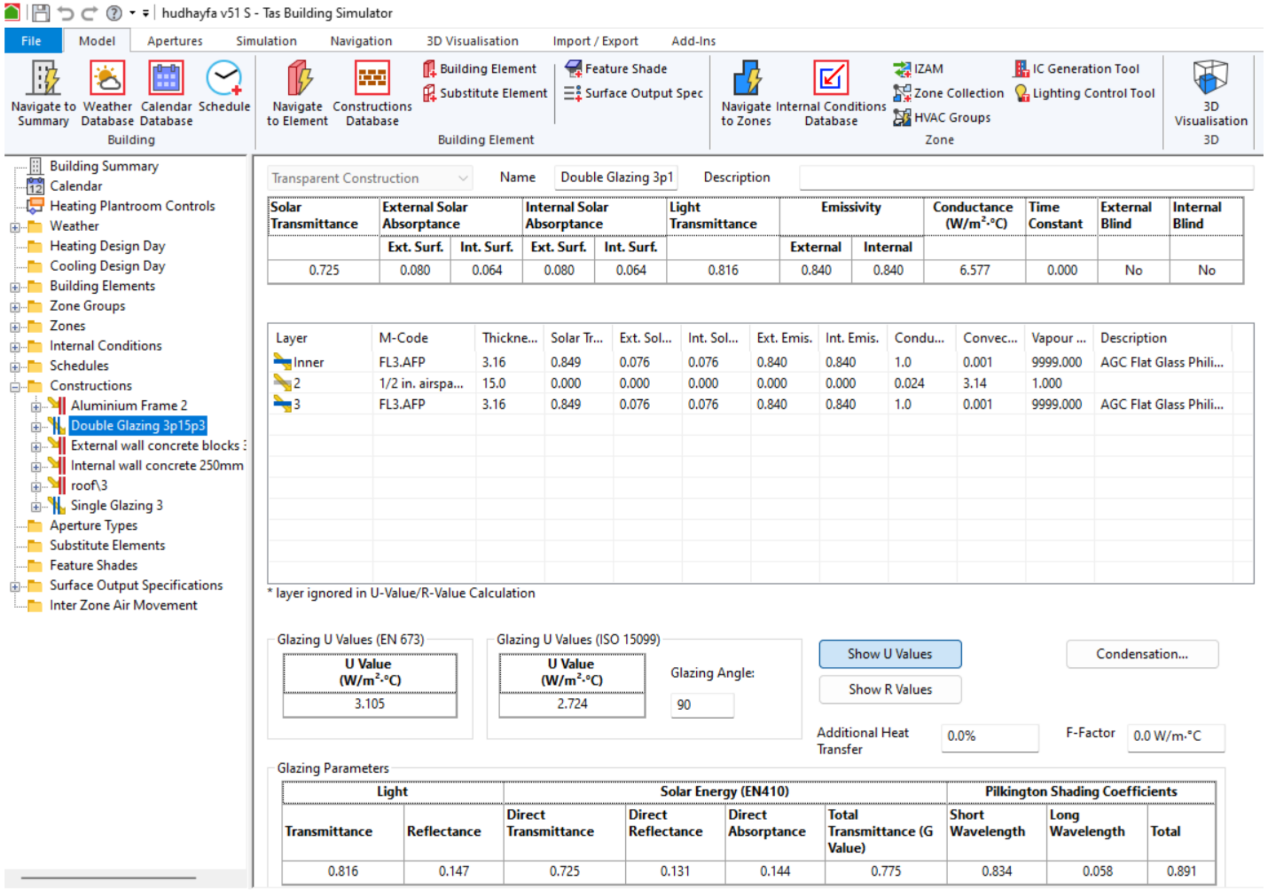
U/R Values (ISO 6946) (Homogenous)

Flow Direction	Internal U Value (W/m²·°C)	External U Value (W/m²·°C)
Horizontal	3.846	5.882
Upward	5.0	7.142
Downward	2.941	4.762

Additional Heat Transfer: 0.0%

F-Factor: 0.0 W/m·°C

Figure 10.4: Frame material (construction) specifications



Transparent Construction

Name: Double Glazing 3p1

Description:

Solar Transmittance	External Solar Absorptance		Internal Solar Absorptance		Light Transmittance	Emissivity		Conductance (W/m^2·°C)	Time Constant	External Blind	Internal Blind
	Ext. Surf.	Int. Surf.	Ext. Surf.	Int. Surf.		External	Internal				
0.725	0.080	0.064	0.080	0.064	0.816	0.840	0.840	6.577	0.000	No	No

Layer	M-Code	Thickne...	Solar Tr...	Ext. Sol...	Int. Sol...	Ext. Emis.	Int. Emis.	Condu...	Convec...	Vapour ...	Description
Inner	FL3.AFP	3.16	0.849	0.076	0.076	0.840	0.840	1.0	0.001	9999.000	AGC Flat Glass Phili...
2	1/2 in. airspa...	15.0	0.000	0.000	0.000	0.000	0.000	0.024	3.14	1.000	
3	FL3.AFP	3.16	0.849	0.076	0.076	0.840	0.840	1.0	0.001	9999.000	AGC Flat Glass Phili...

* layer ignored in U-Value/R-Value Calculation

Glazing U Values (EN 673)

U Value (W/m^2·°C)
3.105

Glazing U Values (ISO 15099)

U Value (W/m^2·°C)
2.724

Glazing Angle: 90

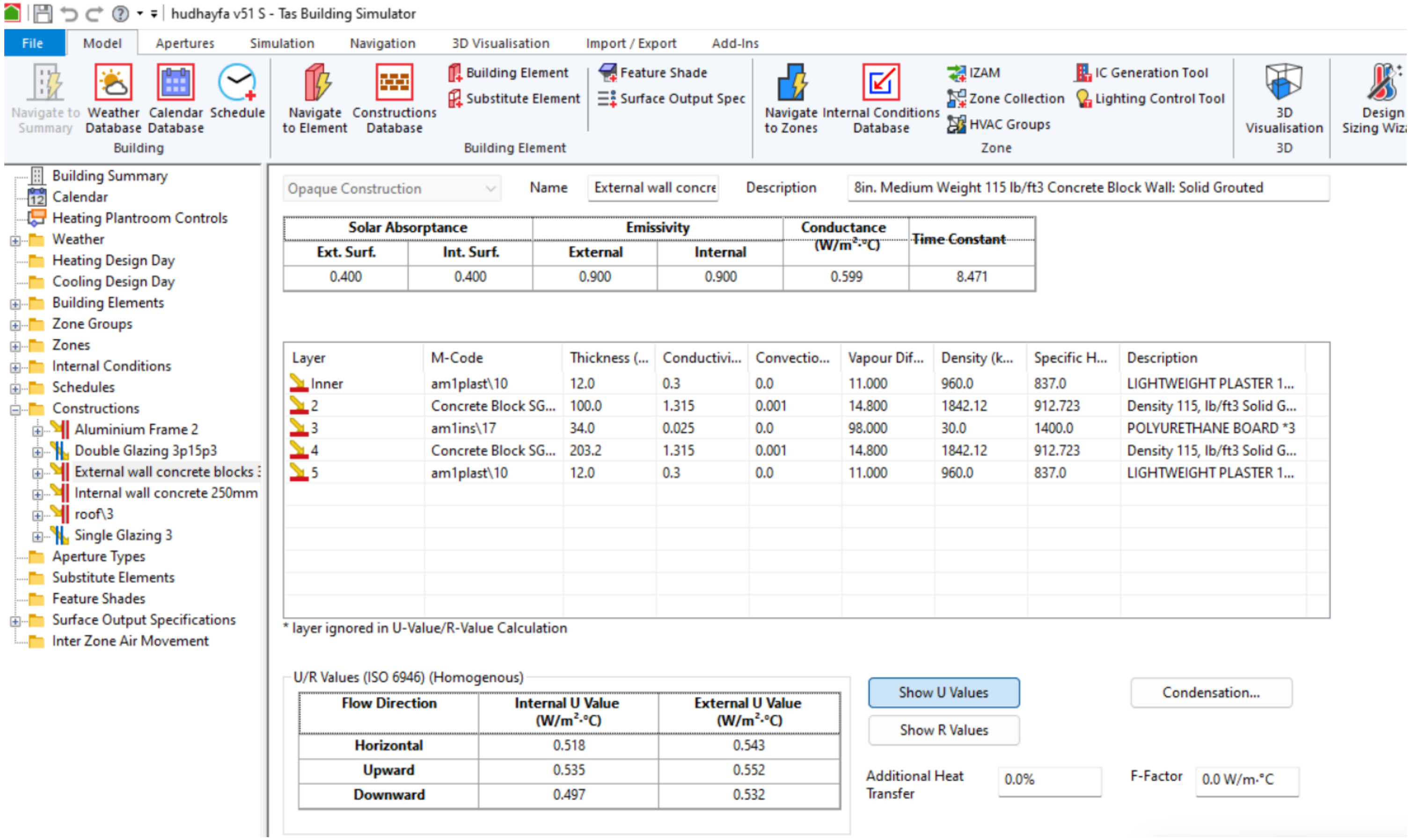
Additional Heat Transfer: 0.0%

F-Factor: 0.0 W/m·°C

Glazing Parameters

Light		Solar Energy (EN410)				Pilkington Shading Coefficients		
Transmittance	Reflectance	Direct Transmittance	Direct Reflectance	Direct Absorptance	Total Transmittance (G Value)	Short Wavelength	Long Wavelength	Total
0.816	0.147	0.725	0.131	0.144	0.775	0.834	0.058	0.891

Figure 10.5: Window pane material (construction) specifications



Opaque Construction

Name: External wall concre

Description: 8in. Medium Weight 115 lb/ft3 Concrete Block Wall: Solid Grouted

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.400	0.900	0.900	0.599	8.471

Layer	M-Code	Thickness (...	Conductivi...	Convectio...	Vapour Dif...	Density (k...	Specific H...	Description
Inner	am1plast\10	12.0	0.3	0.0	11.000	960.0	837.0	LIGHTWEIGHT PLASTER 1...
2	Concrete Block SG...	100.0	1.315	0.001	14.800	1842.12	912.723	Density 115, lb/ft3 Solid G...
3	am1ins\17	34.0	0.025	0.0	98.000	30.0	1400.0	POLYURETHANE BOARD *3
4	Concrete Block SG...	203.2	1.315	0.001	14.800	1842.12	912.723	Density 115, lb/ft3 Solid G...
5	am1plast\10	12.0	0.3	0.0	11.000	960.0	837.0	LIGHTWEIGHT PLASTER 1...

* layer ignored in U-Value/R-Value Calculation

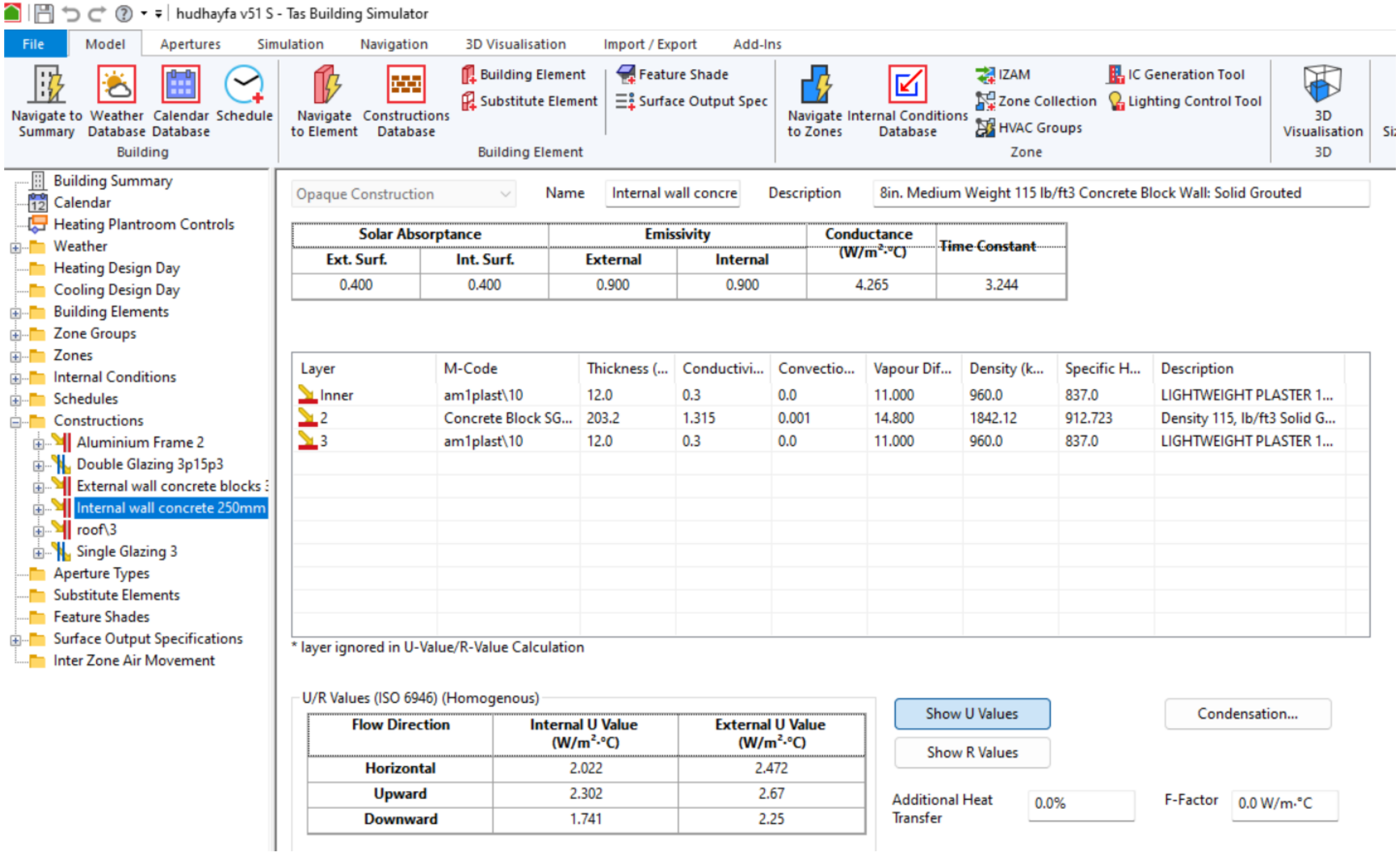
U/R Values (ISO 6946) (Homogenous)

Flow Direction	Internal U Value (W/m²·°C)	External U Value (W/m²·°C)
Horizontal	0.518	0.543
Upward	0.535	0.552
Downward	0.497	0.532

Additional Heat Transfer: 0.0%

F-Factor: 0.0 W/m·°C

Figure 0.6: External wall material (construction) specifications



Opaque Construction

Name: Internal wall concre

Description: 8in. Medium Weight 115 lb/ft3 Concrete Block Wall: Solid Grouted

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.400	0.900	0.900	4.265	3.244

Layer	M-Code	Thickness (...	Conductivi...	Convectio...	Vapour Dif...	Density (k...	Specific H...	Description
Inner	am1plast\10	12.0	0.3	0.0	11.000	960.0	837.0	LIGHTWEIGHT PLASTER 1...
2	Concrete Block SG...	203.2	1.315	0.001	14.800	1842.12	912.723	Density 115, lb/ft3 Solid G...
3	am1plast\10	12.0	0.3	0.0	11.000	960.0	837.0	LIGHTWEIGHT PLASTER 1...

