



Faculty of Engineering

**Enhancing Thermal Comfort in Mosques of Malaysia
through Passive and Low-Energy Approach**

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**Master of Engineering
2022**

Enhancing Thermal Comfort in Mosques of Malaysia
through Passive and Low-Energy Approach

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A thesis submitted

In fulfillment of the requirements for the degree of Master of Engineering

(Building Engineering)

Faculty of Engineering
UNIVERSITI MALAYSIA SARAWAK
2022

DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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Signature



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Date : 20 August 2021

ACKNOWLEDGEMENT

In the name of Allah, the Entirely Merciful, the Especially Merciful. Alhamdulillah, I am ever so grateful to Allah SWT for providing me the opportunity and the blessings to be able to complete this research. Coming from a background of architecture, this extremely technical research has been a long and arduous journey for me. Especially during this Covid-19 times, with twin babies at home, the last couple of years has been extremely trying. But Allah has always been Al-Walee, the Best Guardian to me. His Light guided me through this phase, and I am glad to be finally completing this degree.

I would like to take this opportunity to thank all my direct and indirect supervisors who have helped me throughout my research journey. My supervisors at Universiti Malaysia Sarawak, Prof. Dr. Azhaili Baharun and Dr. Siti Halipah have always been very supportive and understanding. I would like to thank them for believing in me, trusting me, and continually encouraging me to do my best. I am indebted to Dr. Muslum Arici of Kocaeli University, Turkey, for his immense guidance regarding technical aspects of thermodynamics and for always being there to help me with any difficulties I faced in the process of learning such a complicated subject. My sincerest gratitude to Dr. Zin Kandar of Universiti Teknologi Malaysia for inspiring me and helping me formulate the research hypothesis when I began my research journey. I must also acknowledge the contribution of all my lecturers from my undergraduate years at Universiti Teknologi Malaysia who had constantly encouraged my passion for sustainable and low-energy architecture.

I would like to express my deepest gratitude to the management and administration of Universiti Malaysia Sarawak. I appreciate the support of everyone involved throughout the

period of my study, both from Faculty of Engineering and Faculty of Built Environment. I must also thank the Centre for Graduate Studies as well as UNIMAS Global for the support they have extended.

I would like to thank the most important people in my life, my family- who have helped me be who I am today. My grandmother passed away during the time of this study. She has always been there to champion me and support me when no one else did. I wish she could have seen me complete this degree; I know it would have made her immensely happy. I am grateful to my husband for being my biggest support and my most sincere advisor. This degree, or the publications, would not have been possible without his continuous support. Be it in family and household matters, or in brainstorming research-related complications, he has always been there as my most dependable partner and a best friend. I also want to thank my mother, my sister, and my brother for lending a helping hand whenever I needed it, throughout this journey.

This research is a labour of love for me. I am very passionate about passive architecture, and I wholeheartedly believe in the viability of the results of this study. I sincerely wish that the findings would benefit others, both in industry and in academia, towards promoting sustainable and low-energy buildings.

ABSTRACT

Mosques have intermittent operational schedules with short-term occupancy during the five daily prayers. The occupancy level of the daily prayers is a fraction compared to the mandatory Friday prayers with full occupancy. Yet, the same air-conditioning system is operated within the same large prayer hall to maintain the thermal comfort of the occupants. This results in high energy usage in the mosque while oftentimes the thermal comfort requirements are not met due to the short span of operation. The current research aims at employing passive and low energy design approaches in order to achieve better thermal comfort in mosques whilst maintaining energy efficiency and reduced electricity wastage. With that in view, thermal comfort is assessed and analysed holistically to ensure suitable comfort conditions are maintained during the low occupancy daily prayer times without the need for mechanical intervention. CFD simulations are carried out on a validated model of the case study building to investigate the impact of the west facing *Qiblah* wall as the congregation stands in proximity to this wall. The design alternatives are tested in conjunction with ventilation strategies to assess the thermal comfort of the occupants in terms of both the PMV-PPD and adaptive model. Results show that as much as 4-6 °C reduction in indoor wall surface temperature can be achieved with a suitable *Qiblah* wall design, which reduces the mean radiant temperature of the congregation by 2-4 °C. This significantly improves the thermal comfort of the occupants for all the prayer timings with more than a 20% reduction of PMV achieved for the afternoon and evening prayers. Calculations from both thermal comfort models suggest that suitable comfort conditions can be achieved without the need for any air-conditioning for at least two of the five daily prayers. The energy implications of such measures can be as much as 28% reduction in the yearly energy consumption of mosques. Using a passive approach towards design also shifts

the comfort temperature range by 4-7 °C which would have a tremendous impact on the energy efficiency of mosque buildings. This also opens up many research possibilities on the HVAC designing of mosques that may be addressed by future researchers.

Keywords: Mosque building, thermal comfort, passive design strategy, natural ventilation, intermittent occupancy.

Peningkatan Keselesaan Terma Pengguna Masjid di Malaysia Melalui Pendekatan Pasif dan Penggunaan Tenaga Rendah

ABSTRAK

Masjid-masjid mempunyai jadual operasi berkala dengan dengan tempoh penggunaan ruang yang pendek iaitu pada waktu solat 5 kali sehari. Tahap penggunaan ruang masjid semasa waktu solat setiap hari hanyalah satu pecahan yang kecil berbanding penggunaan ruang masjid sepenuhnya ketika Solat Jumaat. Namun pada kedua-dua waktu solat itu, sistem penyaman udara yang sama digunakan di ruang solat yang sama besar untuk mengekalkan keselesaan terma bagi jemaah. Ini mengakibatkan penggunaan tenaga yang tinggi di masjid walaupun selalunya tahap keselesaan terma tidak dapat dicapai kerana jangka waktu operasi yang singkat. Penyelidikan semasa bermatlamat untuk menggunakan pendekatan rekabentuk pasif untuk mencapai persekitaran yang selesa semasa waktu solat harian dengan jumlah jemaah yang sedikit tanpa memerlukan penglibatan penggunaan alatan mekanikal. Simulasi CFD dilakukan pada model bangunan kajian kes yang telah disahkan untuk menyelidik impak dinding Kiblat yang menghadap ke Barat kepada para jemaah yang berdiri berdekatan dengan dinding tersebut. Beberapa reka bentuk alternatif diuji dengan gabungan strategi pengudaraan untuk menilai keselesaan terma pengguna secara menyeluruh dari segi PMV-PPD dan model adaptif. Hasil kajian menunjukkan bahawa pengurangan suhu permukaan dinding dalaman sebanyak 4-6 °C dapat dicapai dengan reka bentuk dinding Kiblat yang sesuai yang dapat mengurangkan min suhu radiasi pengguna sebanyak 2-4 °C. Ini secara signifikan meningkatkan keselesaan terma jemaah sepanjang semua waktu solat dengan pengurangan PMV melebihi 20% yang dicapai untuk waktu solat tengah hari dan petang. Pengiraan daripada kedua-dua model keselesaan terma mencadangkan persekitaran yang sesuai dan selesa dapat dicapai tanpa perlu bergantung

kepada sistem penyaman udara untuk sekurang-kurangnya 2 daripada 5 waktu solat harian. Dengan menggunakan pendekatan rekabentuk pasif juga dapat mengubah julat suhu keselesaan sehingga 4-7 °C, seterusnya memberikan impak yang besar kepada kecekapan tenaga bangunan masjid. Ini juga membuka peluang untuk penyelidikan masa depan mengenai rekabentuk HVAC masjid yang akan ditangani oleh penyelidik yang akan datang.

Kata kunci: *Bangunan masjid, keselesaan terma (haba), strategi reka bentuk pasif, pengudaraan semula jadi, penggunaan berkala.*

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LIST OF ABBREVIATIONS

AC	Air-Conditioning
ACH	Air Changes per Hour
AMV	Actual Mean Vote
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BES	Building Energy Simulation
BIM	Building Information Modelling
CFD	Computational Fluid Dynamics
EUI	Energy Usage Intensity
HD	Hot-Dry
HH	Hot-Humid
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
MRT	Mean Radiant Temperature
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
TMY	Typical Meteorological Year
TSV	Thermal Sensation Vote

LIST OF SYMBOLS

C_p	Constant pressure specific heat
g_x	Gravitational acceleration in x-direction
g_y	Gravitational acceleration in y-direction
g_z	Gravitational acceleration in z-direction
k	Thermal conductivity
p	Pressure
q_v	Volumetric heat source
T	Temperature
t	Time
u	Velocity component in x-direction
v	Velocity component in y-direction
w	Velocity component in z-direction
μ	Viscosity
ρ	Density

CHAPTER 1

INTRODUCTION

1.1 Background

Mosques are establishments where Muslims gather for the five daily congregational prayers that are held at intermittent intervals throughout the day. The prayer times are determined according to the solar position and are conducted at the break of dawn (*Fajr* prayer), after midday (*Dhuhr* prayer), late afternoon (*Asr* prayer), immediately after sunset (*Maghrib* prayer), and beginning part of the night (*Isha* prayer). Additionally, there is a weekly *Jumuah* prayer accompanied by a sermon which is held instead of the *Dhuhr* prayer on Friday. The occupancy level of the mosque is the highest during the *Jumuah* prayers, as it is mandatory to be prayed in congregation, while the daily prayers usually have a much smaller number of congregants (Azmi & Kandar, 2019). Mosques are designed as a large, multi-volume, single-space hall to accommodate for the maximum occupancy during *Jumuah* prayer time. Typically, the main prayer hall is of a square or rectangular plan and is positioned perpendicular to the *Qiblah* axis, which is the direction towards the *Kaa'bah* in Makkah. This facilitates even and equal rows as prayers are held in ranks facing towards the *Qiblah* wall. Each prayer and the accompanying rituals span over a 30-45 min period and the mosques remain empty in between the prayer times. The thermal comfort is of great importance to cater for a suitable ambience during the prayers. In order to maintain indoor thermal comfort during prayer times, most modern mosques employ mechanical means of heating, ventilation and air conditioning (HVAC) systems (Azmi et al., 2021).