* layer ignored in U-Value/R-Value Calculation

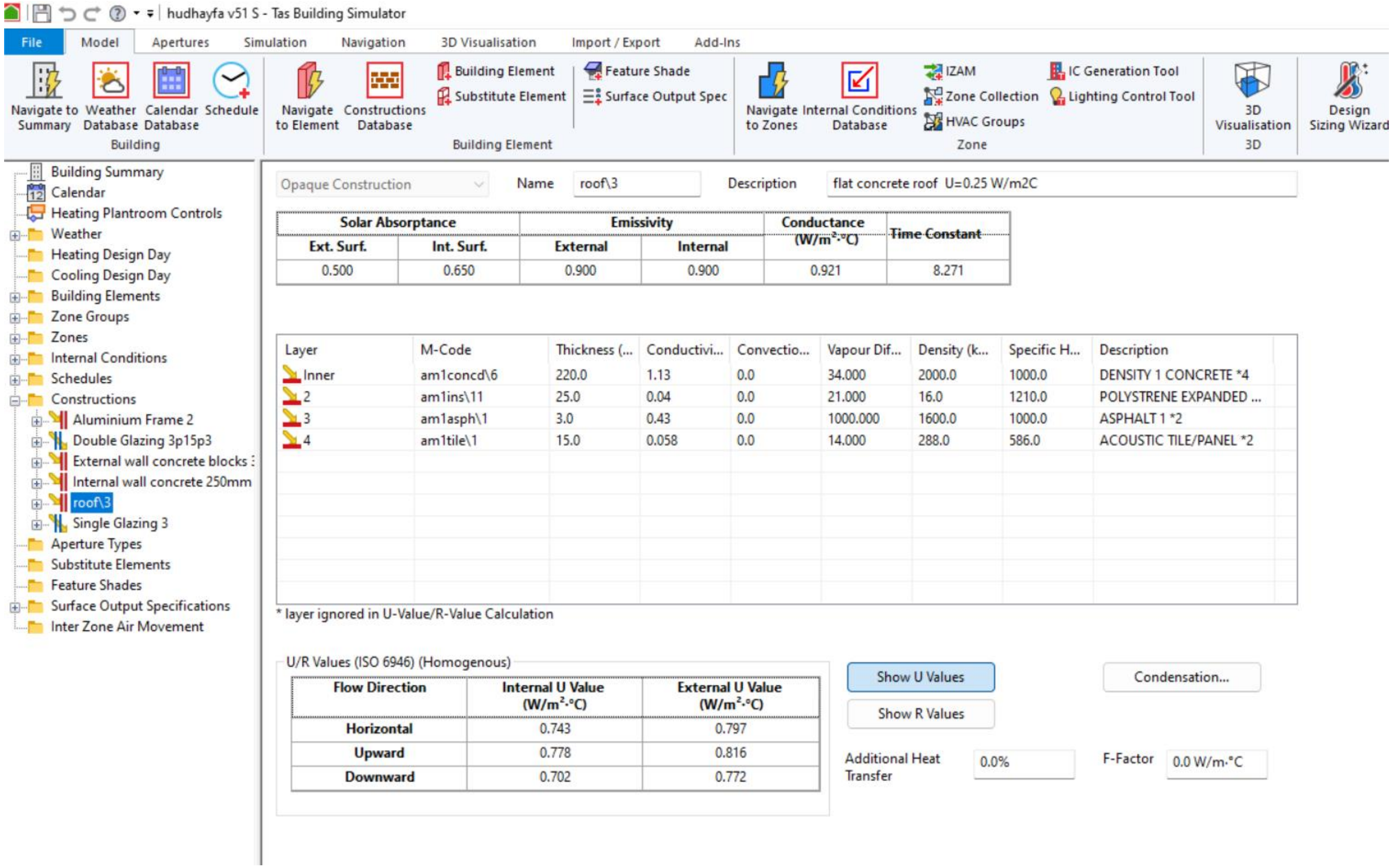
U/R Values (ISO 6946) (Homogenous)

Flow Direction	Internal U Value (W/m²·°C)	External U Value (W/m²·°C)
Horizontal	2.022	2.472
Upward	2.302	2.67
Downward	1.741	2.25

Additional Heat Transfer: 0.0%

F-Factor: 0.0 W/m·°C

Figure 10.7: Internal wall material (construction) specifications



Opaque Construction

Name: roof\3

Description: flat concrete roof U=0.25 W/m2C

Solar Absorptance		Emissivity		Conductance (W/m^2·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.500	0.650	0.900	0.900	0.921	8.271

Layer	M-Code	Thickness (...	Conductivi...	Convectio...	Vapour Dif...	Density (k...	Specific H...	Description
Inner	am1concd\6	220.0	1.13	0.0	34.000	2000.0	1000.0	DENSITY 1 CONCRETE *4
2	am1ins\11	25.0	0.04	0.0	21.000	16.0	1210.0	POLYSTRENE EXPANDED ...
3	am1asph\1	3.0	0.43	0.0	1000.000	1600.0	1000.0	ASPHALT 1 *2
4	am1tile\1	15.0	0.058	0.0	14.000	288.0	586.0	ACOUSTIC TILE/PANEL *2

* layer ignored in U-Value/R-Value Calculation

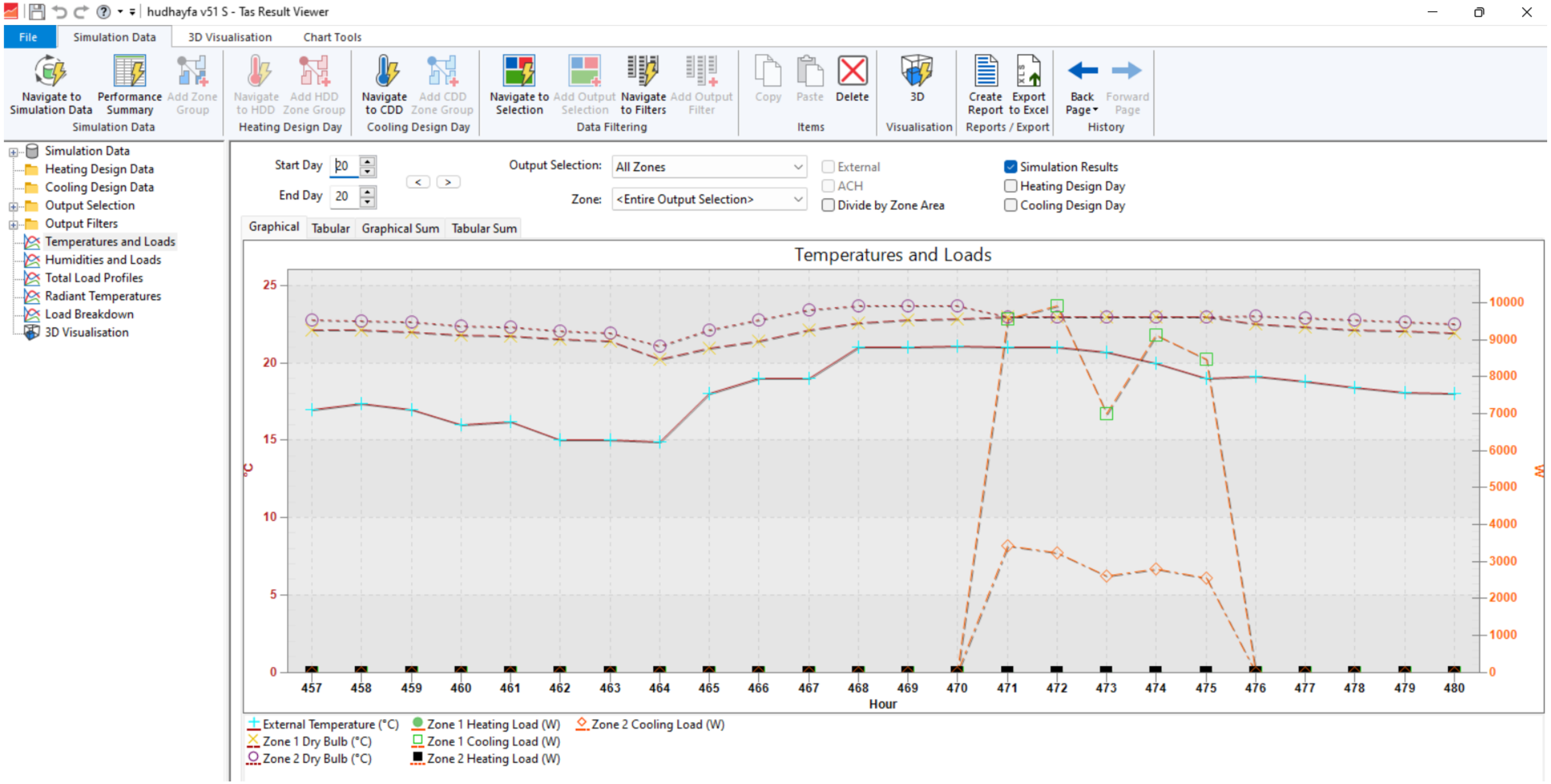
U/R Values (ISO 6946) (Homogenous)

Flow Direction	Internal U Value (W/m^2·°C)	External U Value (W/m^2·°C)
Horizontal	0.743	0.797
Upward	0.778	0.816
Downward	0.702	0.772

Additional Heat Transfer: 0.0%

F-Factor: 0.0 W/m·°C

Figure 10.8: Roof material (construction) specifications



Start Day 20

End Day 20

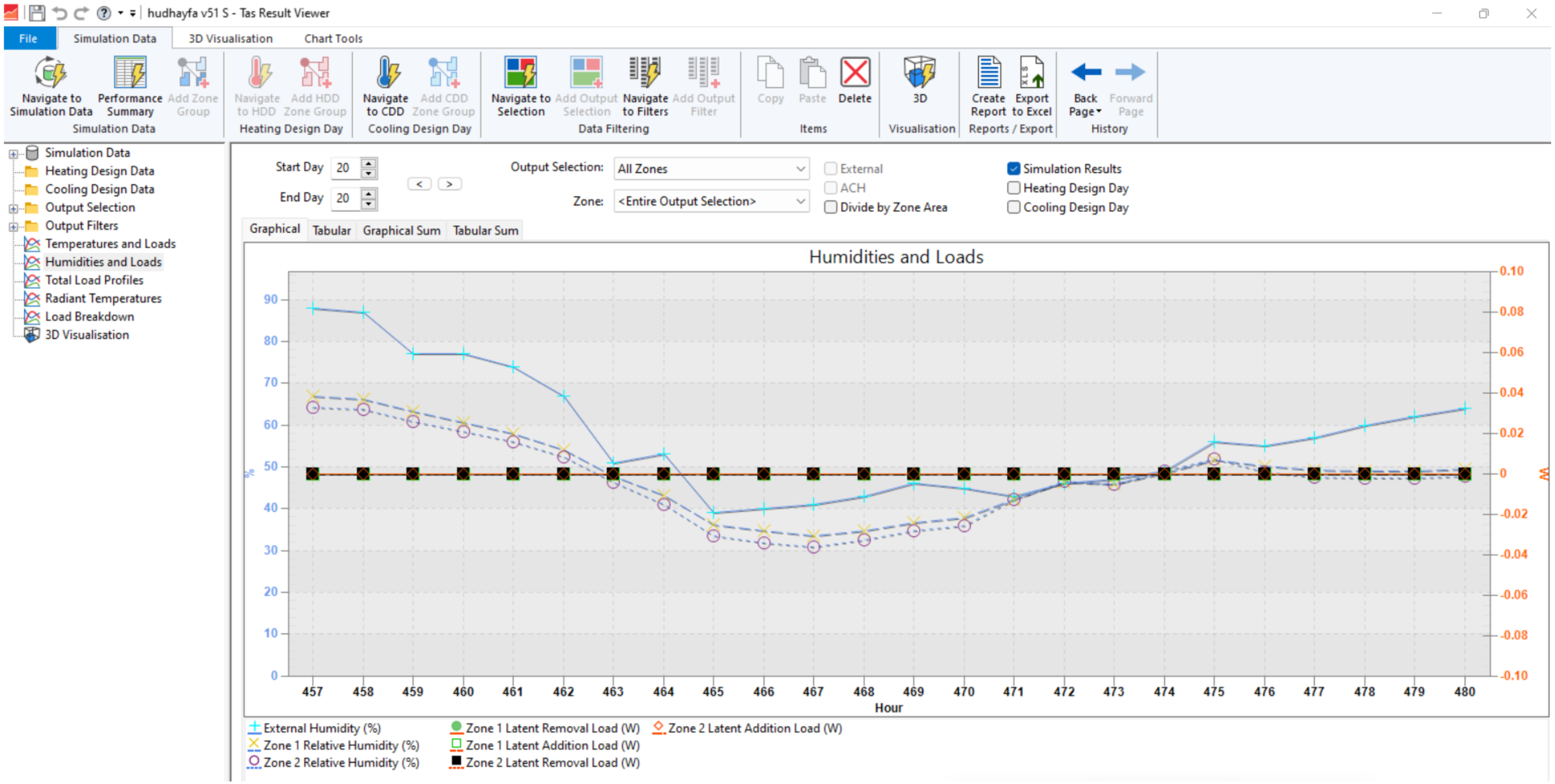
Output Selection: All Zones

Zone: <Entire Output Selection>

☐ External
☐ ACH
☐ Divide by Zone Area

☑ Simulation Results
☐ Heating Design Day
☐ Cooling Design Day

Figure 10.9: External Temperature, DBT, and cooling load during day 20 for zones 1 and 2 (TAS Results software).



Start Day 20

End Day 20

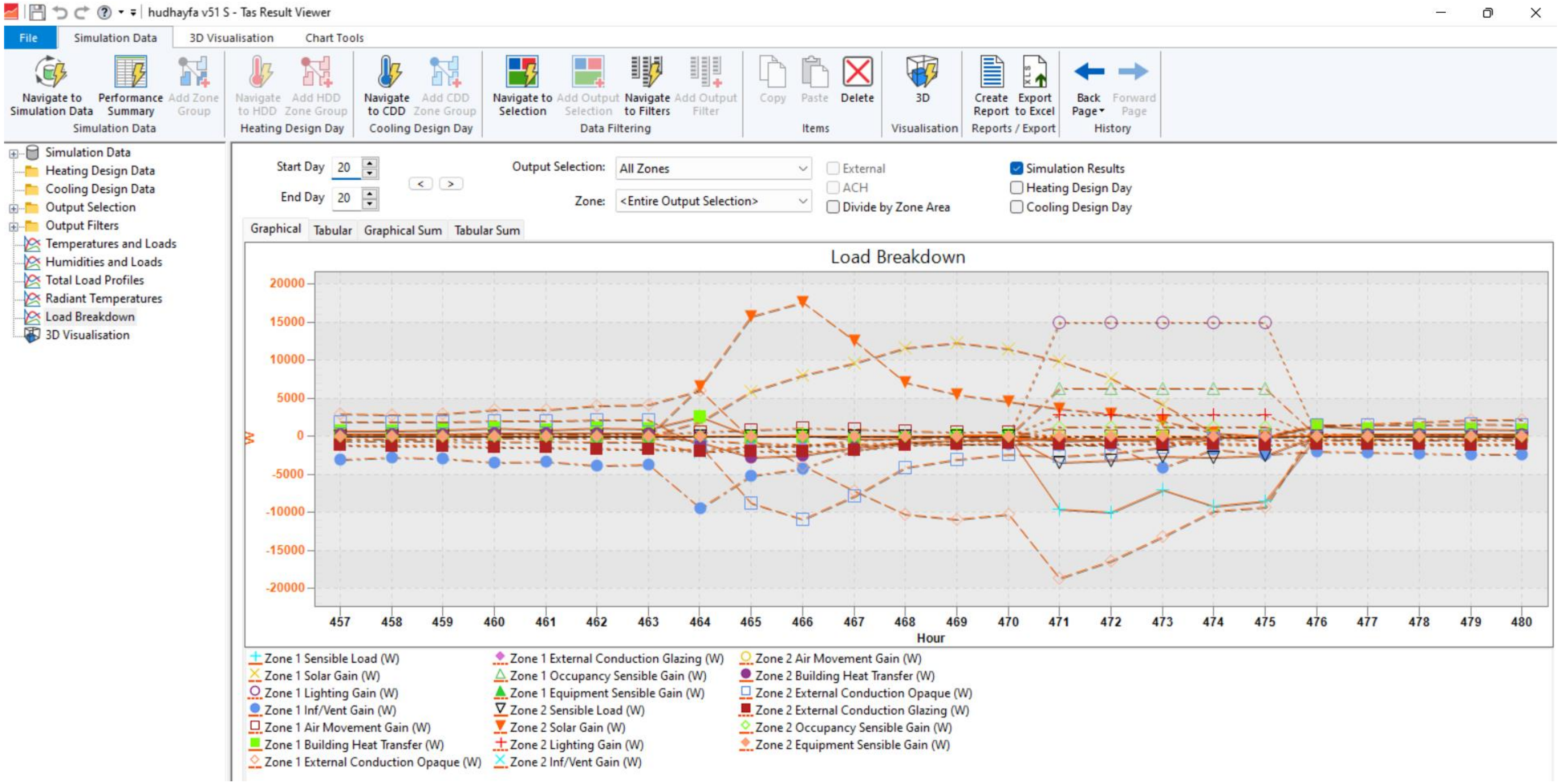
Output Selection: All Zones

Zone: <Entire Output Selection>

☐ External
☐ ACH
☐ Divide by Zone Area

☑ Simulation Results
☐ Heating Design Day
☐ Cooling Design Day

Figure 10.10: Internal and External relative humidity during day 20 for zones 1 and 2 (TAS Results software).