The operational timing of the HVAC systems follows the occupancy profile whereby it is switched on before each prayer and switched off once the prayers are over (Al-Homoud

et al., 2005a). Typically, mosques utilize the same prayer space and operate the same HVAC system during both high and low occupancy prayer times (Abdou et al., 2002). Maintaining the comfort conditions for such a large space at intermittent intervals becomes energy intensive. Energy audits in both hot-dry (HD) and hot-humid (HH) climates have shown that mosques have a similar energy usage as that of offices, educational facilities or commercial spaces for the same climate (Azmi et al., 2021). For Saudi Arabia the average energy usage intensity (EUI) has been found to be around 170 kWh/m².year (Abdou et al., 2005) while for Malaysia it is around 150 kWh/m².year (Hussin et al., 2018b), which is similar to the average non-residential buildings of each country, respectively. Contrary to other non-residential building types where the HVAC system uses 50-60% of the total consumed energy (Saidur, 2009), about 90% is used for HVAC purposes in mosques (Al-Homoud et al., 2005b). However, the overall operation timing of mosques is less than half of other such buildings (Azmi et al., 2021), and regular occupancy is estimated at 10-20% of the capacity (Azmi & Kandar, 2019). Thus, for the purpose of attaining thermal comfort, mosques have a high EUI per unit area as well as high energy usage per capita. Additionally, due to the shorter occupancy timings, mosques have high hourly energy requirements when it is in operation (Abdou et al., 2005). Yet, in spite of the high energy usage, a lot of mosques were found to reach comfort conditions only during *Fajr* and *Isha* prayers, which means thermal comfort conditions were not met during the daytime prayers (Al-Homoud et al., 2009). With the intermittent and varying occupancy schedule coupled with a functional requirement of a large prayer hall, it becomes difficult to design for optimum thermal comfort while maintaining energy efficiency in mosques (Azmi & Kandar, 2019).

Mosques are buildings with user-centric activities and thus, termed as external-load or skin-load dominated buildings. For such buildings, the internal thermal load is mostly

dictated by the design features which are influenced by the outside climate, such as the orientation, surroundings, building envelope etc. (Al-Homoud, 2005). Therefore, the optimal thermal performance of the building is of paramount importance in maintaining the thermal comfort of the occupants as well as the energy efficiency of the building (Azmi & Ibrahim, 2020). Research regarding thermal comfort in mosques is a relatively new field and not many studies have been conducted. There are numerical analyses that have addressed architectural styles (Asfour, 2009), building form (Mushtaha and Helmy, 2017) or individual building elements like the roof (Ibrahim et al., 2014), walls (Hameed, 2011), and propose design alternatives for better thermal comfort conditions. Others have optimized building envelope thermal design (Budaiwi, 2011) or proposed retrofits to existing mosques (Budaiwi et al., 2013) with the aim of lowering thermal loads. Field experiments have shown that the existing thermal comfort scales might not be suitable for the occupancy type of mosque buildings (Al-ajmi, 2010) and suitable adaptive scales may need to be developed to measure thermal comfort for intermittent occupancy schedules (Calis et al., 2015, Hussin et al., 2015). There has also been research that addresses HVAC system efficiency (Al Anzi and Al-Shammeri, 2010), improvements in operation strategies (Samiuddin, 2014), or thermal zoning for such systems (Al-Shaalan et al., 2017, Al-Tamimi et al., 2020). Most findings from these studies indicate that only when design parameters and operational schedules of the mosque building are optimized, acceptable thermal comfort levels can be achieved while also allowing for reduced energy usage.

Optimizing the HVAC parameters is aimed at reducing energy consumption while passive design strategies can reduce the thermal load and overall energy requirements of the building. Various research of other building types have shown that adopting passive building technologies through suitable materials, shading, orientation as well as natural ventilation

strategies through wind towers, cross ventilation or solar chimneys can reduce the building energy requirements by 30-50% (Sadineni et al., 2011). Focusing on the passive strategies of the building design can also help improve thermal comfort conditions at no added energy expenditure (Toe and Kubota, 2015). Since the mosque remains empty during most of the day, and the occupancy for daily prayers is very minimal, aiming for passive means of thermal comfort during the low occupancy periods can be a sustainable and low-energy alternative. Addressing the building thermal performance through design optimization also lowers the thermal loads gained from the outside environment. This can help reduce the energy consumption for the HVAC systems when it is necessary to be utilized during high occupancy periods. Through parametric studies of the critical design components, optimum design variables can be determined that can improve the building thermal performance and help maintain the thermal comfort of the occupants whilst ensuring energy efficiency. Thus, establishing appropriate design guidelines through extensive research and comparison with existing standards is important in order to lay the foundations of a sustainable approach towards mosque designing.

1.2 Problem Statement

The thermal comfort requirements of the occupants, the thermal performance of a building, and its impact on the HVAC usage pattern are largely dependent on the climatic conditions of a region. Most of the relevant research found pertaining to the mosque building typology have been carried out in countries with HD or temperate climates, such as Egypt (Abdallah, 2016), Kuwait (Al Anzi and Al-Shammeri, 2010), Iraq (Hameed, 2011), Saudi Arabia (Alabdullatief et al., 2016), UAE (Mushtaha and Helmy, 2017), Turkey (Atmaca and Gedik, 2019). Therefore, the findings from these studies may not be applicable for the HH climates of Malaysia where the high humidity factor significantly impacts the thermal

comfort conditions. Although there have been multiple studies on thermal comfort for other building typologies in Malaysia such as hospitals (Yau and Chew, 2009), residences (Nugroho et al., 2007), offices (Damiani et al., 2016), the occupancy pattern and functional characteristics of mosque buildings vary widely from other building types. As such, there is a need for similar research for mosque buildings in the context of Malaysia. Malaysia is situated near the equator and has a year-round hot weather, coupled with high daily and annual solar radiation. Thus, the building envelope components such as the roof, walls and windows, always remain exposed to the direct solar rays for long hours and transmit this heat to the interior. Proper thermal designing of the envelope components ensures better thermal performance of the building, whereby less heat is introduced to the interior. This lowers the thermal gain from the outside climate and keeps the ambient indoor temperature lower. Thus, increased thermal comfort conditions can be maintained for the occupants in addition to less need for mechanical interventions for cooling.

Even though the roof is exposed to the direct solar rays for long hours, high ceilings create a buffer zone as air is a bad conductor of heat, protecting the occupant-level height from direct heat exposure (Engineering Toolbox, 2021). Walls, on the other hand, have shown to greatly impact thermal comfort as the transmitted heat reaches the occupants who are at proximity (Guo et al., 2020). In the context of Malaysia, the direction of prayers (*Qiblah*) is the north-west 292° , towards which the congregants face for prayers. Even during low occupancy timings, congregants will gather very near to this portion since this is the front part of the mosque. The north-west *Qiblah* wall is susceptible to heat gains from the afternoon sun and can negatively impact the thermal comfort of the occupants during prayer times. Thus, proper thermal designing of the *Qiblah* wall with suitable parameters is of utmost importance to maintain thermal comfort. Since experiments at a real scale building

for different design variations are improbable due to the time and cost involved, simulation studies can serve to be a suitable alternative towards deciding optimum design configurations. By conducting parametric studies on the *Qiblah* wall design and construction variables, suitable design parameters can be established that allow for improved performance of the building thermal envelope which contributes to enhanced comfort conditions. On one hand, it will enable better thermal comfort conditions for the occupants as there will be less radiant and conductive heat gain through the wall, ensuring that the areas adjacent to the wall will have lower temperature levels. On the other hand, lower cooling loads due to less heat gain through the envelope will result in a lower capacity requirement for the HVAC, as well as shorter operation timings, which can help achieve energy efficiency in mosques.

1.3 Aims and Objectives

This research aims to propose passive and low energy design approaches that can be applied to new constructions as well as adapted to existing mosques in order to achieve better thermal comfort in mosques whilst maintaining energy efficiency and reduced electricity wastage. To fulfil this aim, the research objectives are as follows:

- i) To identify the relation between mosque thermal comfort requirements and energy usage pattern through energy audit of case study mosque.
- ii) To evaluate the current thermal comfort conditions and the viability of natural ventilation during low occupancy periods in order to reduce energy usage by HVAC.
- iii) To numerically analyse the influence of the design of the *Qiblah* wall in influencing the thermal comfort of the occupants in Malaysian mosques.

iv) To propose architectural design solutions for the *Qiblah* wall in conjunction with ventilation strategies that allow for optimum thermal comfort.