Start Day 20

End Day 20

Output Selection: All Zones

Zone: <Entire Output Selection>

☐ External

☐ ACH

☐ Divide by Zone Area

☑ Simulation Results

☐ Heating Design Day

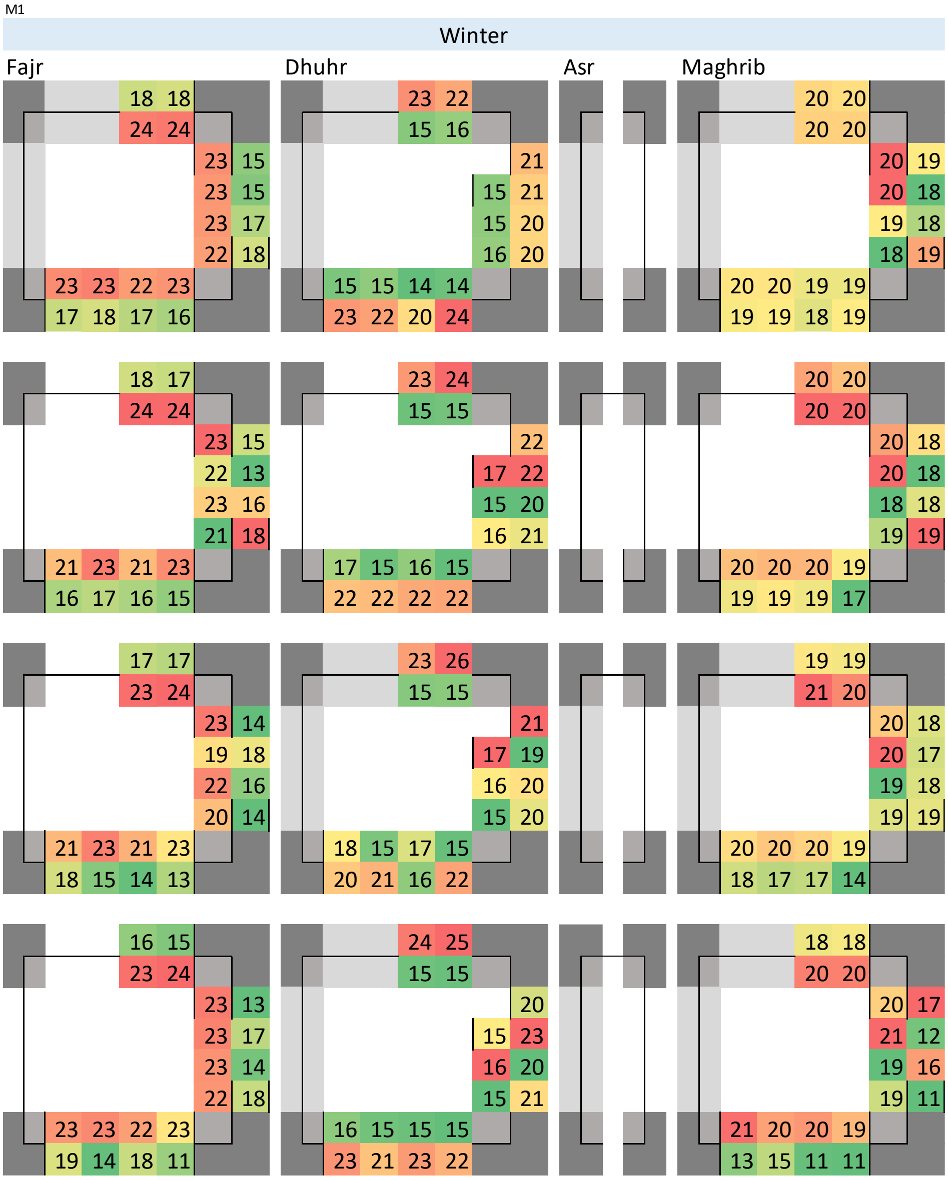
☐ Cooling Design Day

Figure 10.11: Load breakdown during day 20 for zones 1 and 2 (TAS Results software).

APPENDIX B: FIELD MEASUREMENT WALL SURFACE TEMPERATURE DETAILS FOR ALL CASE STUDIES

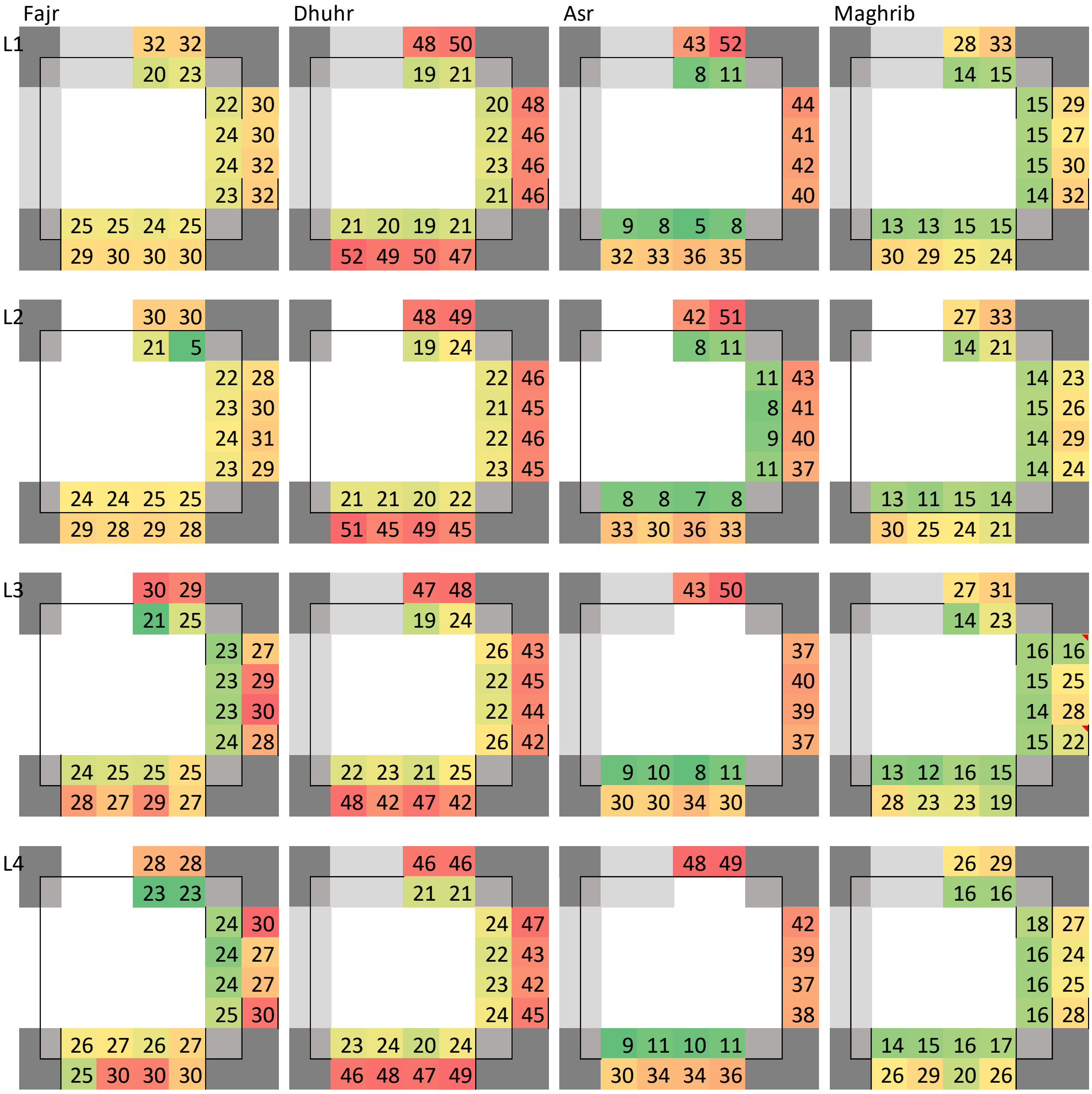
9.9.1 Hudhayfah Bin Al Yaman Mosque (M1)

Wall Surface Temperature for M1 during summer at four different heights measured at Fajr, Dhuhr, and Maghrib.



M1

Summer



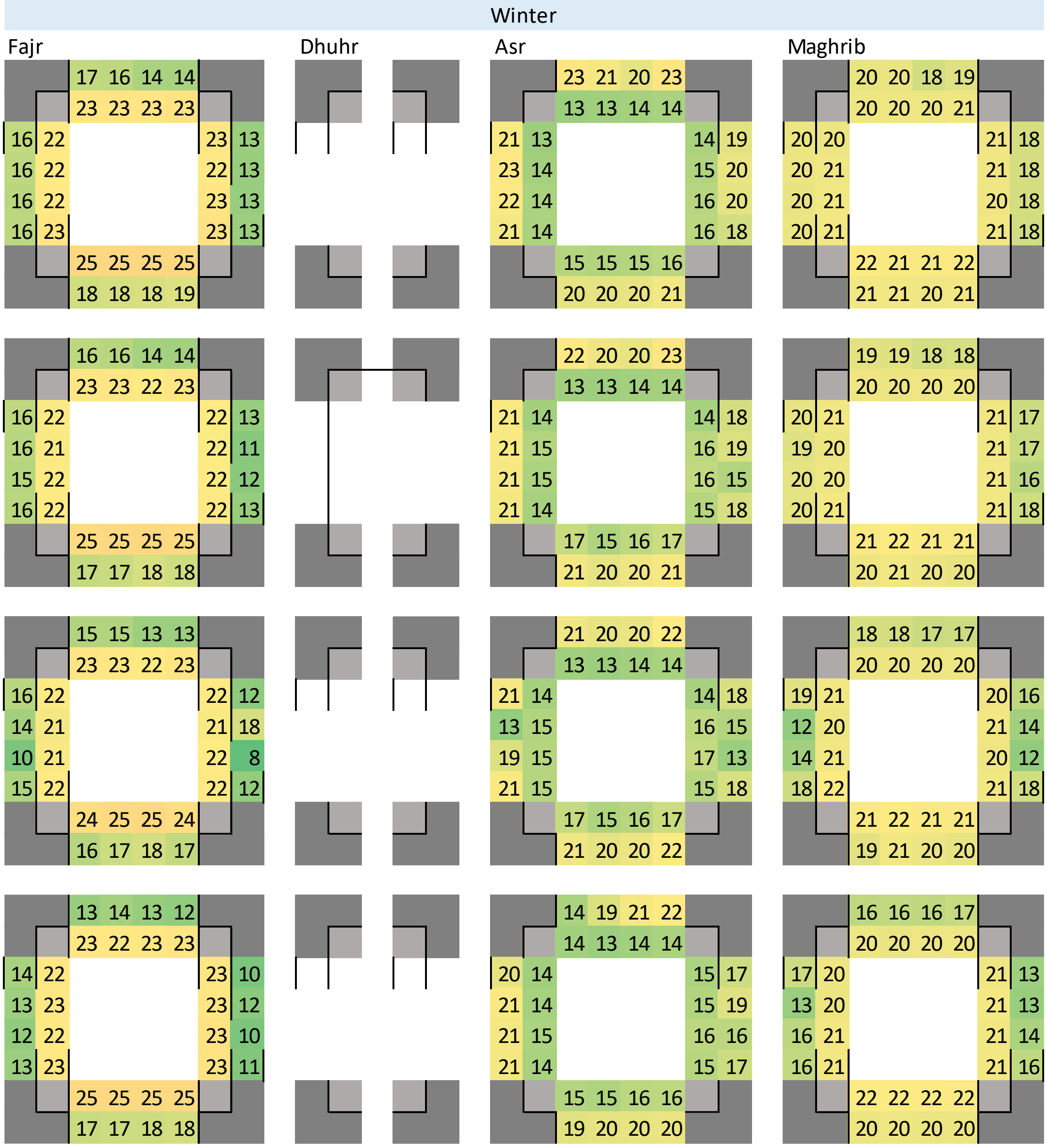
L1	Fajr	Dhuhr	Asr	Maghrib
	32 32	48 50	43 52	28 33
	20 23	19 21	8 11	14 15
	22 30	20 48	44	15 29
	24 30	22 46	41	15 27
	24 32	23 46	42	15 30
	23 32	21 46	40	14 32
	25 25 24 25	21 20 19 21	9 8 5 8	13 13 15 15
	29 30 30 30	52 49 50 47	32 33 36 35	30 29 25 24

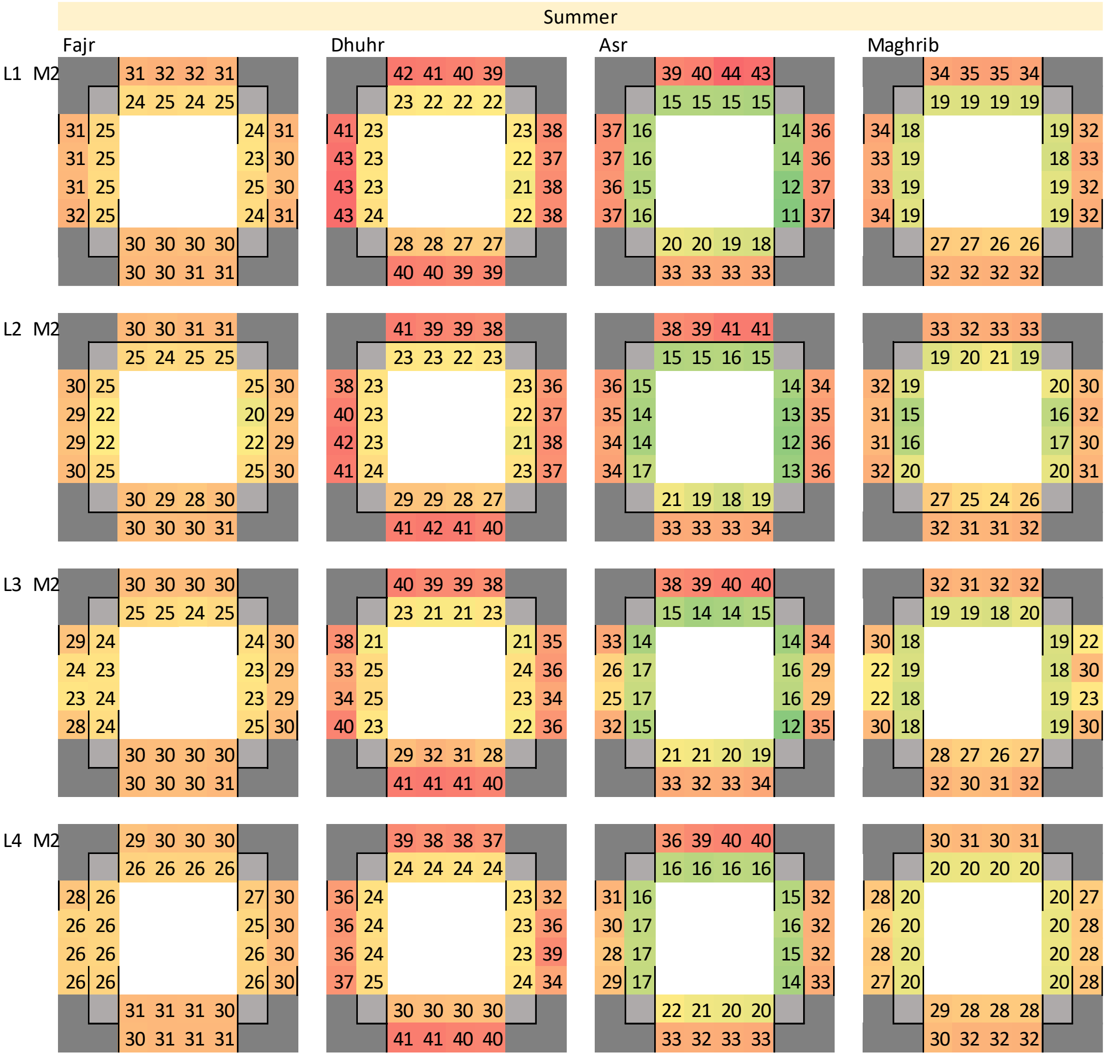
L2	Fajr	Dhuhr	Asr	Maghrib
	30 30	48 49	42 51	27 33
	21 5	19 24	8 11	14 21
	22 28	22 46	11 43	14 23
	23 30	21 45	8 41	15 26
	24 31	22 46	9 40	14 29
	23 29	23 45	11 37	14 24
	24 24 25 25	21 21 20 22	8 8 7 8	13 11 15 14
	29 28 29 28	51 45 49 45	33 30 36 33	30 25 24 21

L3	Fajr	Dhuhr	Asr	Maghrib
	30 29	47 48	43 50	27 31
	21 25	19 24		14 23
	23 27	26 43	37	16 16
	23 29	22 45	40	15 25
	23 30	22 44	39	14 28
	24 28	26 42	37	15 22
	24 25 25 25	22 23 21 25	9 10 8 11	13 12 16 15
	28 27 29 27	48 42 47 42	30 30 34 30	28 23 23 19

L4	Fajr	Dhuhr	Asr	Maghrib
	28 28	46 46	48 49	26 29
	23 23	21 21		16 16
	24 30	24 47	42	18 27
	24 27	22 43	39	16 24
	24 27	23 42	37	16 25
	25 30	24 45	38	16 28
	26 27 26 27	23 24 20 24	9 11 10 11	14 15 16 17
	25 30 30 30	46 48 47 49	30 34 34 36	26 29 20 26

9.9.2 Abu Hamza Al Shari Mosque (M2)





Summer

	Fajr								Dhuhr								Asr								Maghrib							
L1 M2			31	32	32	31					42	41	40	39					39	40	44	43					34	35	35	34		
			24	25	24	25					23	22	22	22					15	15	15	15					19	19	19	19		
	31	25					24	31	41	23					23	38	37	16					14	36	34	18					19	32
	31	25					23	30	43	23					22	37	37	16					14	36	33	19					18	33
	31	25					25	30	43	23					21	38	36	15					12	37	33	19					19	32
	32	25					24	31	43	24					22	38	37	16					11	37	34	19					19	32
			30	30	30	30					28	28	27	27					20	20	19	18					27	27	26	26		
			30	30	31	31					40	40	39	39					33	33	33	33					32	32	32	32		
L2 M2			30	30	31	31					41	39	39	38					38	39	41	41					33	32	33	33		
			25	24	25	25					23	23	22	23					15	15	16	15					19	20	21	19		
	30	25					25	30	38	23					23	36	36	15					14	34	32	19					20	30
	29	22					20	29	40	23					22	37	35	14					13	35	31	15					16	32
	29	22					22	29	42	23					21	38	34	14					12	36	31	16					17	30
	30	25					25	30	41	24					23	37	34	17					13	36	32	20					20	31
			30	29	28	30					29	29	28	27					21	19	18	19					27	25	24	26		
			30	30	30	31					41	42	41	40					33	33	33	34					32	31	31	32		
L3 M2			30	30	30	30					40	39	39	38					38	39	40	40					32	31	32	32		
			25	25	24	25					23	21	21	23					15	14	14	15					19	19	18	20		
	29	24					24	30	38	21					21	35	33	14					14	34	30	18					19	22
	24	23					23	29	33	25					24	36	26	17					16	29	22	19					18	30
	23	24					23	29	34	25					23	34	25	17					16	29	22	18					19	23
	28	24					25	30	40	23					22	36	32	15					12	35	30	18					19	30
			30	30	30	30					29	32	31	28					21	21	20	19					28	27	26	27		
			30	30	30	31					41	41	41	40					33	32	33	34					32	30	31	32		
L4 M2			29	30	30	30					39	38	38	37					36	39	40	40					30	31	30	31		
			26	26	26	26					24	24	24	24					16	16	16	16					20	20	20	20		
	28	26					27	30	36	24					23	32	31	16					15	32	28	20					20	27
	26	26					25	30	36	24					23	36	30	17					16	32	26	20					20	28
	26	26					26	30	36	24					23	39	28	17					15	32	28	20					20	28
	26	26					26	30	37	25					24	34	29	17					14	33	27	20					20	28
			31	31	31	30					30	30	30	30					22	21	20	20					29	28	28	28		
			30	31	31	31					41	41	40	40					33	32	33	33					30	32	32	32		

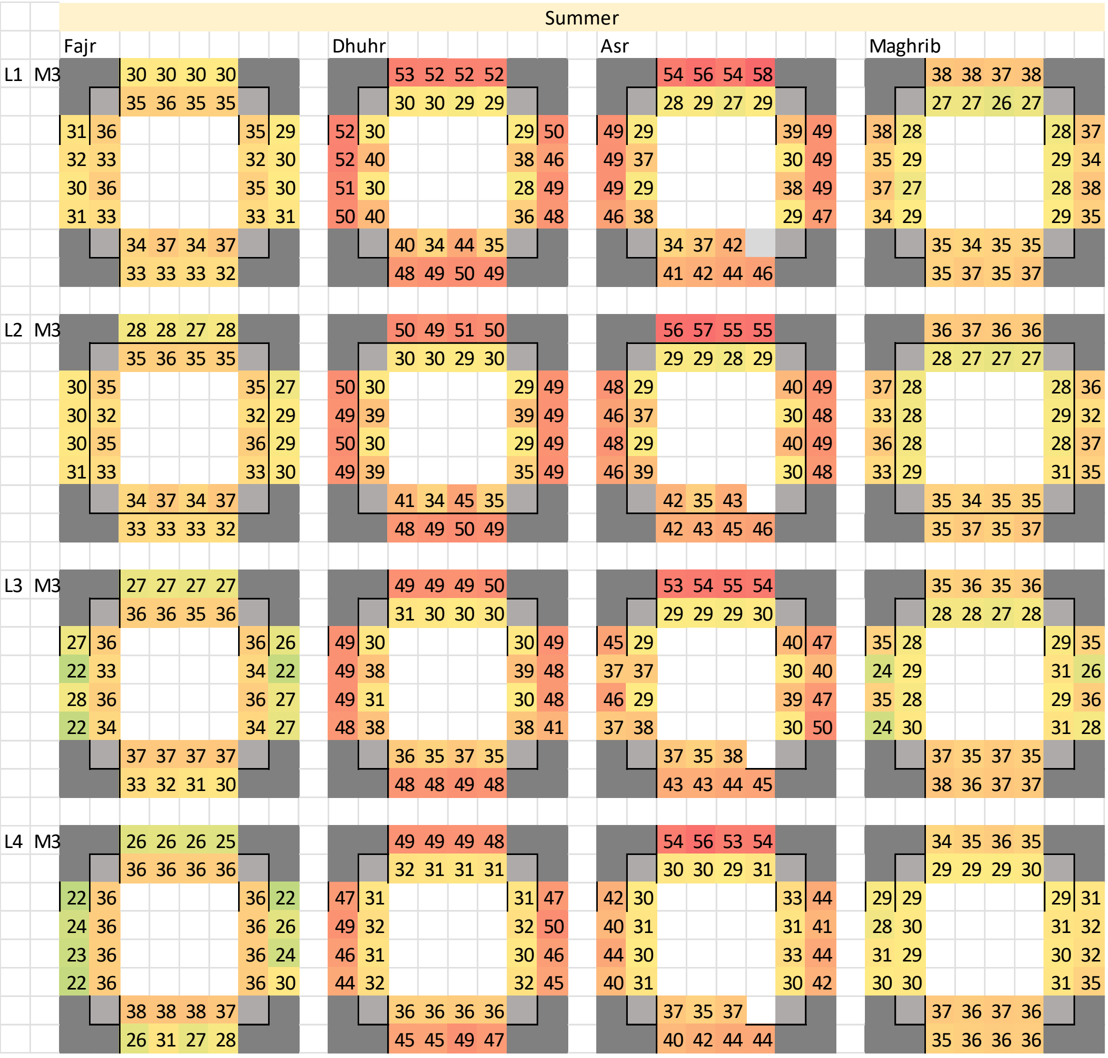
9.9.3 Othman bin Afan Mosque (M3)

	Winter			
	Fajr	Dhuhr	Asr	Maghrib
M3	15 15 15 14	30 29 28 26		22 21 22 21
	25 24 24 24	21 19 19 19		22 22 21 21
	16 21 23 13	40 20 18 22		21 22 19 20
	17 25 20 15	43 24 21 23		23 22 20 20
	17 21 24 14	41 21 18 20		21 22 20 19
	17 24 21 15	45 24 20 21		23 22 20 20
	22 25 22 25	24 21 24 20		23 23 22 22
	16 17 17 15	30 33 28 26		21 22 20 21

M3	14 13 14 13	28 27 26 25		21 21 21 20
	24 24 24 24	21 19 19 19		22 21 21 21
	16 21 23 12	38 21 18 21		21 22 19 19
	17 25 21 15	43 36 20 23		22 21 20 19
	17 21 24 14	40 21 19 20		21 22 20 18
	17 24 22 15	49 37 20 22		23 21 20 19
	23 25 22 25	24 21 24 20		23 23 22 22
	16 16 17 15	31 33 30 27		20 22 21 21

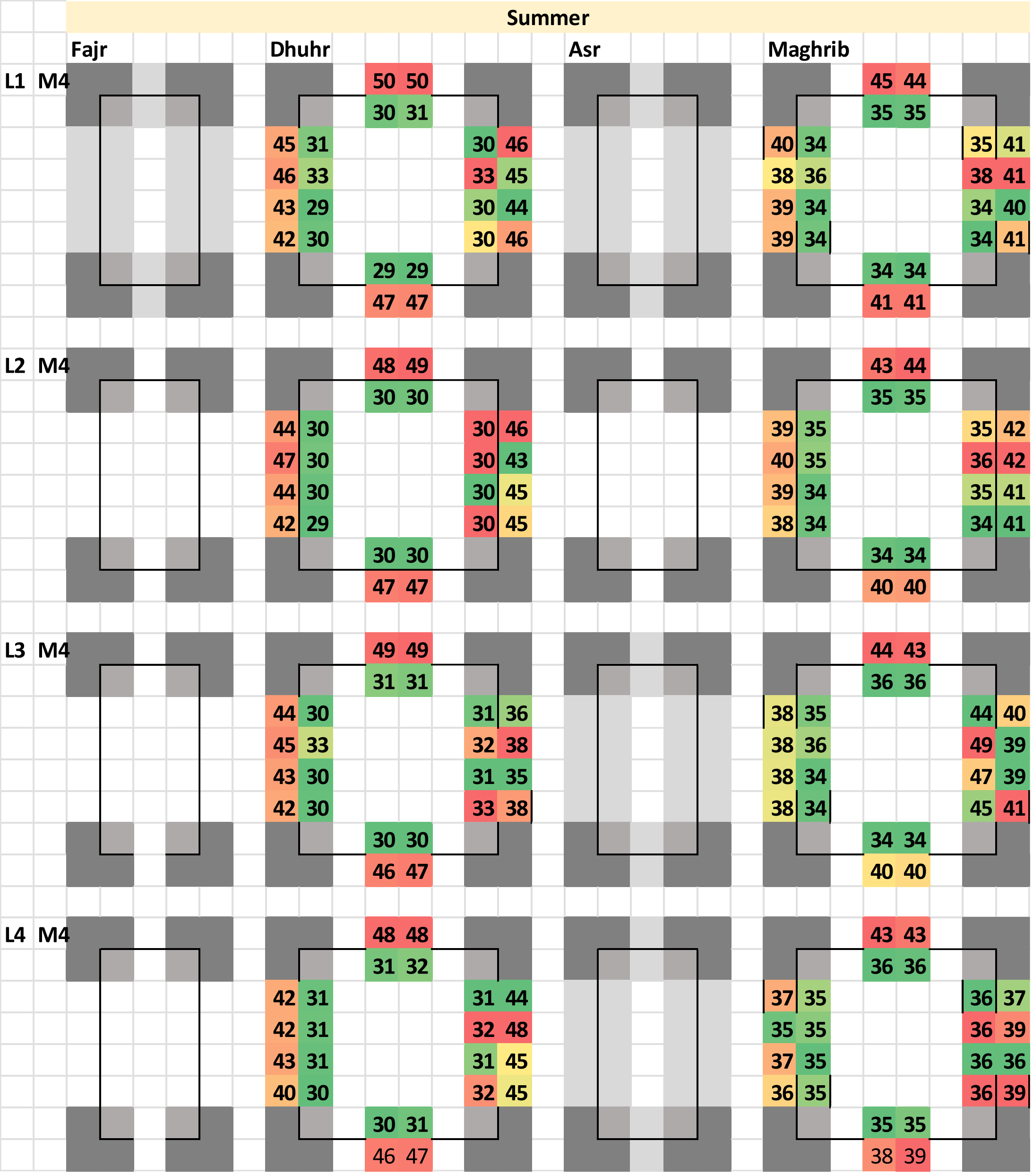
M3	13 12 13 13	27 26 25 25		20 20 20 20
	24 24 24 24	20 19 18 19		22 21 21 21
	15 21 23 11	36 21 18 20		14 22 20 17
	11 25 21 10	39 41 22 17		21 22 20 13
	15 21 24 13	39 21 18 19		14 22 20 17
	17 24 21 11	44 42 22 19		22 22 20 14
	24 25 24 25	23 21 21 20		24 23 23 23
	16 16 15 15	31 33 27 27		20 22 21 20

M3	12 12 12 12	25 25 24 24		19 19 19 20
	24 24 24 24	20 19 18 19		22 21 20 21
	14 24 23 11	36 21 18 20		24 22 20 17
	15 25 23 13	32 40 19 22		22 24 20 19
	18 24 24 12	38 21 18 20		23 22 20 19
	17 25 23 16	35 42 19 21		24 25 21 19
	25 25 25 25	22 21 21 21		24 24 23 23
	14 16 15 14	31 32 27 27		22 22 21 19