1.4 Scopes and Limitations

This research will investigate different designs for *Qiblah* wall parameters with the aim of proposing optimum design parameters. The variables will be set in terms of wall structure, construction details, and materials properties that are common practice in the construction industry in Malaysia. In doing the simulations, different alternative design options will be set up for the base case of the existing case study mosque. The scopes and limitations of the research are as follows:

- The research will be carried out in the context of Malaysia where the HH climate is characterized by its high humidity along with high temperatures. By definition, results in an optimization study are applicable given similar resources, situation and constraints set in the assumptions. In building engineering studies, the contextual backdrop of the climate and geo-location are important variables in the analysis. Hence, the optimum solution of this study is limited to the context of the locations with similar climatic factors and with the *Qiblah* direction situated at the west. However, the scope can be extended to other countries and HD climates with necessary modifications.
- The scope of this study is limited to medium-sized mosques that conduct both the daily and Friday prayers. Large monumental-scale mosques or small mosques accommodating only the daily prayers are beyond the scope of this research.
- For this study, the variables in parameters of the wall are selected based on technical and structural feasibility. Hence, the parameters are studied not as a continuous

variable, but as discrete points which aligns with the common industrial practices in Malaysia. Therefore, only specific realistic design solutions for walls are studied in this analysis.

- This research will study the building as a whole system and the consequent impact of the built environment on the thermal comfort of the occupants. Thus, it does not limit itself to calculating only the heat transfer through the wall or simulating the thermal gain through the *Qiblah* wall. Although that is the variable to be studied and optimized, the whole building will be considered to simulate the thermal comfort conditions.
- As an objective standard towards optimization, the research will evaluate the thermal comfort of the occupants. The overall thermal load of the building or the energy usage of the HVAC will not be taken into consideration. Although the energy efficiency of the HVAC system is an important element of sustainable building designing, such systems are applicable for active thermal regulation. However, this study will focus on the passive design strategies which will enhance thermal comfort while concurrently lowering the necessity of active thermal control interventions.
- The research has its limitations due to employing computer-based numerical software in predicting thermal comfort as a steady-state model. However, limitations due to incorrect input parameters and simulations settings will be minimized through verification and validation of the results.

1.5 Significance of Research

According to the 2020 year-ending statistics of Malaysian government (JAKIM, 2019), there are a total of 24,722 mosques in Malaysia. Of them, 7,160 are termed as *Masjid*,

where both the daily and Friday prayers are held, while the remaining 17,562 are known as *Surau*, which are smaller in size and only accommodate the daily prayers. Majority of the mosques have been found to be air-conditioned in order to maintain the thermal comfort of the occupants (Eusof et al., 2015). Through optimizing the thermal performance of mosque buildings using passive design strategies, better thermal comfort conditions can be ensured. Moreover, since improved thermal performance reduces the thermal load gained through the building envelope, it will also allow for reduced energy consumption for the HVAC systems in the mosques. As there are many mosques in Malaysia, such an impact will allow for huge energy savings that will be both environmentally sustainable and financially feasible. A similar methodology of this research can also be carried out for other building components such as the roof or windows to optimize those design parameters as well. Such validated research can help establish comprehensive design guidelines which will help architects and engineers design more sustainable and energy efficient mosques. Additionally, such findings may also be replicated for other locations and climate types, through relevant research and necessary modifications. As of 2019, there are over 4 million mosques in the world (Deloitte, 2019), the majority of which are located in the HD or HH countries (Azmi & Kandar, 2019). Thus, the energy saving implications of this research, both monetarily as well as environmentally, can be immense.

1.6 Organisation of the Thesis

This thesis constitutes five chapters in total. This chapter covers the background for the research and identifies the problem statement. The objectives and scopes of study are also presented along with the significance of the research.

Chapter 2 reviews and discusses existing literature with a view to establishing a basis for this current research. The chapter provides a brief discourse on the factors influencing

human thermal comfort as well as the established models to assess and enhance comfort conditions. Thereafter, thermal comfort conditions in mosque buildings, and the consequential usage of energy are discussed. This chapter also highlights the relevant studies done in Malaysia and concludes with a summary that illustrates the research gaps.

In Chapter 3, the methodology carried out for this study is presented in detail. It includes initial study decisions, data collection procedures, and the development of the numerical model. It also includes the various details for the numerical simulation such as governing equations, boundary conditions, solver codes, and validation methods. The variables and options set for this parametric study are also illustrated in this chapter as well as the justification for such decisions.

Chapter 4 presents and analyses the results from the field measurements and software simulations. This chapter includes, in detail, the results for each of the alternative designs studied for the parametric analysis. The results are presented in the form of diagrams and graphs, while explanations are provided for such results. Commentary has also been made with regards to the effect of different design variables on the thermal comfort levels. Additionally, it discusses the implications of such findings in terms of energy saving potential.

Chapter 5 concludes and summarizes the research by mentioning the significant findings with respect to the objectives posed at the beginning of the study. The contributions of this research are highlighted, both in the context of academia as well as the industry. Besides, several recommendations for practical applications and probable future research scopes are also provided.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A thorough and in-depth literature review was carried out on the thermal comfort and energy efficiency of mosque buildings to identify the research gaps in this area. The available research included peer-reviewed, indexed articles from journals and conference proceedings as well as theses and reports from the institutional repositories of various universities. Subsequently, other literature were also consulted in order to get a thorough understanding of the concepts of thermal comfort, thermal performance, and energy efficiency. Additionally, literature related to the objectives and scope of this research in addition to resources on the applicability of different simulation softwares were also consulted throughout the period of this study. This section begins with a general overview of human thermal comfort discussing the contributing factors, assessment criteria, and enhancement of comfort conditions. Thereafter, the findings regarding thermal comfort, energy usage, and thermal performance of mosque buildings are presented. Furthermore, research and findings regarding mosques in the context of Malaysia are discussed elaborately. This chapter concludes with a summary by identifying the research gaps and highlighting the need for this research.

2.2 Human Thermal Comfort

The human body maintains an energy balance with its immediate environment through the thermoregulation process (Guyton and Hall, 2015). Thermoregulation of the human body is generally achieved through four types of heat transfer mechanisms- conduction, convection, radiation and evaporation (Cheng et al., 2012). These heat transfer

methods of the body are balanced against the metabolic rate of the occupant to achieve an energy balance (Gao et al., 2007). If the heat entering into the body from the environment is greater than the heat exiting the body, then the occupant will feel warm or hot. On the contrary, if the heat entering into the body from the environment is lesser than the heat exiting the body then the thermal perception of the occupant will be in the range of cool to cold. Thermal comfort is achieved when the thermal sensation of the human body achieved through thermoregulation is neither hot nor cold and the person is comfortable with their surroundings. In literature, it is defined as ‘that condition of mind that expresses satisfaction with the thermal environment’ (ASHRAE, 2013). Both personal and environmental factors affect the thermoregulation mechanisms and the subsequent attainment of human thermal comfort. Six factors influence thermal comfort- metabolic rate, clothing insulation, air temperature, relative humidity, air speed and mean radiant temperature. Of these, the first two are personal or subjective factors while the remaining four are environmental or objective factors. Additionally, cultural norms and psychological factors also vastly impact human thermal comfort (Zhao et al., 2020). Moreover, behavioural adjustments, as well as long-term adaptations or physiological acclimatization due to habituation with the prevalent weather also influence the thermal perception of a person (Brager and De Dear, 1998). Figure 2.1 shows how the variation in these factors can impact the energy balance in a human body and thus, provide a thermal sensation that is cooler or warmer.

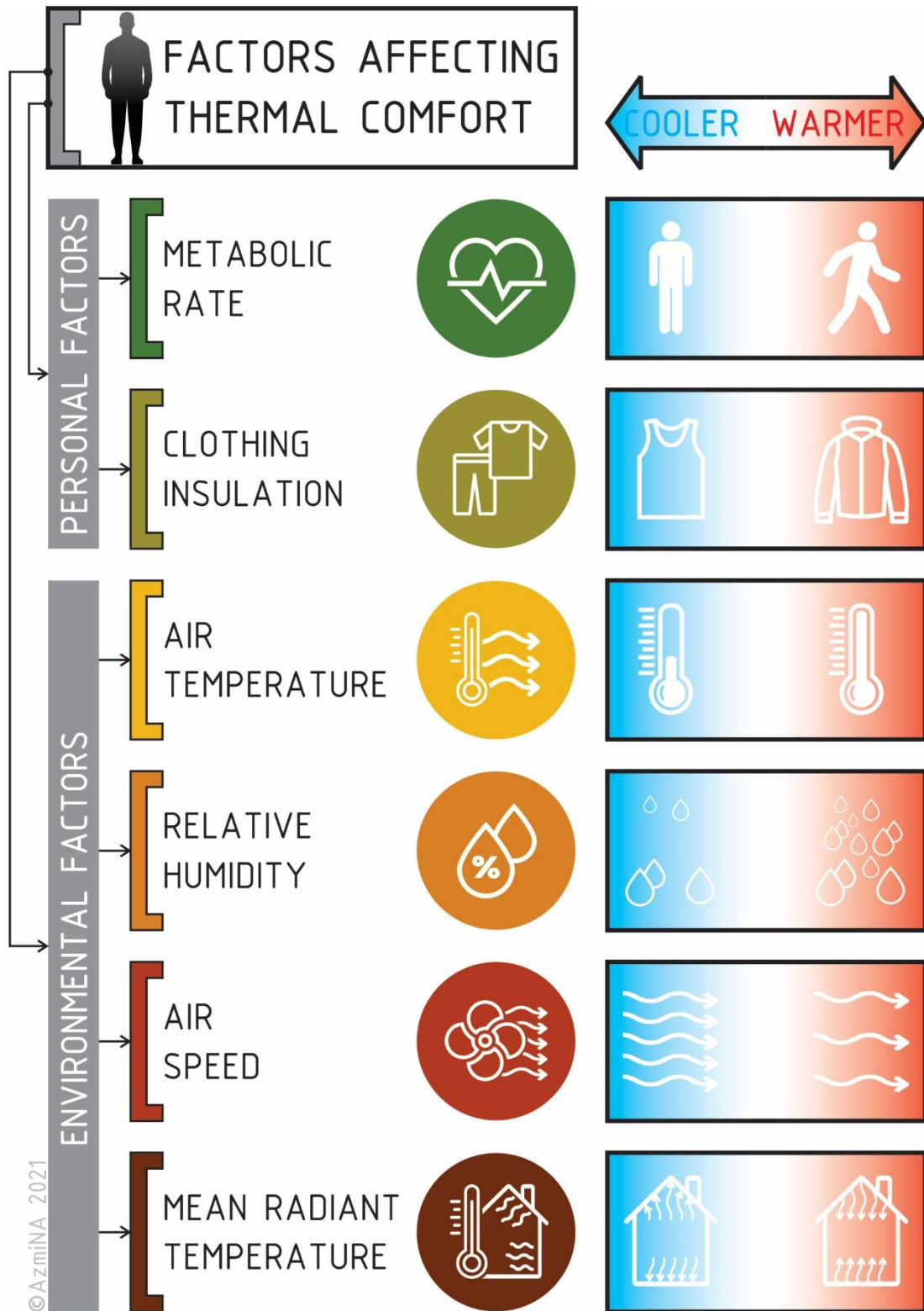


Figure 2.1: Factors affecting human thermal comfort.

2.2.1 Assessing Thermal Comfort

Energy balance equations draw a relation between the heat coming into the body and the heat exiting the body in order to quantify the combined influence of the environmental and personal factors of thermal comfort (Fiala et al., 1999). There have been many such thermal comfort models standardized in literature that helps assess the thermal comfort levels or thermal perceptions of the occupants. What differentiates one model from the other is the calculation of the relative weightage of each contributing factor and how the energy equation is balanced. The most widely used thermal comfort model is the PMV-PPD model developed by PO Fanger (Fanger and Toftum, 2002). The model uses an energy equation to determine the predicted mean vote (PMV) of the occupants' thermal sensations for a given set of conditions. Consequently, a predicted percentage dissatisfied (PPD), derived from the PMV values, indicates the percentage of people who would be dissatisfied under such conditions (Figure 2.2). The PMV is expressed as a continuous variable that ranges from -3 to +3. The perfect energy balance is at 0, where the occupants are thermally neutral. A positive value indicates more energy is entering the body than exiting, and thus, the occupant will feel warm to hot. On the contrary, a negative value indicates more energy is being lost to the environment from the body inducing a feeling of cool or cold. The acceptable range of PMV values is between -0.5 to +0.5 which has a corresponding level of PPD of 10%, indicating that 90% of the occupants ought to feel comfortable under existing conditions. The neutral temperature values for thermal comfort conditions are also calculated from the -0.5 to +0.5 PMV range.

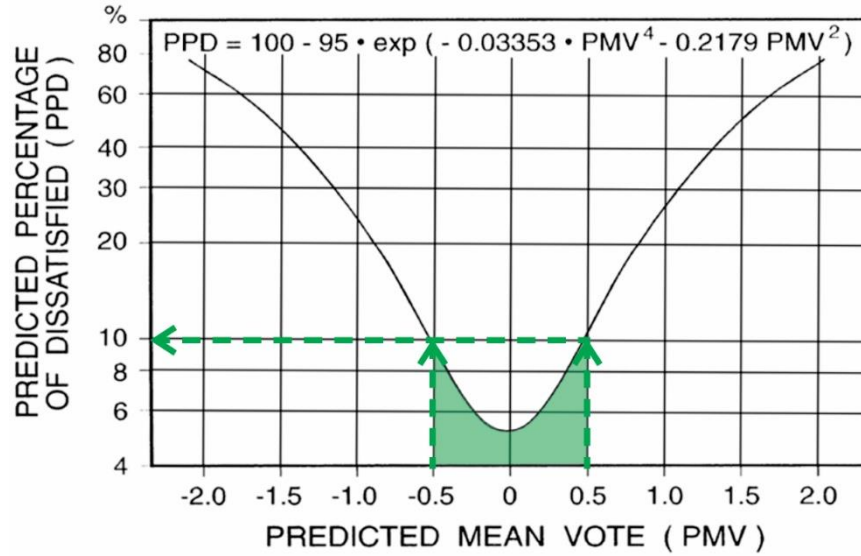


Figure 2.2: Relation between PMV and PPD (ASHRAE, 2017a).

The PMV model is a steady-state heat balance equation that has been established through empirical studies under controlled laboratory conditions. However, researchers have found that in real-life circumstances, the results and findings may not be at par with the theoretical calculations (Humphreys and Nicol, 2002). Actual mean votes (AMV) or thermal sensation votes (TSV) from surveys have shown that there is a discrepancy between the values from PMV-PPD calculations compared to the thermal comfort as reported by the occupants (Cheung et al., 2019). This implies that while calculations may predict people will feel hot or cold, in actual reality the occupants are acclimatized to the existing weather conditions and express satisfaction with the circumstances. Especially in the context of hot climates, PMV commonly overestimates the thermal sensation of the subjects (Nicol, 2004). Thus, even when the positive PMV values indicate discomfort due to high temperatures above the recommended levels, people from hot climates may still feel comfortable with their surroundings at that temperature due to their higher tolerance level (Prianto and Depecker, 2003). Thermal comfort surveys have found that the comfort temperature range can be as much as 3°C higher for occupants in hot climates (Nicol, 2004). Thus, for such

climates, the recommended comfort temperature levels derived through the PMV model may be misleading, often resulting in excessive HVAC usage and consequential energy wastage. Despite much debate involving the PMV-PPD model, it is still commonly used in the research field due to its scientific and definitive nature. It has also been accepted in the ASHRAE 55 standard (ASHRAE, 2013) published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as well as the ISO 7730 standards (ISO Standards, 2005) published by the International Organization for Standardization.

In order to minimize the discrepancies between actual findings from surveys and results from theoretical calculations, researchers recommend using the adaptive thermal comfort model (Nicol and Humphreys, 2002). This model is calculated based on the operative temperature and has been established from field survey data gathered throughout the world for different climatic conditions (Figure 2.3). Thus, it takes into consideration the adaptation measures by people and the physiological acclimatization due to prevalent outdoor conditions. The PMV model shows the highest amount of deviation for naturally ventilated buildings in the HH climates (Nicol, 2004). In such climatic settings, using adaptive comfort scales may be a more suitable option considering the thermal comfort of the occupants as well as the energy efficiency of the buildings (Nicol et al., 2012). Apart from these two widely used thermal comfort assessment scales, many other models exist in literature, such as Effective Temperature (ET) scale, Corrected Effective Temperature (CET) scale, Standard Effective Temperature (SET) scale, UC Berkeley (UCB) thermal comfort model. These models also provide energy-balance equations with slightly different quantification of the variables (Spagnolo and De Dear, 2003), a detailed discussion of which is beyond the scope of this dissertation. However, irrespective of the mathematical model being used to assess the thermal comfort conditions, the influencing environmental and

personal factors remain the same as depicted previously in Figure 2.1. What varies between the models is the relative weightage of the factors towards the calculation of the energy-balance equation of human thermal comfort. Therefore, modifying these six influencing factors would qualitatively enhance the thermal comfort conditions, despite whatever the final output value a specific model would give in terms of quantitative measures.

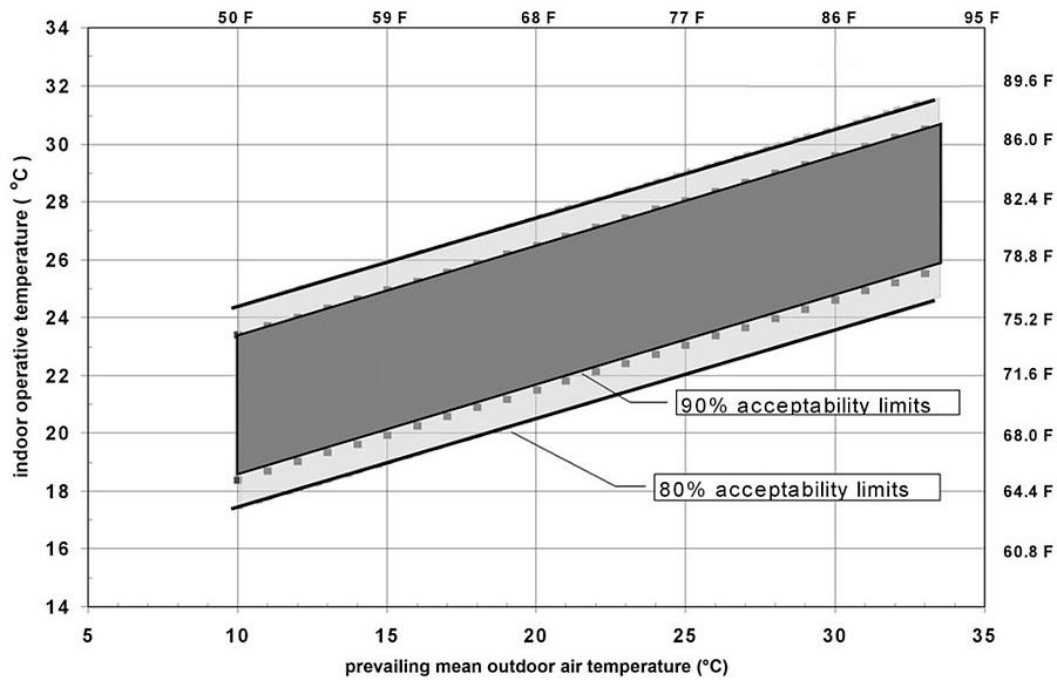


Figure 2.3: Adaptive thermal comfort model (ISO Standards, 2005).