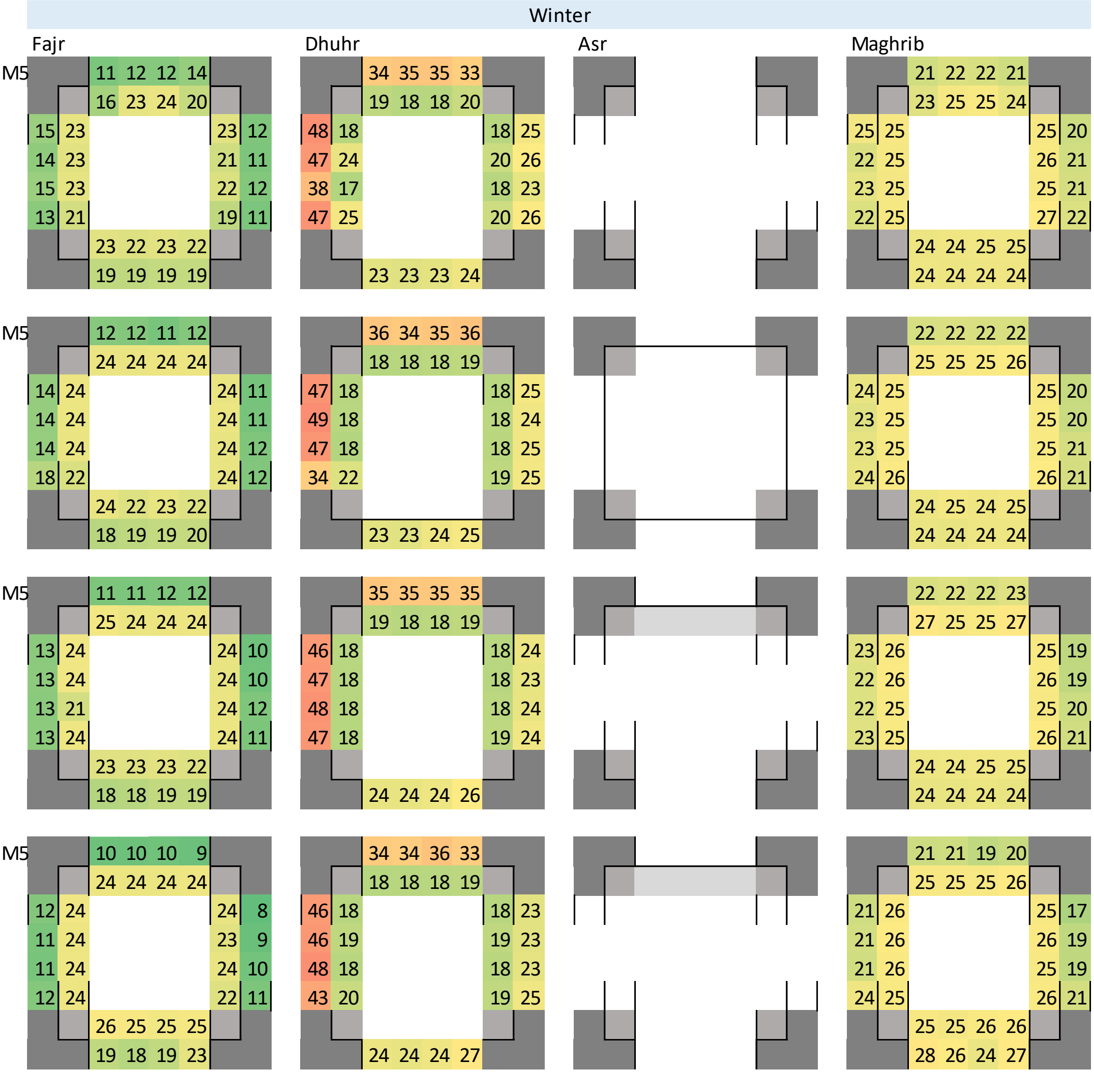


		Summer																															
		Fajr								Dhuhr								Asr								Maghrib							
L1	M3			30	30	30	30					53	52	52	52					54	56	54	58					38	38	37	38		
				35	36	35	35					30	30	29	29					28	29	27	29					27	27	26	27		
		31	36					35	29	52	30					29	50	49	29					39	49	38	28					28	37
		32	33					32	30	52	40					38	46	49	37					30	49	35	29					29	34
		30	36					35	30	51	30					28	49	49	29					38	49	37	27					28	38
		31	33					33	31	50	40					36	48	46	38					29	47	34	29					29	35
				34	37	34	37					40	34	44	35					34	37	42						35	34	35	35		
				33	33	33	32					48	49	50	49					41	42	44	46					35	37	35	37		
L2	M3			28	28	27	28					50	49	51	50					56	57	55	55					36	37	36	36		
				35	36	35	35					30	30	29	30					29	29	28	29					28	27	27	27		
		30	35					35	27	50	30					29	49	48	29					40	49	37	28					28	36
		30	32					32	29	49	39					39	49	46	37					30	48	33	28					29	32
		30	35					36	29	50	30					29	49	48	29					40	49	36	28					28	37
		31	33					33	30	49	39					35	49	46	39					30	48	33	29					31	35
				34	37	34	37					41	34	45	35					42	35	43						35	34	35	35		
				33	33	33	32					48	49	50	49					42	43	45	46					35	37	35	37		
L3	M3			27	27	27	27					49	49	49	50					53	54	55	54					35	36	35	36		
				36	36	35	36					31	30	30	30					29	29	29	30					28	28	27	28		
		27	36					36	26	49	30					30	49	45	29					40	47	35	28					29	35
		22	33					34	22	49	38					39	48	37	37					30	40	24	29					31	26
		28	36					36	27	49	31					30	48	46	29					39	47	35	28					29	36
		22	34					34	27	48	38					38	41	37	38					30	50	24	30					31	28
				37	37	37	37					36	35	37	35					37	35	38						37	35	37	35		
				33	32	31	30					48	48	49	48					43	43	44	45					38	36	37	37		
L4	M3			26	26	26	25					49	49	49	48					54	56	53	54					34	35	36	35		
				36	36	36	36					32	31	31	31					30	30	29	31					29	29	29	30		
		22	36					36	22	47	31					31	47	42	30					33	44	29	29					29	31
		24	36					36	26	49	32					32	50	40	31					31	41	28	30					31	32
		23	36					36	24	46	31					30	46	44	30					33	44	31	29					30	32
		22	36					36	30	44	32					32	45	40	31					30	42	30	30					31	35
				38	38	38	37					36	36	36	36					37	35	37						37	36	37	36		
				26	31	27	28					45	45	49	47					40	42	44	44					35	36	36	36		

9.9.4 Sa’al Mosque (M4)



9.9.5 Al Wafi Mosque (M5)



Winter

Fajr

M5			11	12	12	14		
			16	23	24	20		
	15	23					23	12
	14	23					21	11
	15	23					22	12
	13	21					19	11
			23	22	23	22		
			19	19	19	19		
M5			12	12	11	12		
			24	24	24	24		
	14	24					24	11
	14	24					24	11
	14	24					24	12
	18	22					24	12
			24	22	23	22		
			18	19	19	20		
M5			11	11	12	12		
			25	24	24	24		
	13	24					24	10
	13	24					24	10
	13	21					24	12
	13	24					24	11
			23	23	23	22		
			18	18	19	19		
M5			10	10	10	9		
			24	24	24	24		
	12	24					24	8
	11	24					23	9
	11	24					24	10
	12	24					22	11
			26	25	25	25		
			19	18	19	23		

Dhuhr

		34	35	35	33		
		19	18	18	20		
48	18					18	25
47	24					20	26
38	17					18	23
47	25					20	26
		23	23	23	24		
		36	34	35	36		
		18	18	18	19		
47	18					18	25
49	18					18	24
47	18					18	25
34	22					19	25
		23	23	24	25		
		35	35	35	35		
		19	18	18	19		
46	18					18	24
47	18					18	23
48	18					18	24
47	18					19	24
		24	24	24	26		
		34	34	36	33		
		18	18	18	19		
46	18					18	23
46	19					19	23
48	18					18	23
43	20					19	25
		24	24	24	27		

Asr

Maghrib

		21	22	22	21		
		23	25	25	24		
25	25					25	20
22	25					26	21
23	25					25	21
22	25					27	22
		24	24	25	25		
		24	24	24	24		
		22	22	22	22		
		25	25	25	26		
24	25					25	20
23	25					25	20
23	25					25	21
24	26					26	21
		24	25	24	25		
		24	24	24	24		
		22	22	22	23		
		27	25	25	27		
23	26					25	19
22	26					26	19
22	25					25	20
23	25					26	21
		24	24	25	25		
		24	24	24	24		
		21	21	19	20		
		25	25	25	26		
21	26					25	17
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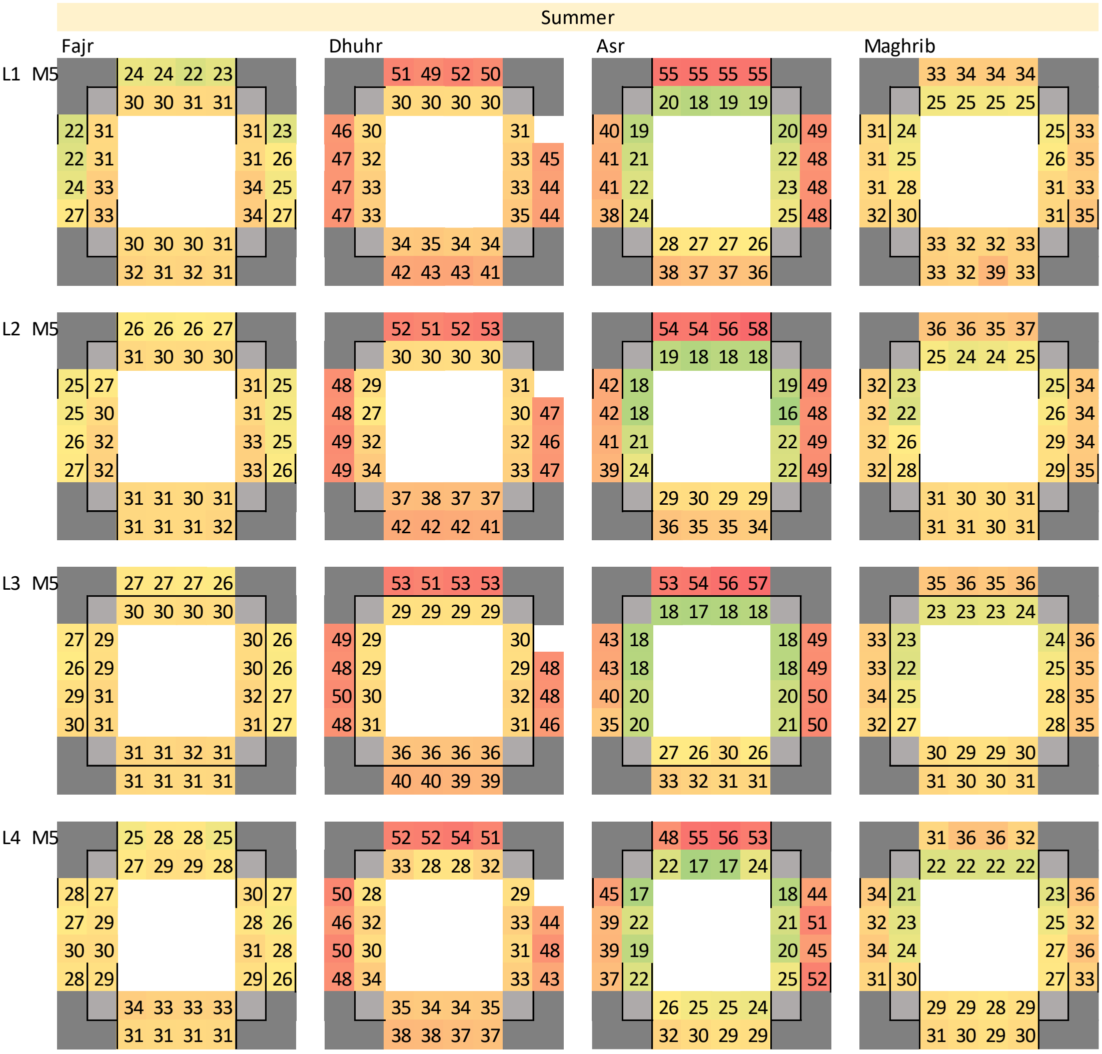
21	26					25	19
24	25					26	21
		25	25	26	26		
		28	26	24	27		



	Summer																															
	Fajr								Dhuhr								Asr								Maghrib							
L1 M5			24	24	22	23					51	49	52	50					55	55	55	55					33	34	34	34		
			30	30	31	31					30	30	30	30					20	18	19	19					25	25	25	25		
	22	31					31	23	46	30					31		40	19					20	49	31	24					25	33
	22	31					31	26	47	32					33	45	41	21					22	48	31	25					26	35
	24	33					34	25	47	33					33	44	41	22					23	48	31	28					31	33
	27	33					34	27	47	33					35	44	38	24					25	48	32	30					31	35
			30	30	30	31					34	35	34	34					28	27	27	26					33	32	32	33		
			32	31	32	31					42	43	43	41					38	37	37	36					33	32	39	33		
L2 M5			26	26	26	27					52	51	52	53					54	54	56	58					36	36	35	37		
			31	30	30	30					30	30	30	30					19	18	18	18					25	24	24	25		
	25	27					31	25	48	29					31		42	18					19	49	32	23					25	34
	25	30					31	25	48	27					30	47	42	18					16	48	32	22					26	34
	26	32					33	25	49	32					32	46	41	21					22	49	32	26					29	34
	27	32					33	26	49	34					33	47	39	24					22	49	32	28					29	35
			31	31	30	31					37	38	37	37					29	30	29	29					31	30	30	31		
			31	31	31	32					42	42	42	41					36	35	35	34					31	31	30	31		
L3 M5			27	27	27	26					53	51	53	53					53	54	56	57					35	36	35	36		
			30	30	30	30					29	29	29	29					18	17	18	18					23	23	23	24		
	27	29					30	26	49	29					30		43	18					18	49	33	23					24	36
	26	29					30	26	48	29					29	48	43	18					18	49	33	22					25	35
	29	31					32	27	50	30					32	48	40	20					20	50	34	25					28	35
	30	31					31	27	48	31					31	46	35	20					21	50	32	27					28	35
			31	31	32	31					36	36	36	36					27	26	30	26					30	29	29	30		
			31	31	31	31					40	40	39	39					33	32	31	31					31	30	30	31		
L4 M5			25	28	28	25					52	52	54	51					48	55	56	53					31	36	36	32		
			27	29	29	28					33	28	28	32					22	17	17	24					22	22	22	22		
	28	27					30	27	50	28					29		45	17					18	44	34	21					23	36
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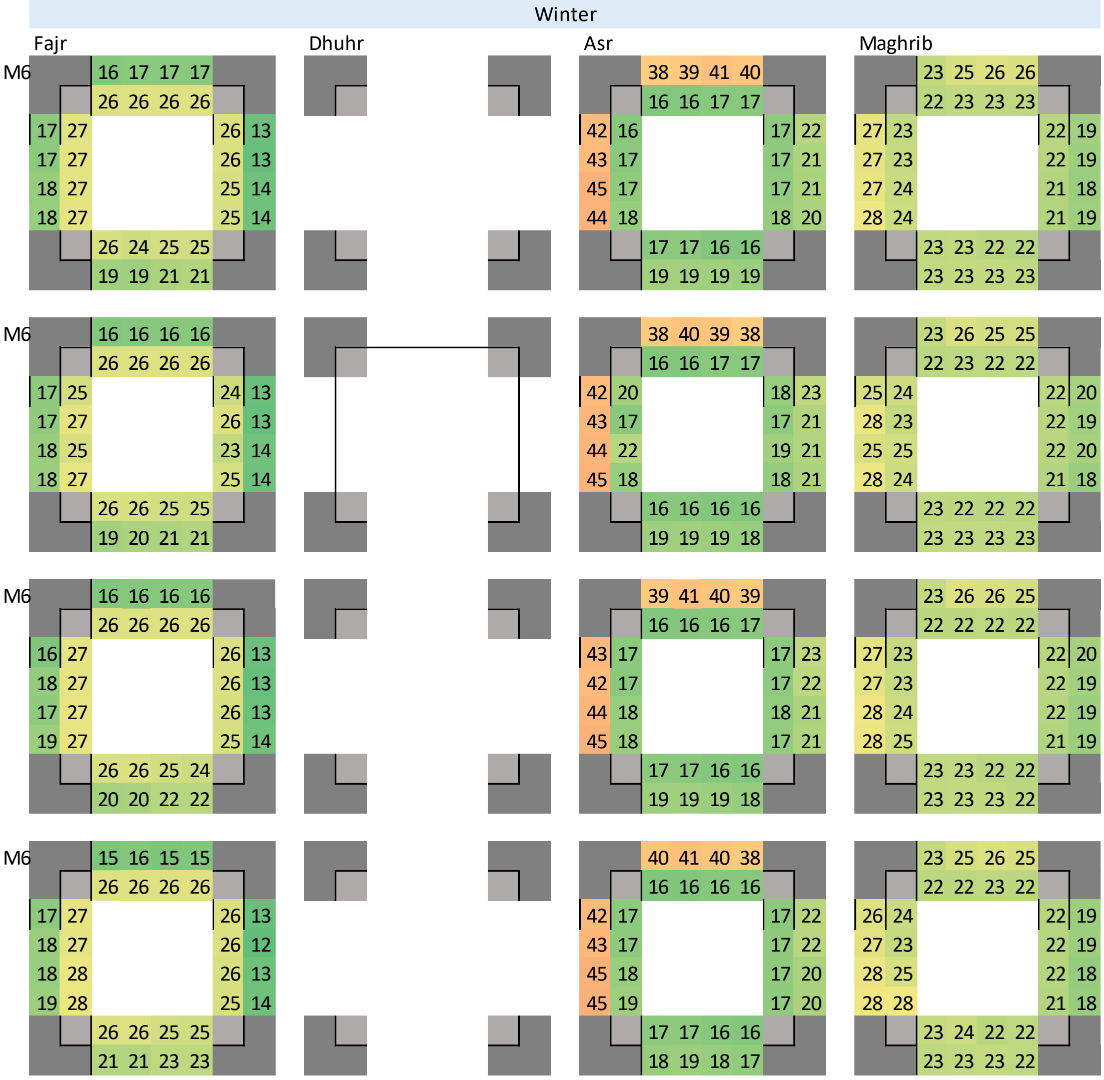
9.9.6 Aal Hamoodah Mosque (M6)