2.2.2 Enhancing Comfort Conditions

A variation in the personal and environmental factors of thermal comfort determines the dominant and auxiliary thermoregulation mechanism of a human body. For a given activity level, the total heat generation or metabolic rate for human beings remains the same but the percentage values of conduction, convection, radiation and evaporation vary according to the other five influencing factors (Djongyang et al., 2010). For example, with higher temperature, there is more latent heat loss through evaporation and less sensible heat loss through conduction, convection and radiation (Engineering Toolbox, 2021). The

spectrum of values for the different factors either facilitate or hinder this heat exchange with the environment, inducing a thermal sensation that ranges from cold to hot. The percentage range of the various thermoregulation methods at any given time has been empirically (Guyton and Hall, 2015) or numerically (Fiala et al., 1999) established in literature. The relationship of human thermoregulation mechanisms with the thermal comfort factors can be depicted as in Figure 2.4. In order to enhance the thermal comfort, these factors can be optimized to better facilitate the heat-balance of human beings leading to better thermal sensation. Hence, for a fixed clothing and activity level, the four environmental parameters can be optimized for better thermal comfort conditions. The most commonly used technique to achieve thermal comfort in a building is the mechanical HVAC system (Ma et al., 2021), which addresses the air temperature, relative humidity, and to some extent, the air speed. This controls human heat regulation by modulating the latent and sensible heat loss through evaporation and convection, respectively.

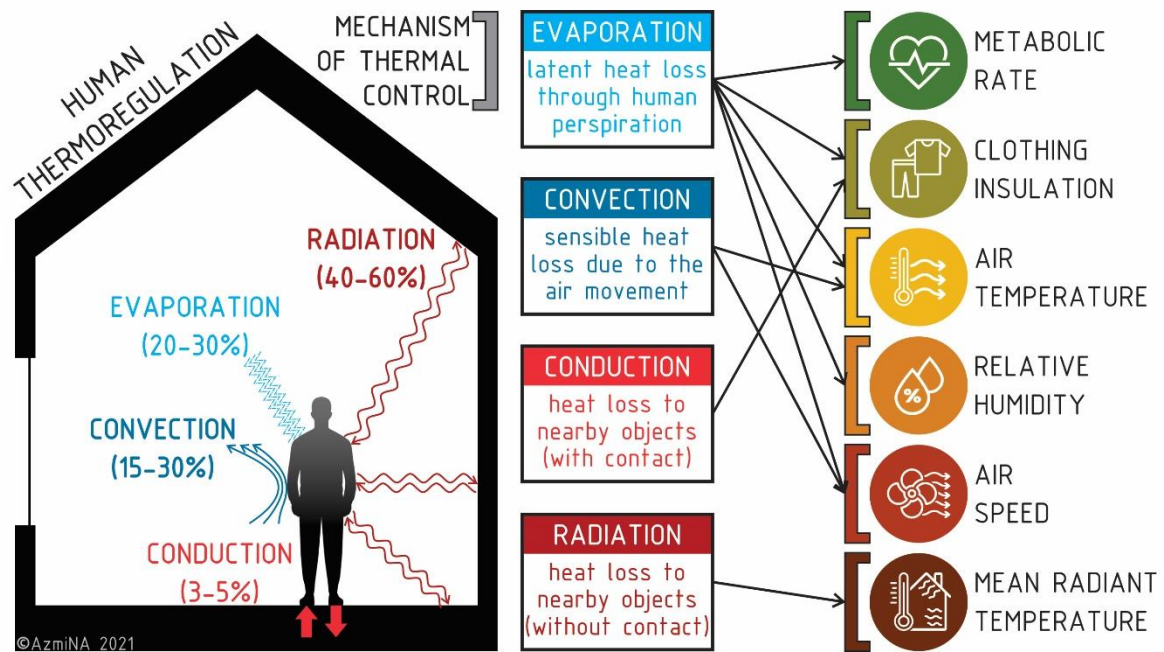


Figure 2.4: Thermal comfort factors affecting human thermoregulation.

In the context of hot climates or under summer conditions, the recommended comfort temperature range by ASHRAE is 23-27 °C (ASHRAE, 2013). However, Figure 2.5 shows that the other factors considered for deriving this temperature range are restrictive and limiting, which would not be the same for most instances. In HD climates, the ambient outdoor temperature is much higher (Kottek et al., 2006) and the HVAC thermal load is mostly sensible load in the form of modulating the air temperature. On the contrary, in HH climates the temperature range is merely a few degrees higher than the comfort range. But with constant 70-90% humidity levels, the apparent temperature, also referred to as heat-index, can feel as much as 3-6 °C hotter (Nguyen et al., 2014). To satisfy the heat-balance equation, the comfort temperature range would be lower in order to compensate for the higher humidity levels (Olesen and Parsons, 2002). In such a climatic context, the HVAC systems are designed to also absorb the latent load of the water vapor in the air (Murakami et al., 2001). Therefore, although the temperature gap is not very high, the total thermal load

requires a significant amount of energy to maintain the comfort levels (Sekhar, 1995). However, if the humidity can be controlled in other ways, then the load for HVAC will be significantly lower (Kim et al., 2001), thus requiring less energy usage. Using desiccants can be a cheap alternative in removing excess humidity in the air but air movement has been proven to be a more effective solution (Qi et al., 2012). Maintaining air movement can help the occupants attain thermal comfort through sensible cooling in the form of convection as well as latent cooling through facilitating the evaporation of sweat (Kaynakli and Kilic, 2005). Therefore, an elevated air speed can help offset the recommended temperature levels, ensuring that thermal comfort conditions can be achieved at higher temperature ranges (Yang and Zhang, 2008). Figure 2.6 shows the offset of comfort temperature with elevated wind speeds, as highlighted in the newer ASHRAE standards (ASHRAE, 2017a).

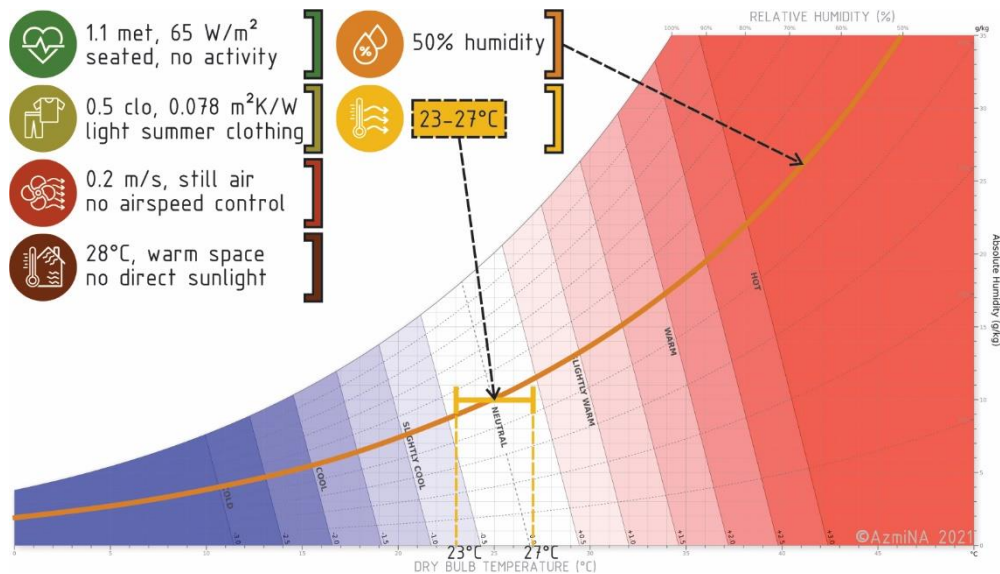


Figure 2.5: Comfort temperature and neutral temperature as recommended by ASHRAE.