Winter

	Fajr								Dhuhr	Asr								Maghrib							
M6			16	17	17	17						38	39	41	40					23	25	26	26		
			26	26	26	26						16	16	17	17					22	23	23	23		
	17	27					26	13		42	16					17	22	27	23					22	19
	17	27					26	13		43	17					17	21	27	23					22	19
	18	27					25	14		45	17					17	21	27	24					21	18
	18	27					25	14		44	18					18	20	28	24					21	19
			26	24	25	25						17	17	16	16					23	23	22	22		
			19	19	21	21						19	19	19	19					23	23	23	23		
M6			16	16	16	16						38	40	39	38					23	26	25	25		
			26	26	26	26						16	16	17	17					22	23	22	22		
	17	25					24	13		42	20					18	23	25	24					22	20
	17	27					26	13		43	17					17	21	28	23					22	19
	18	25					23	14		44	22					19	21	25	25					22	20
	18	27					25	14		45	18					18	21	28	24					21	18
			26	26	25	25						16	16	16	16					23	22	22	22		
			19	20	21	21						19	19	19	18					23	23	23	23		
M6			16	16	16	16						39	41	40	39					23	26	26	25		
			26	26	26	26						16	16	16	17					22	22	22	22		
	16	27					26	13		43	17					17	23	27	23					22	20
	18	27					26	13		42	17					17	22	27	23					22	19
	17	27					26	13		44	18					18	21	28	24					22	19
	19	27					25	14		45	18					17	21	28	25					21	19
			26	26	25	24						17	17	16	16					23	23	22	22		
			20	20	22	22						19	19	19	18					23	23	23	22		
M6			15	16	15	15						40	41	40	38					23	25	26	25		
			26	26	26	26						16	16	16	16					22	22	23	22		
	17	27					26	13		42	17					17	22	26	24					22	19
	18	27					26	12		43	17					17	22	27	23					22	19
	18	28					26	13		45	18					17	20	28	25					22	18
	19	28					25	14		45	19					17	20	28	28					21	18
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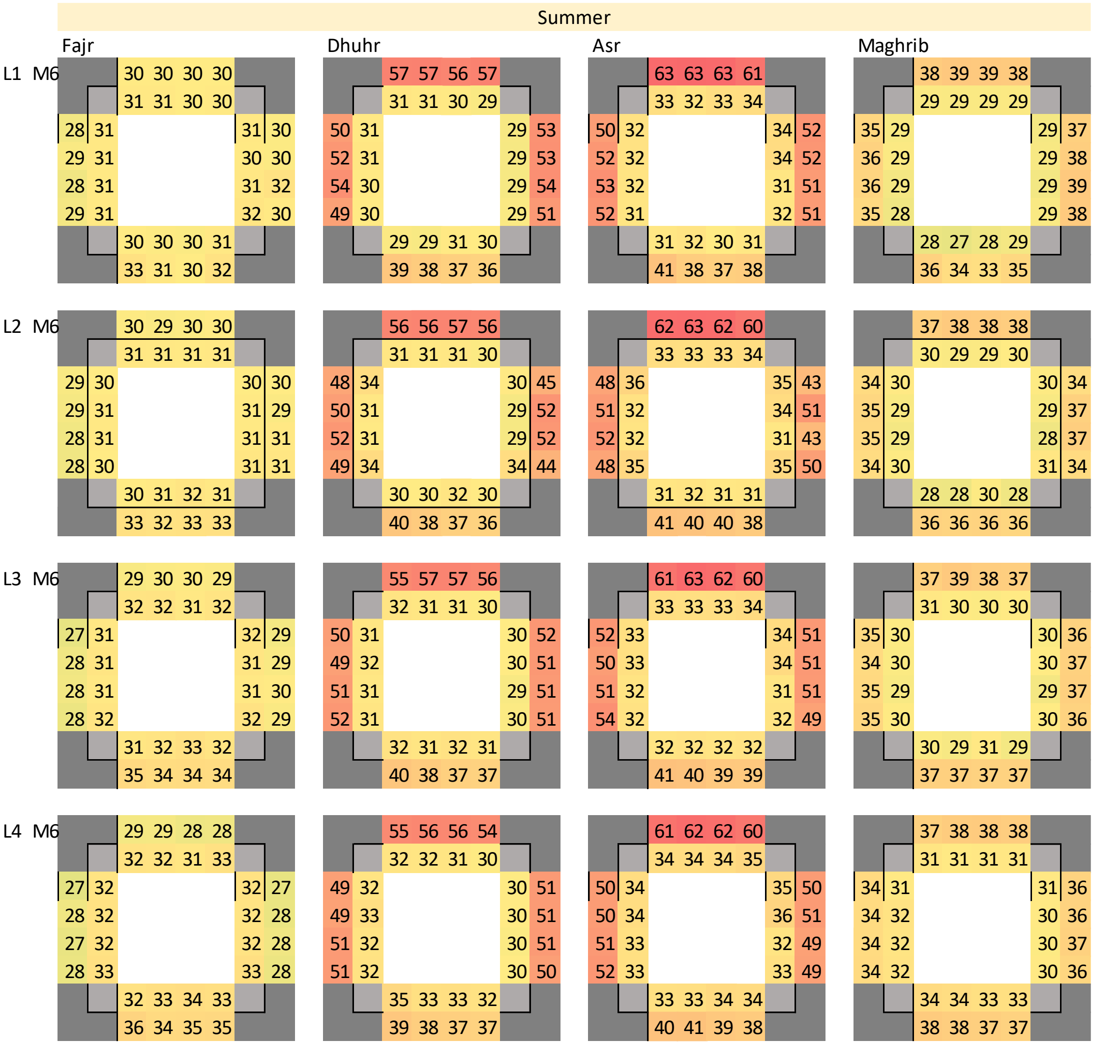
			21	21	23	23						18	19	18	17					23	23	23	22		



Summer

	Fajr								Dhuhr								Asr								Maghrib							
L1 M6			30	30	30	30					57	57	56	57					63	63	63	61					38	39	39	38		
			31	31	30	30					31	31	30	29					33	32	33	34					29	29	29	29		
	28	31					31	30	50	31					29	53	50	32					34	52	35	29					29	37
	29	31					30	30	52	31					29	53	52	32					34	52	36	29					29	38
	28	31					31	32	54	30					29	54	53	32					31	51	36	29					29	39
	29	31					32	30	49	30					29	51	52	31					32	51	35	28					29	38
			30	30	30	31					29	29	31	30					31	32	30	31					28	27	28	29		
			33	31	30	32					39	38	37	36					41	38	37	38					36	34	33	35		

	Fajr								Dhuhr								Asr								Maghrib							
L2 M6			30	29	30	30					56	56	57	56					62	63	62	60					37	38	38	38		
			31	31	31	31					31	31	31	30					33	33	33	34					30	29	29	30		
	29	30					30	30	48	34					30	45	48	36					35	43	34	30					30	34
	29	31					31	29	50	31					29	52	51	32					34	51	35	29					29	37
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	28	30					31	31	49	34					34	44	48	35					35	50	34	30					31	34
			30	31	32	31					30	30	32	30					31	32	31	31					28	28	30	28		
			33	32	33	33					40	38	37	36					41	40	40	38					36	36	36	36		

	Fajr								Dhuhr								Asr								Maghrib							
L3 M6			29	30	30	29					55	57	57	56					61	63	62	60					37	39	38	37		
			32	32	31	32					32	31	31	30					33	33	33	34					31	30	30	30		
	27	31					32	29	50	31					30	52	52	33					34	51	35	30					30	36
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	28	31					31	30	51	31					29	51	51	32					31	51	35	29					29	37
	28	32					32	29	52	31					30	51	54	32					32	49	35	30					30	36
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			35	34	34	34					40	38	37	37					41	40	39	39					37	37	37	37		

	Fajr								Dhuhr								Asr								Maghrib							
L4 M6			29	29	28	28					55	56	56	54					61	62	62	60					37	38	38	38		
			32	32	31	33					32	32	31	30					34	34	34	35					31	31	31	31		
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	27	32					32	28	51	32					30	51	51	33					32	49	34	32					30	37
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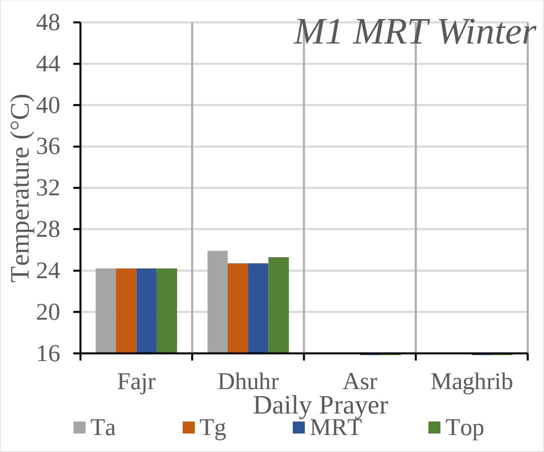
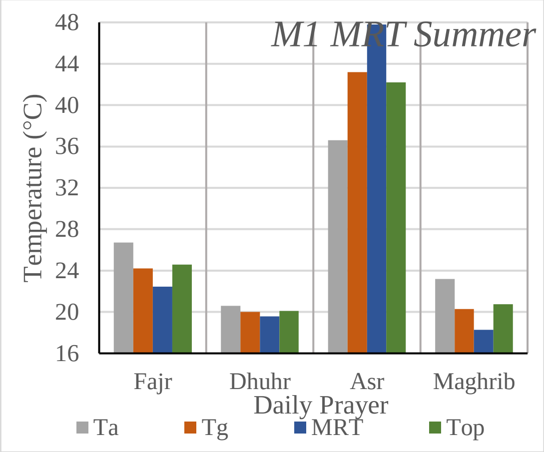
			36	34	35	35					39	38	37	37					40	41	39	38					38	38	37	37		

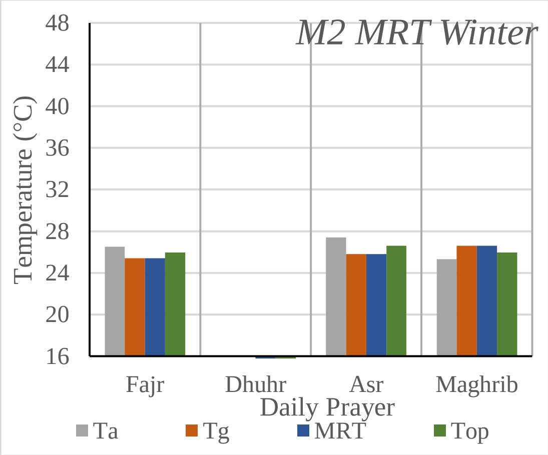
APPENDIX C: FIELD MEASUREMENTS INDOOR MEAN RADIANT TEMPERATURES FOR ALL CASE STUDIES

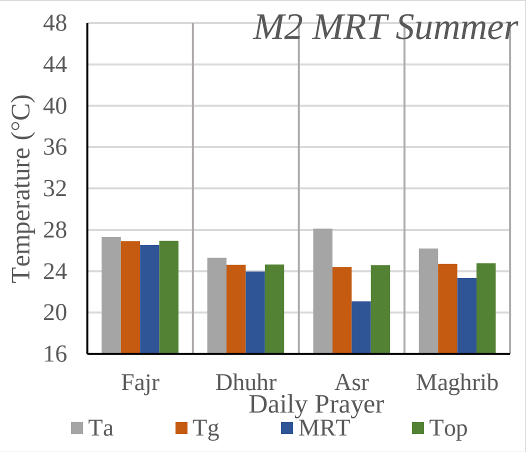
9.9.7 Hudhayfah Bin Al Yaman Mosque (M1)



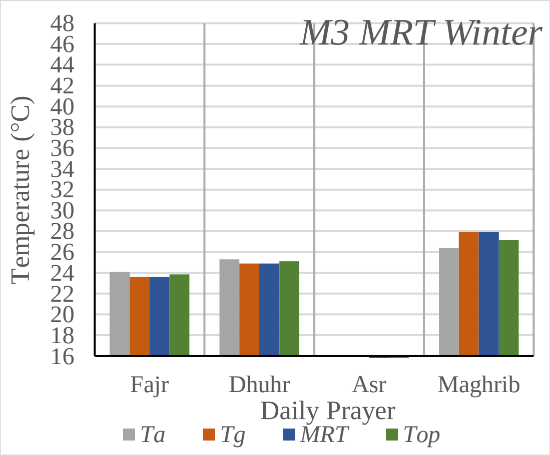


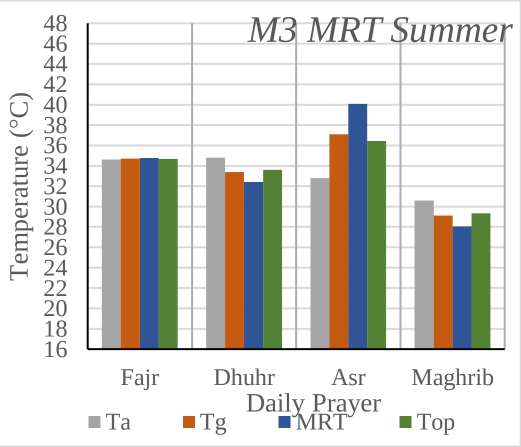
9.9.8 Abu Hamza Al Shari Mosque (M2)



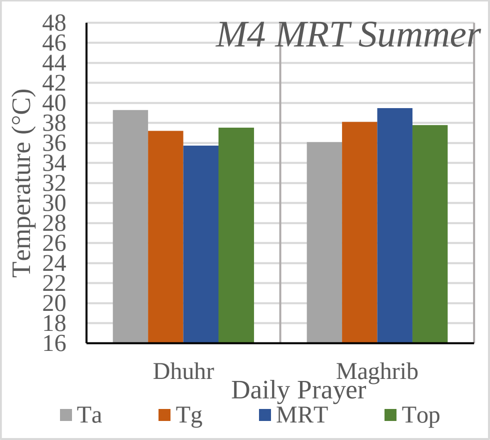


9.9.9 Othman bin Afan Mosque (M3)

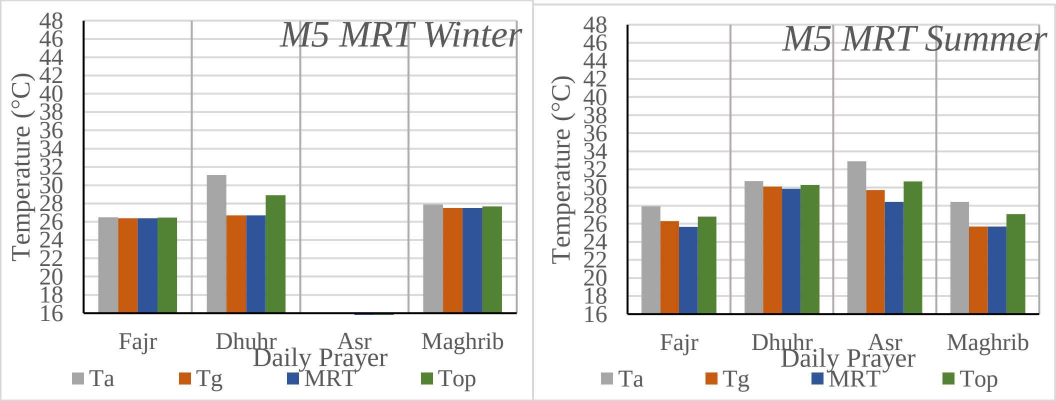




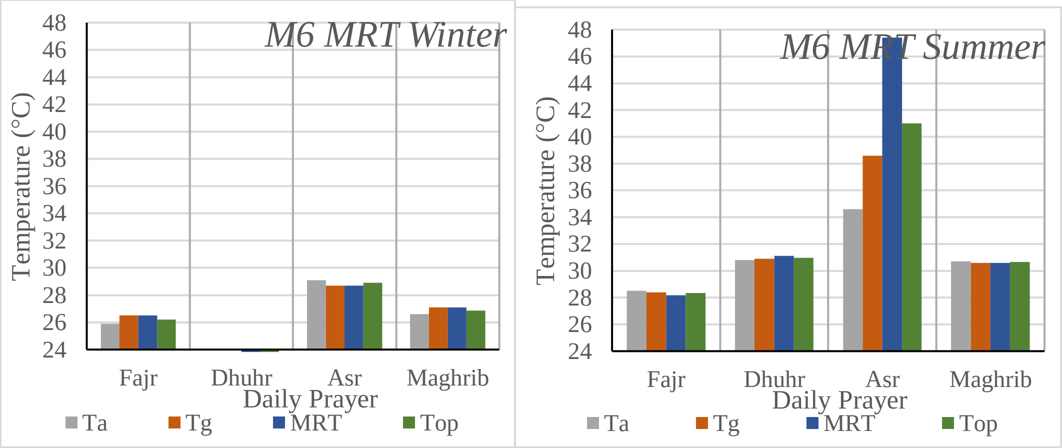
9.9.10 Sa’al Mosque (M4)



9.9.11 Al Wafi Mosque (M5)

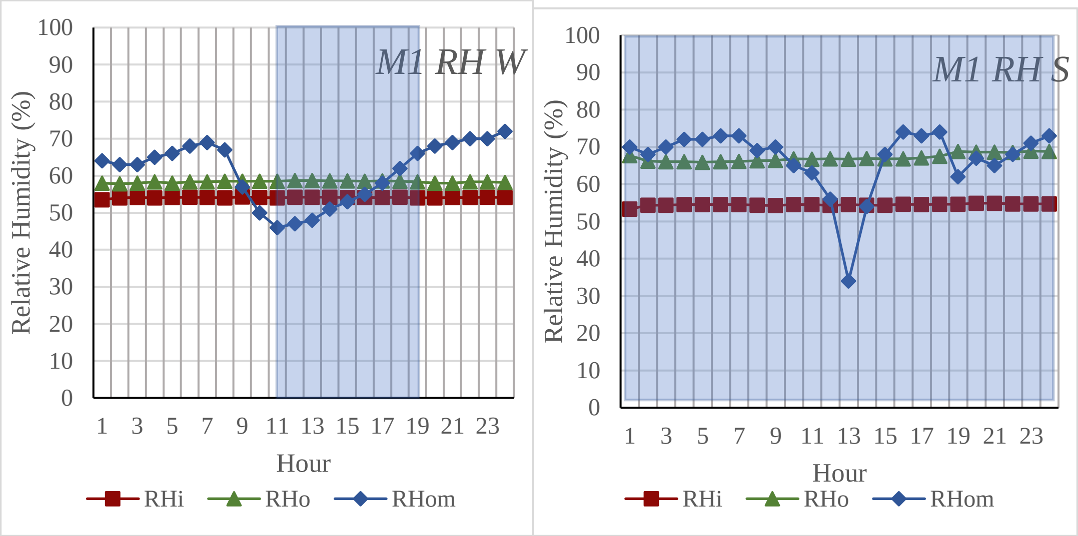


9.9.12 Aal Hamoodah Mosque (M6)

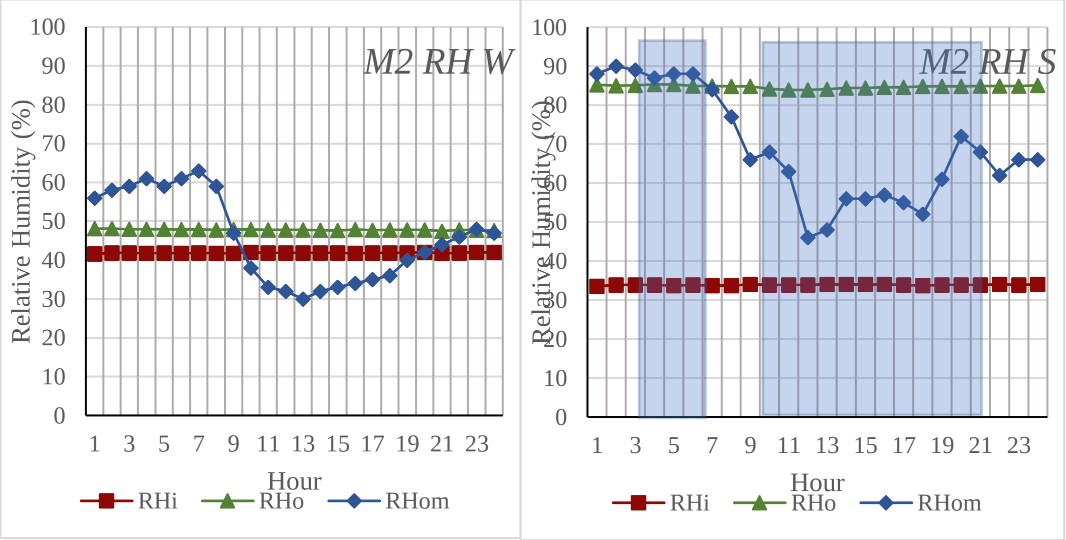


APPENDIX D: FIELD MEASUREMENT RELATIVE HUMIDITY DETAILS FOR ALL CASE STUDIES

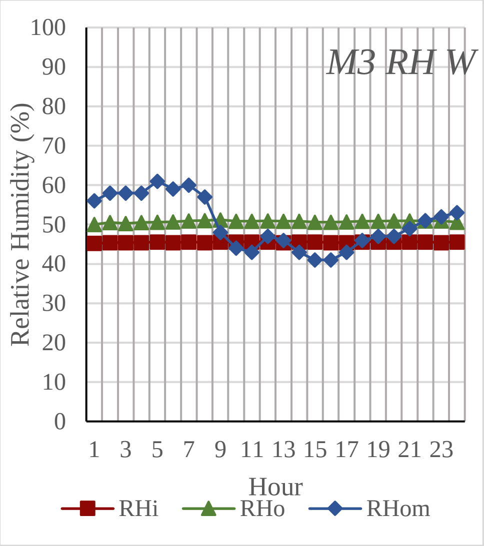
9.9.13 Hudhayfah Bin Al Yaman Mosque (M1)

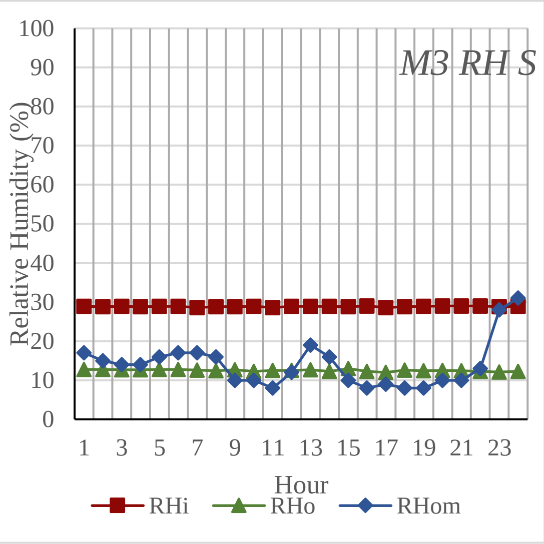


9.9.14 Abu Hamza Al Shari Mosque (M2)

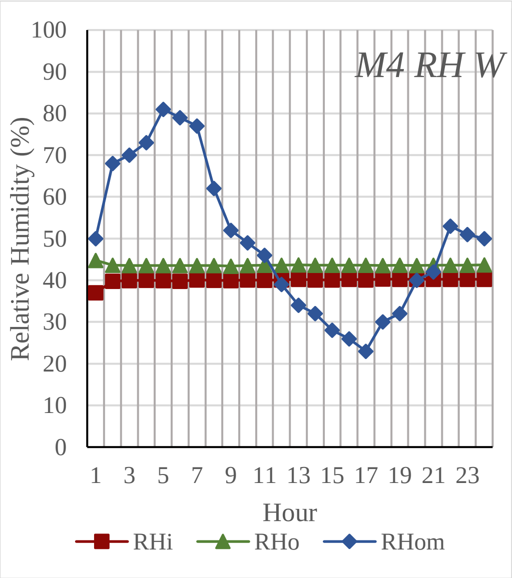


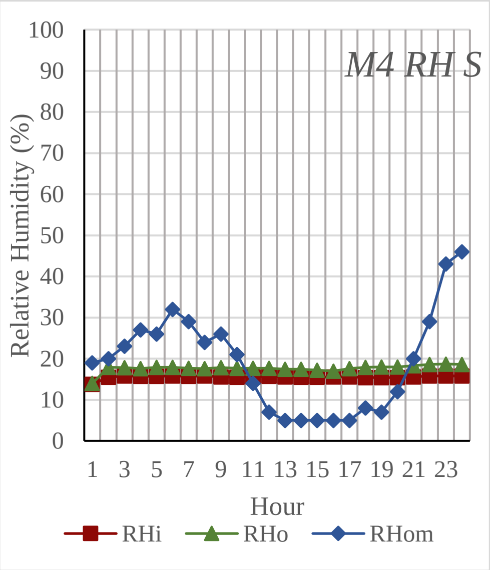
9.9.15 Othman bin Afan Mosque (M3)



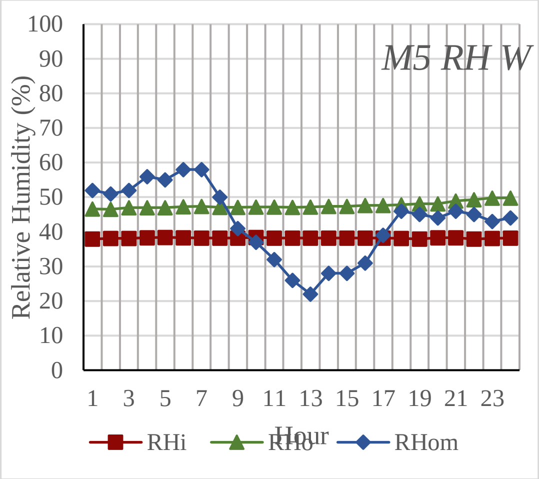


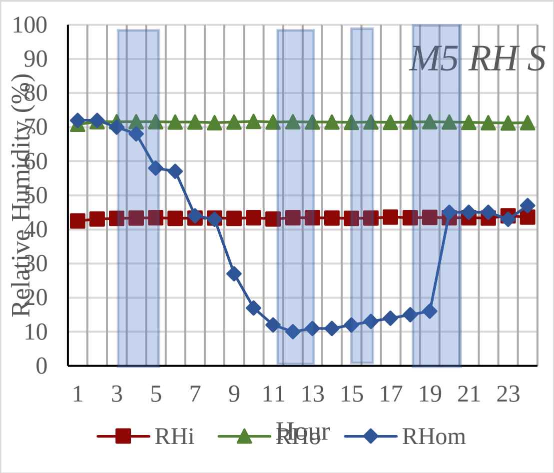
9.9.16 Sa’al Mosque (M4)



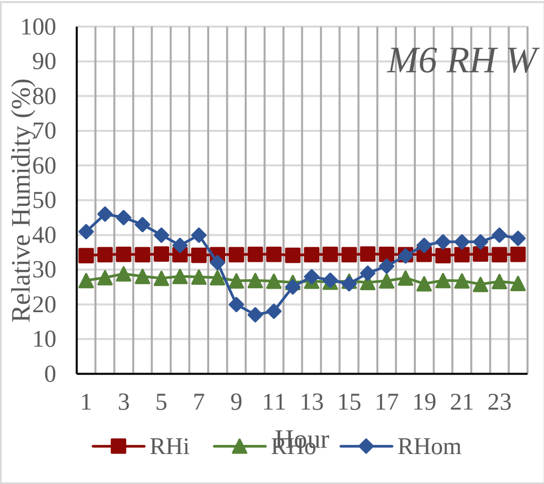


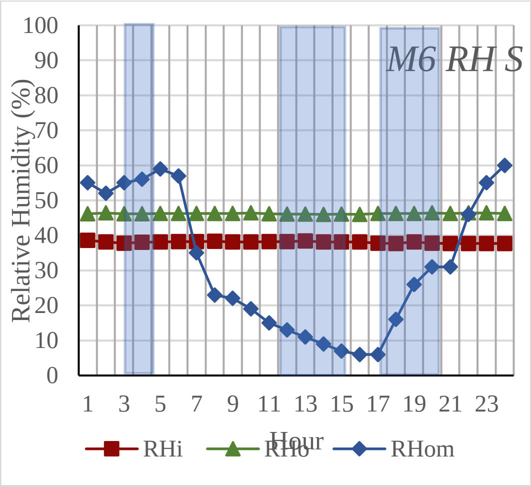
9.9.17 Al Wafi Mosque (M5)



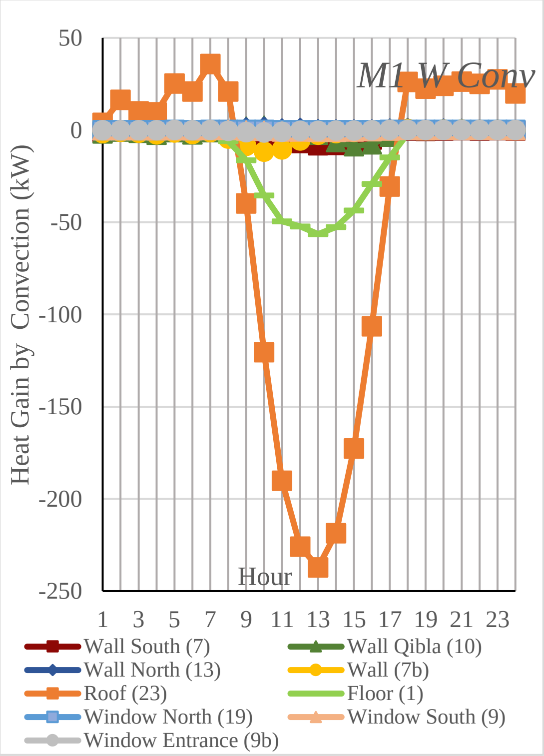


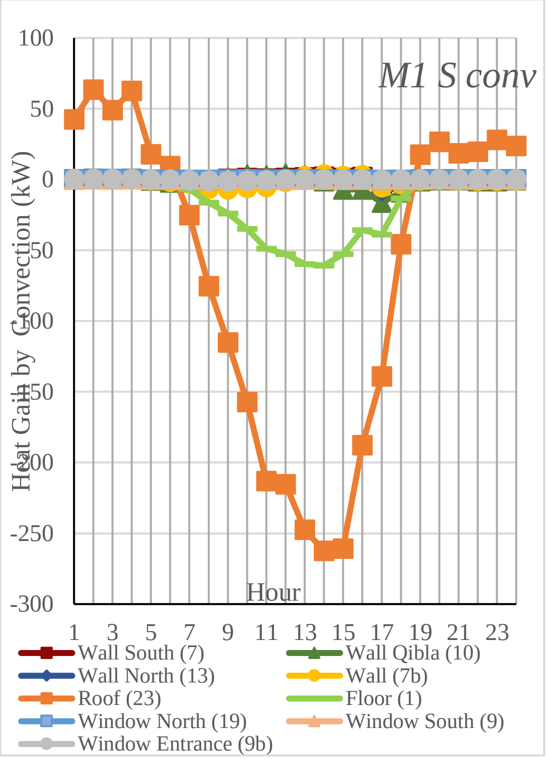
9.9.18 Aal Hamoodah Mosque (M6)