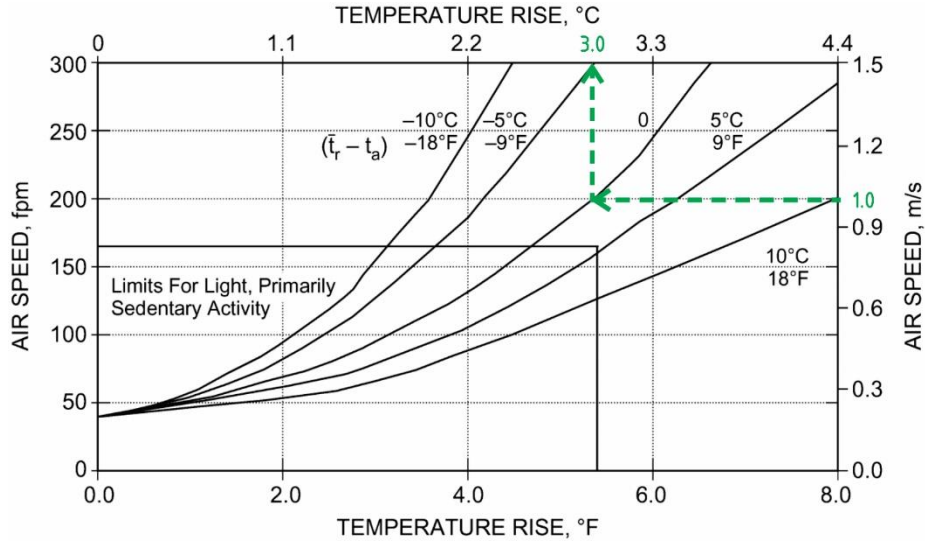


Figure 2.6: Offset of comfort temperature with elevated wind speeds (ASHRAE, 2017a).

As can be seen from the figure, an air speed of 1 m/s can allow for thermal comfort at 3 °C higher than the recommended level. The adaptive thermal comfort scale indicates that people can adapt to 2 °C with an air speed of 1 m/s (Nicol, 2004). Although ASHRAE standards recommend a maximum air speed of 0.8 m/s, this is more applicable for colder climates as occupants in hot countries preferred higher wind speed levels at above 1m/s (Cândido et al., 2010). In another survey, 80% of occupants at sedentary activity levels showed satisfaction at 2 °C higher than the upper limits when the air speed was 1 m/s (de Dear et al., 2013). The tolerance went up to as much as 31 °C, a 4 °C rise from the original when the air speed was increased to 1.4 m/s. At high humidity levels, the elevated wind speed has a psychological effect in attaining thermal comfort as well (Tablada et al., 2005). Therefore, personalized ventilation in the form of fans may be a more effective method to maintain thermal comfort than centralized ventilation (Gao et al., 2007). It must be noted that an elevated wind speed is only effective in providing better thermal comfort when there is no additional heat gain from the mean radiant temperature (MRT) (Prianto and Depecker, 2003). Where natural ventilation is concerned, an elevated wind speed may not be as

effective in places with high MRT, such as urban and high-density built-up areas or in the open areas under direct sunlight (Lau et al., 2016). Thus, for indoor or shaded conditions, MRT from indirect radiation also needs to be assessed and addressed in order to provide comfort conditions for the occupants.

As shown previously in Figure 2.4, the majority of heat exchange and energy balance of the human body is achieved through radiation. Despite its high importance in human thermal regulation, MRT has been the least studied aspect for the thermal comfort of occupants (Karmann et al., 2017). This is due to the fact that MRT is considered to be the most difficult parameter to be correctly measured in an experimental setting (Krüger et al., 2014). Due to the significant impact of direct solar radiation, MRT has mostly been studied for outdoor environments in literature (Wang et al., 2017). In the context where there is no direct sunlight, the combined effect of indirect radiation and reradiation from the surroundings may also greatly impact the thermal comfort in outdoor settings (Guo et al., 2020). In indoor settings, the MRT was found to be very similar to the ambient temperature, and whatever slight difference was found had an insignificant impact on the thermal comfort studies (Alfano et al., 2013). Thus, in most cases, the MRT is considered the same as the air temperature of an interior so as to simplify the research procedure (Dawe et al., 2020). However, in instances where there is a difference between the two temperatures, MRT has the highest influence on the thermal sensation of the occupants (Chaudhuri et al., 2016). This holds true especially for hot climates where the PMV calculations in this study showed the highest deviation when MRT was assumed to be the same as air temperature. In reality, the MRT was higher than the air temperature for this setting, and up to 63% of people preferred cooler conditions. Hence, in designing a naturally ventilated interior or an energy efficient

HVAC system for the hot climates, reducing the MRT can be a key component towards enhancing thermal comfort of the occupants (Chen et al., 2020).

High MRT levels are not always observable and thus, oftentimes ignored in the thermal designing of a building. Interior places with access to direct solar radiation, such as areas next to the windows are mostly responsible for the high MRT in hot countries (Cannistraro et al., 2015). Field studies show that occupants positioned near the windows reported a higher level of discomfort due to the comparatively higher MRT levels (Godbole, 2018). Even in the cases where there is no direct solar radiation through windows, un-insulated walls and ceilings caused higher thermal discomfort for the occupants (Atmaca et al., 2007). This is because the building envelope gets heated up due to being exposed to strong solar shortwave radiation and later releases the heat in the form of longwave radiation into the interior. Depending on the building materials' properties and the design of the building envelope, this transfer of heat to the indoors can happen immediately or at a time lag (Toe and Kubota, 2015). Hence, researchers suggest considering the MRT whilst making design decisions and material choices for the building (Naboni et al., 2017a). Enhancing the thermal comfort through optimizing the MRT can be in the form of low-cost active means such as cooling ceilings (Catalina et al., 2009) or radiant cooling wall panels (Teitelbaum et al., 2020a). Better comfort conditions can also be achieved by using passive design strategies for suitable building envelope thermal design which can help reduce the indoor MRT in hot climates. In an experiment in Singapore, employing shading techniques ensured that the wall surface temperature could be reduced by 10 °C (Tan et al., 2014), which significantly reduced the MRT for the interior. Another study shows that the indoor temperature can be reduced by 2-3 °C compared to the outdoor by façade design alone as it limits the stored and transmitted heat through the walls (Liping and Hien, 2007).

2.2.3 Parametric Simulation Studies of Thermal Comfort

To enhance thermal comfort conditions, both environmental and personal factors need to be considered. The four environmental factors are directly influenced by the overall thermal performance of the building which is dictated by the building design and construction parameters (Azmi & Ibrahim, 2020). Hence, a parametric analysis of various building components can indicate optimum design solutions to achieve better thermal comfort for the occupants. Research on human thermal comfort involves comprehensive calculations where both heat transfer, as well as fluid dynamics, are to be considered. Studying such thermo-fluid dynamics problems can be done in three ways- theoretically, experimentally or numerically (Davis, 2016). Theoretical studies are limited to simple geometry and physics due to the complexity of the involved equations. On the other hand, experimental studies are costly at a building scale as it is limited to the specific building type and the climatic conditions under which the experiment was undertaken. Thus, for parametric studying of various design options, numerical simulations can be a suitable alternative to help analyse the trade-off at an affordable cost (Lau et al., 2016). In analysing the building performance and thermal comfort conditions, researchers use various tools which can be broadly categorized into two types- Building Energy Simulation (BES) softwares and Computational Fluid Dynamics (CFD) softwares. BES softwares are geared more towards optimizing the energy usage for HVAC and calculating the thermal loads of the building (Zhai et al., 2002). CFD softwares, on the other hand, are good for thermal exchange calculations, especially concerning radiative and convective heat exchange of human beings with their environment (Gao and Niu, 2005). Each type of software has its limitations, and researchers select the most suitable one appropriate for the methodology and objectives of their respective research projects.

BES and CFD softwares may be thought of as complimentary to one another. While BES gives the energy consumption data, CFD provides the comfort data (Zhai and Chen, 2006). In literature, CFD is mainly used to evaluate the short-term thermal performance of a building, often for worst-case scenario situations (Zhai, 2006). Since CFD programs are resource intensive, BES softwares are utilized to predict prolonged performance to avoid excessive computing time (Zhai et al., 2002). Depending on the complexity of the problem, CFD models have a 5-15% acceptable error rate while calibrated BES models have an error margin within 5-10% (Yi and Feng, 2013). Nevertheless, both types of softwares are widely used in research and have been proven to yield accurate results to meet the aims of the respective projects (Harish and Kumar, 2016). It is to be noted that BES assumes a well-mixed air for the interior, which is nearly never the case for naturally ventilated buildings (Zhai, 2006). Thus, in cases where localized thermal discomfort, draft, or thermal stratification of air are to be considered, BES may not give correct results. In general, where convection and stack effects are to be considered due to the buoyancy resulting from the temperature distribution, CFD provides a more comprehensive output (Zhai and Chen, 2006). Additionally, for thermal analyses comprising of non-uniform heat transfer involving convection and radiation, CFD can provide high-density information on the indoor thermal qualities as the BES tools were not designed to provide such data (Naboni et al., 2017a). Considering the importance of air speed and MRT that have been mentioned in the previous section, CFD seems to be a more suitable option for assessing thermal comfort for hot climates (Tanabe et al., 2002).

An additional benefit CFD provides while calculating thermal comfort is that it can provide near accurate data of the real-life MRT values (Alfano et al., 2013). All other parameters for thermal comfort, except for the MRT, can be physically assessed and directly

quantified using readily available tools and techniques (Khrit et al., 2017). The MRT, however, requires mathematical calculations involving many variables such as surface properties, angle factors, radiation fluxes etc. In experimental settings, MRT is usually calculated with a globe thermometer which incorporates a near blackbody to quickly assess the radiant heat (Teitelbaum et al., 2020b). However, even the best of such equipment does not provide precise data since it cannot accurately take into consideration the angle factor which is the most reliable means of calculating MRT (Naboni et al., 2019). Therefore, validated simulation results for MRT may be a good alternative to experimental data collection or when high-accuracy globe thermometer and radiation details are not available (Krüger et al., 2014). Furthermore, due to the grid structure and concurrent analyses at multiple points, CFD considers an angle factor while determining the MRT, allowing better approximation as compared to the area-averaged or surface-weighted MRT that is typical of BES softwares (Naboni et al., 2017a). If the limitations of the software are known and biases are eliminated, then CFD may be the best option for parametric studies involving MRT (Lara et al., 2017). Researchers recommend using CFD for making design decisions especially in the cases where localized thermal discomfort may be an issue (Mishra et al., 2016). Typically, coupled simulations combining BES and CFD can give comprehensive data regarding human thermal comfort and the associated energy usage by the HVAC systems (Wang and Wong, 2009). A detailed comparison between the applicability and suitability of various software with regard to the aims and objectives of this study will be further discussed in Section 3.2.2.

2.3 Thermal Comfort in Mosques

Through an extensive literature search, a total of 116 papers related to mosque buildings were obtained that have been published over the last 25 years (1996-2020).

Excluding the duplicates and irrelevant research papers, a total of 92 papers were thoroughly reviewed, classified and analysed to identify the research gap and research prospects in this field. Depending on the research focus and objectives, the available literature can be classified into three categories– (i) thermal comfort, (ii) building design, and (iii) energy efficiency (Figure 2.7). As it can be seen from Figure 2.8, research regarding mosque thermal comfort and energy efficiency is a relatively new yet emerging field with more publications in recent years. Thus, there have not been many comprehensive studies conducted in this niche. Based on the initial study that was done for this research, two elaborate literature review papers have already been published in indexed, high-impact factor Q1 journals. The papers are titled ‘*A review on the factors influencing energy efficiency of mosque buildings*’ (Azmi et al., 2021), and ‘*A comprehensive review on thermal performance and envelope thermal design of mosque buildings*’ (Azmi & Ibrahim, 2020), which are included in Appendix A and Appendix B, respectively. It is to be noted that this section gives an abridged summary of the background studies that have been conducted as a detailed discussion is beyond the word limit of this thesis. Before proceeding with the discussion, it must be mentioned that the majority of the research have been conducted on case study mosques situated in the HD or HH climates (Figure 2.9). Thus, the discourse in the following sections is dictated by findings for such climatic contexts.

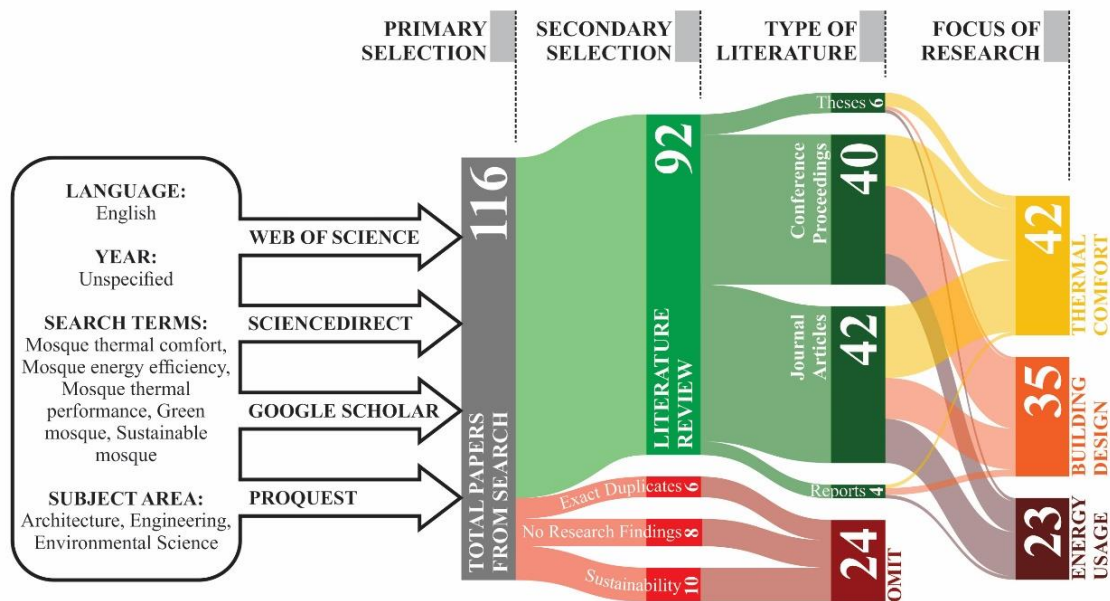


Figure 2.7: Classification and categorization of literature.

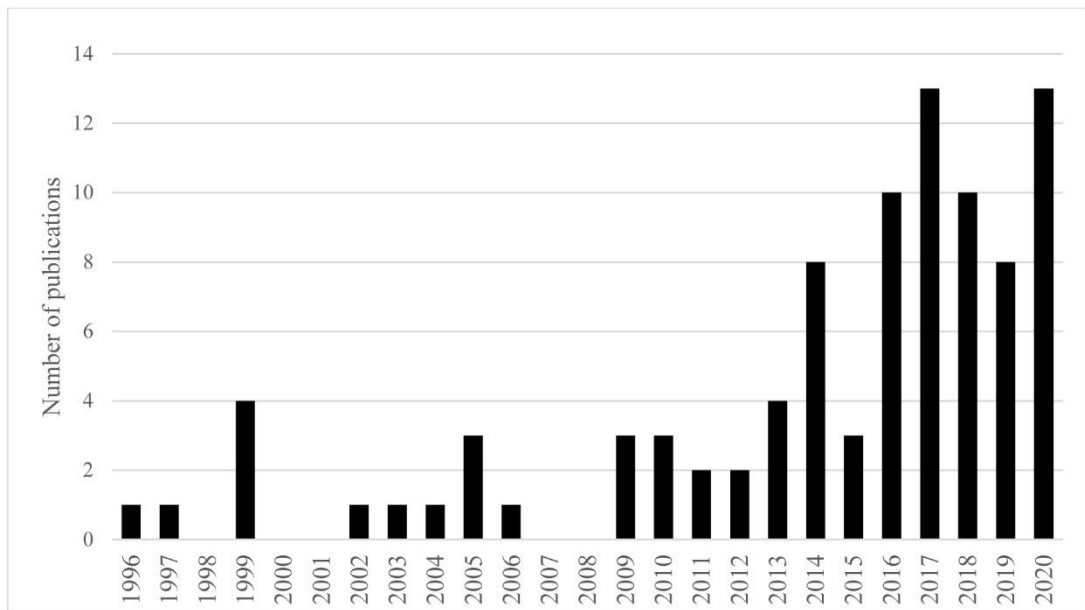


Figure 2.8: Mosque research publications over the last 25 years (1996-2020).

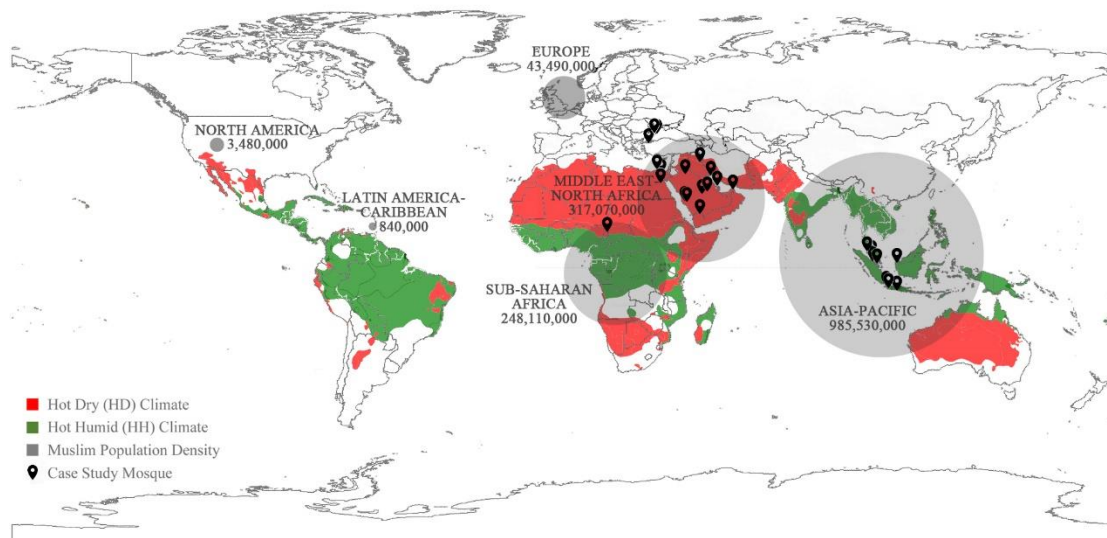


Figure 2.9: Location of case study mosques found in the literature.

2.3.1 Mosque Design and Occupancy Characteristics

The main component of a mosque is the prayer hall which is designed as a large rectangular or square-shaped hall. This multi-volume, single-spaced hall allows congregational prayers to be held concurrently for a large group of people. Most mosques utilize the main prayer hall for conducting community events, such as lectures and seminars as well. Other service spaces such as ablution facilities, toilets, maintenance office, stores are often placed next to the prayer hall or as a separate wing adjacent to the hall. Depending on the cultural practice and availability of space, some mosques have a separate prayer area dedicated for the females at the mezzanine level while other mosques integrate it within the main prayer hall. The *Qiblah* wall usually has minimal glazing and openings to allow for concentration in prayers while windows and doors are located at the other three walls. The size and capacity of a mosque are generally determined depending on the maximum expected occupancy which is seen during the mandatory weekly prayer at Friday noon (*Jumuah*). Typically, mosque designing has no fixed requirement apart from the functional necessity of a large prayer hall and thus, varies according to the architect's concept or desired forms.