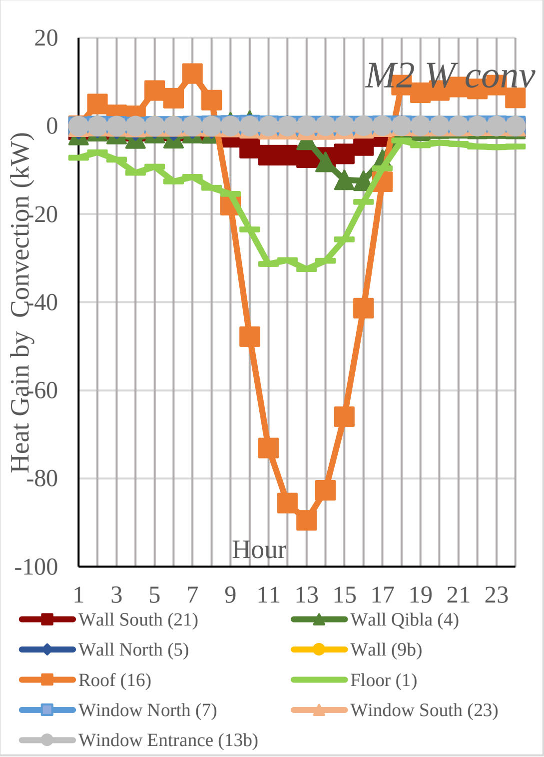


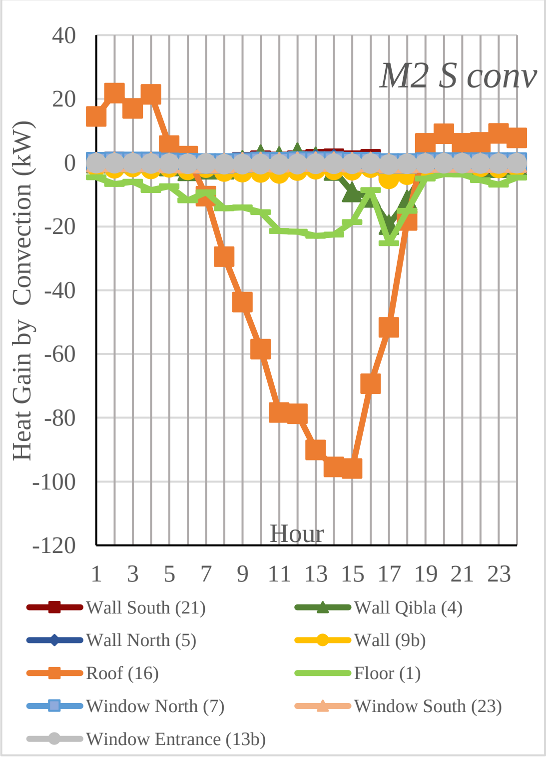


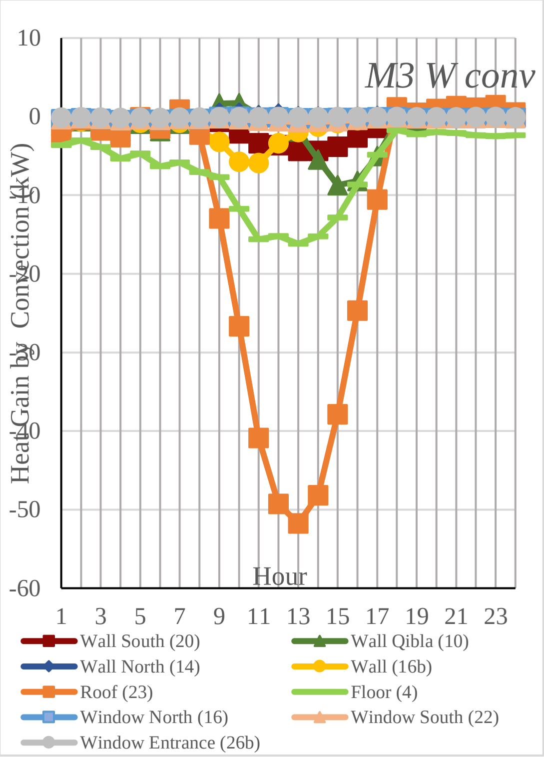
APPENDIX E: HEAT GAIN/LOSS BY CONVECTION FOR ALL CASE STUDIES

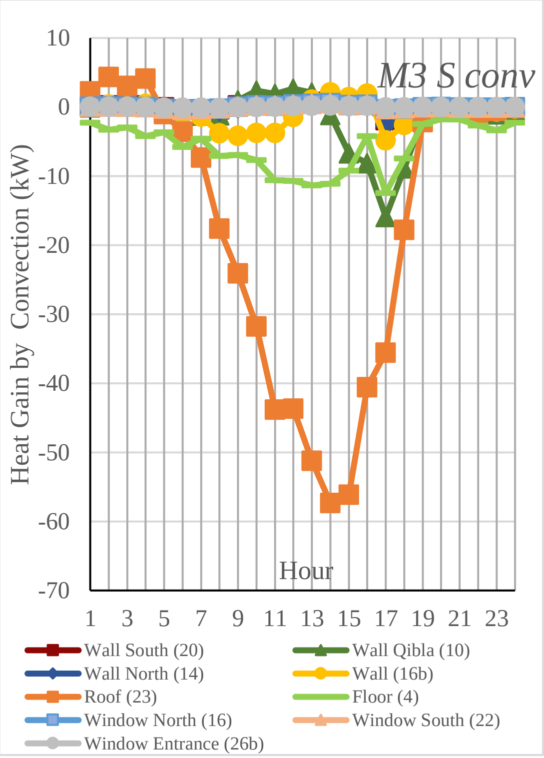


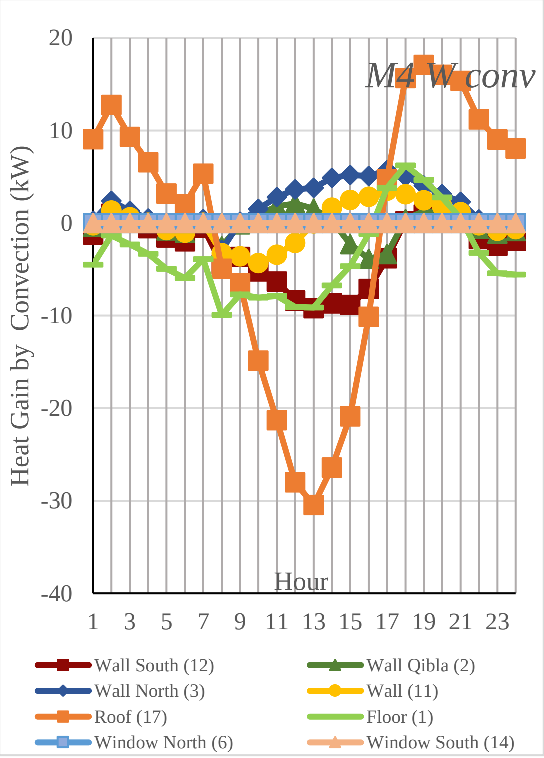


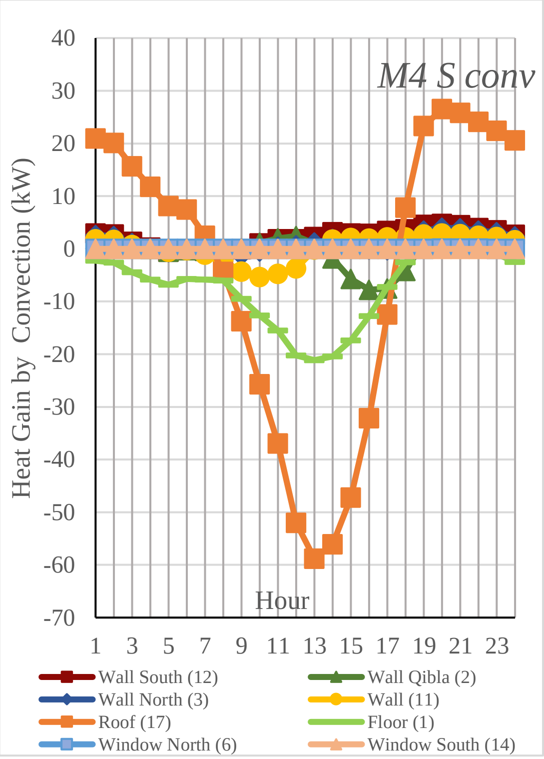


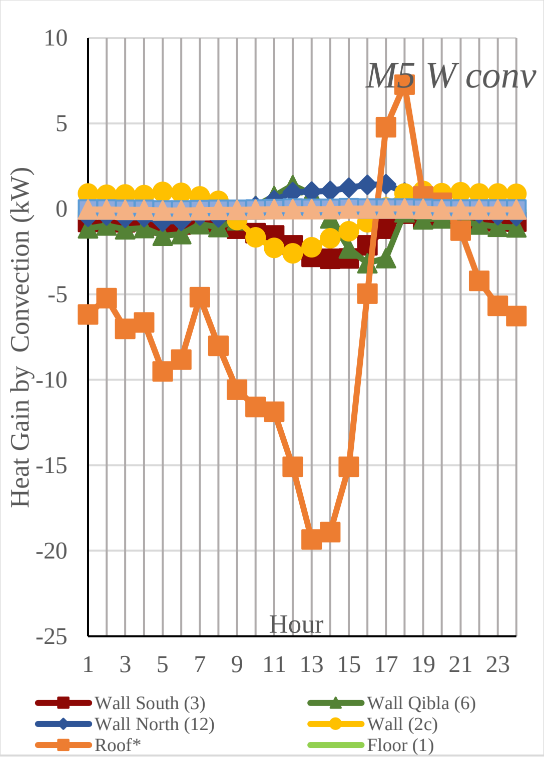


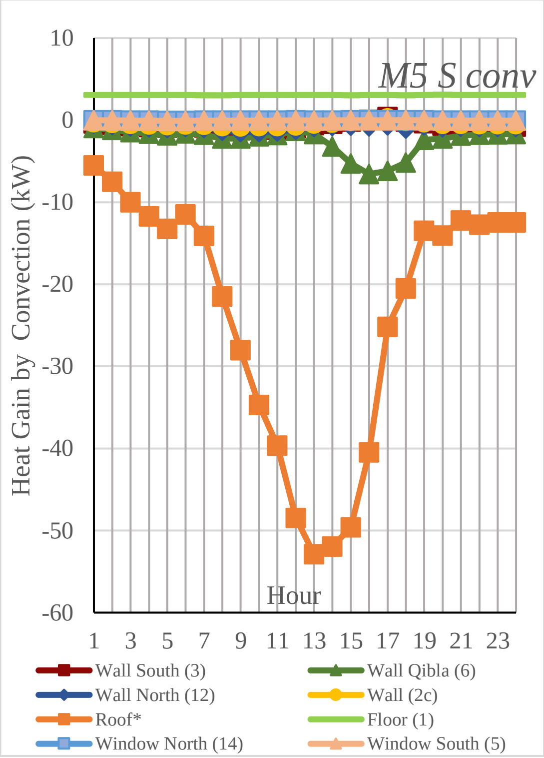

M3 W conv
Heat Gain by Convection (kW)
10
0
-10
-20
-30
-40
-50
-60
Hour
1 3 5 7 9 11 13 15 17 19 21 23
Wall South (20)
Wall Qibla (10)
Wall North (14)
Wall (16b)
Roof (23)
Floor (4)
Window North (16)
Window South (22)
Window Entrance (26b)

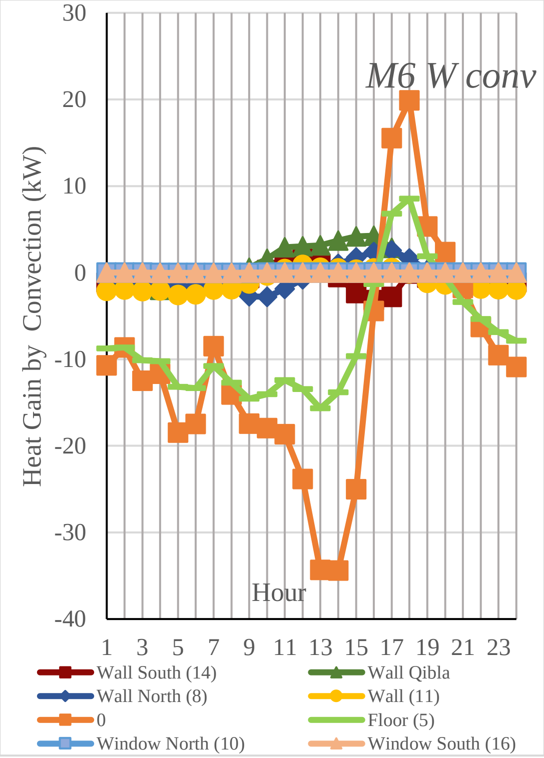

M3 S conv
Heat Gain by Convection (kW)
10
0
-10
-20
-30
-40
-50
-60
-70
Hour
1 3 5 7 9 11 13 15 17 19 21 23
Wall South (20)
Wall Qibla (10)
Wall North (14)
Wall (16b)
Roof (23)
Floor (4)
Window North (16)
Window South (22)
Window Entrance (26b)

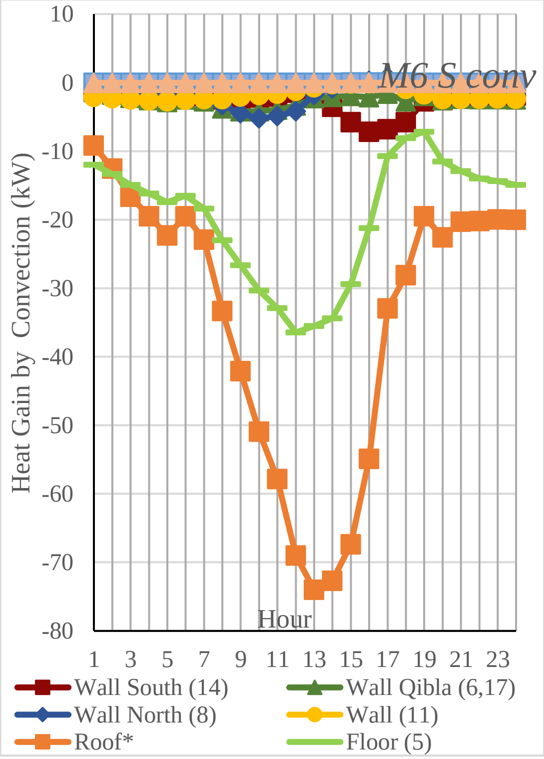

M4 W conv
Heat Gain by Convection (kW)
20
10
0
-10
-20
-30
-40
Hour
1 3 5 7 9 11 13 15 17 19 21 23
Wall South (12)
Wall Qibla (2)
Wall North (3)
Wall (11)
Roof (17)
Floor (1)
Window North (6)
Window South (14)


M4 S conv
Heat Gain by Convection (kW)
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
Hour
1 3 5 7 9 11 13 15 17 19 21 23
Wall South (12)
Wall Qibla (2)
Wall North (3)
Wall (11)
Roof (17)
Floor (1)
Window North (6)
Window South (14)


M5 W conv
Heat Gain by Convection (kW)
10
5
0
-5
-10
-15
-20
-25
Hour
1 3 5 7 9 11 13 15 17 19 21 23
Wall South (3)
Wall Qibla (6)
Wall North (12)
Wall (2c)
Roof*
Floor (1)


M5 S conv
Heat Gain by Convection (kW)
10
0
-10
-20
-30
-40
-50
-60
Hour
1 3 5 7 9 11 13 15 17 19 21 23
Wall South (3)
Wall Qibla (6)
Wall North (12)
Wall (2c)
Roof*
Floor (1)
Window North (14)
Window South (5)


M6 W conv
Heat Gain by Convection (kW)
30
20
10
0
-10
-20
-30
-40
Hour
1 3 5 7 9 11 13 15 17 19 21 23
Wall South (14)
Wall Qibla
Wall North (8)
Wall (11)
0
Floor (5)
Window North (10)
Window South (16)


M6 S conv
Heat Gain by Convection (kW)
10
0
-10
-20
-30
-40
-50
-60
-70
-80
Hour
1 3 5 7 9 11 13 15 17 19 21 23
Wall South (14)
Wall Qibla (6,17)
Wall North (8)
Wall (11)
Roof*
Floor (5)