There are many architectural styles of mosques that differ widely depending on locality, culture, tradition, as well as design constraints such as funding, available area. However, it is a common practice to design mosques symmetrically along the *Qiblah* axis and with the prayer hall being the central focus (Azmi & Kandar, 2019).

Prayer is performed in tight-knit rows while facing towards the direction of the *Qiblah*. The timings for the prayers are predetermined according to the solar positions. Therefore, depending on the time of the year as well as the latitude and longitude of the specific geolocation, the prayer timings can vary widely. The maximum occupancy is during the weekly *Jumuah* prayer when most mosques are at full capacity (Azmi & Kandar, 2019). This prayer, including the preceding sermon, has a total duration of approximately 2 hours. Depending on the locality, the daily five prayers generally have about 10-20% occupancy of the full capacity of the mosque (Azmi & Kandar, 2019, Al-Shaalan et al., 2017). The occupancy for each prayer lasts between 30-45 minutes, including the pre and post rituals. The mosque remains empty during the remaining times of the day unless there are other religious events or social gatherings. Thus, in total, mosques are occupied for an average of 4 hours a day, at five different timings with intermittent intervals. The thermal comfort of the occupants is of great importance to cater for a suitable ambience during the prayers. As such, mosques usually employ HVAC systems, the operational schedule of which are generally dictated by the prayer timings and follow the same intermittent schedule (Al-Homoud, 1999). With such intermittent and varying occupancy patterns throughout the day and week, designing a mosque with optimum thermal comfort conditions whilst maintaining energy efficient measures becomes quite challenging.

2.3.2 Thermal Comfort Conditions in Mosques

Maintaining thermal comfort for mosques in hot climates implies using passive or active means to lower the temperature and bringing it within comfort range. Although ASHRAE recommends a comfort temperature range of 23-27 °C (ASHRAE, 2013), field studies in mosques have concluded that people from hot climates are more adapted to, and thus, comfortable with higher ranges (Azmi & Kandar, 2020). In order to find the suitable comfort temperature range, a few surveys have been carried out, the results of which are depicted in Figure 2.10. These studies have been conducted in Kuwait (Al-ajmi, 2010), Malaysia (Hussin et al., 2015, Hussin et al., 2018a, Maarof, 2014), Nigeria (Shodiya et al., 2016), and Turkey (Calis et al., 2015). It can be seen that the results are not conclusive and specific inference cannot be made with only these findings. However, the figure does indicate that the tolerance towards higher temperatures is prevalent for people in hot climates. All of the results illustrate that the comfort temperature range is generally higher and broader than the suggested range in standards. Hence, as with other buildings of the hot climates, scales according to ASHRAE standards have been found to underestimate the neutral temperature for occupants who have experience with higher climatic conditions (Hussin et al., 2014). While the standards may dictate that the existing condition is too hot, occupants have found those conditions acceptable and sometimes even desirable. In all of these studies, it was concluded that the AMV of the occupants' thermal comfort is much lower than the PMV, implying that the occupants do not feel as hot as the thermal comfort model predicts. Similarly, the PPD is higher than TSV, indicating that a thorough revision of the existing scales is a must.

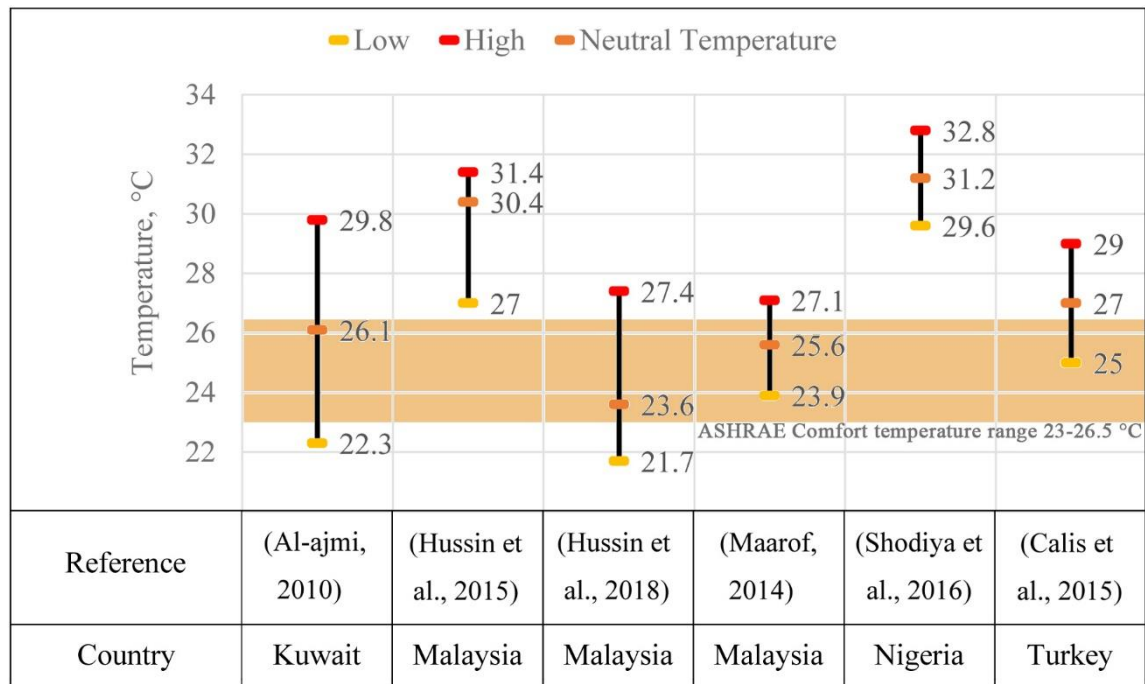


Figure 2.10: Comfort temperature and neutral temperature findings from the literature.

Despite the above-mentioned discrepancies between actual findings and theoretical predictions, optimization studies have used the PMV-PPD model to determine thermal comfort conditions in mosques (Saeed, 1996, Khalil et al., 2013, Hussin et al., 2014, Al - ajmi et al., 2017, Samiuddin, 2014). However, all these studies have been conducted in mosques that have employed HVAC systems as the thermal control mechanism. The PMV model is fairly accurate where such mechanical cooling is employed while deviating largely for naturally ventilated buildings (De Dear & Brager, 2002). Additionally, it may be interesting to note that all of these optimization studies are in the context of HD climates where the low humidity level does not pose a problem for the thermal comfort of the occupants, which would not be the case for high humidity climates. Some researchers (Budaiwi, 2011) have commented that for such a short duration of time, the use of steady-state thermal comfort models may not be appropriate as the human body intuitively takes time to adjust to the new environment. Hence, using adaptive models may be more accurate

to assess the thermal comfort conditions of the occupants as the physiological and psychological adaptations are reflected in such a model. Conversely, other researchers (Khalil et al., 2013) argue against the adaptive model, stating that behavioural changes such as walking around, changing clothing levels or opening the windows significantly influence the comfort scales. Since people frequent mosques only during prayer times and no additional movement is allowed within the prayer, adaptive comfort scales might not be realistic.

Apart from the PMV-PPD model, a few other measurement standards have also been used as a determining factor for assessing the interior thermal conditions of mosques, such as Corrected Effective Temperature (CET) (Ibrahim et al., 2014) and Discomfort Degree Hours (DDH) (Asfour, 2009). There are other studies (Budaiwi et al., 2013, Budaiwi, 2011, Al-Homoud et al., 2009) that do not take into account the air speed, relative humidity or MRT and assess the comfort conditions based solely on the air temperature. However, these studies have been conducted in the context of HD climates where the relative humidity is within acceptable limits. The researchers have stated that in low humidity climates, and with minimal variations of the other environmental factors, the air temperature has the highest influence over thermal comfort for a short duration of occupancy. Nonetheless, they do recommend using a more comprehensive thermal comfort index where the MRT and air speed are important factors to be considered, especially in the context of HH climates. Since the relevant research is very limited, comparing the applicability of different models and commenting on their suitability in the context of the occupancy pattern of mosques is not viable. However, it can be concluded that most thermal comfort models may not be representative of the intermittent occupancy pattern in mosques for people in hot climates. Thus, more field studies and experimental research need to be carried out to determine the

modifications in the existing scales for assessing the thermal comfort conditions of mosque buildings.

2.3.3 Energy Usage in Mosques

To create a suitable ambiance for prayers it is important to maintain the optimum thermal comfort of the congregants, often requiring mechanical means of thermal control. It has been found that most mosques in Malaysia (Aziz, 2016), Kuwait (Al-Dabbous et al., 2013), Iraq (Hameed, 2011), Saudi Arabia (Alabdullatief et al., 2016), and UAE (Mushtaha & Helmy, 2017) employ HVAC to improve indoor comfort conditions. These HVAC systems are energy intensive and have been found to use about 80-90% of the total energy usage, in both HD (Al-Homoud et al., 2005a) and HH climates (Hussin et al., 2019). In general, mosque energy usage per unit area is similar to that of an average office building of a particular region (Abdou et al., 2005). However, given that the mosque occupancy is much lower and remains empty for the majority part of the day, it translates to a much higher per capita as well as per unit area energy usage than other buildings (Al-Homoud et al., 2009). The energy bill of mosques has been found to be astoundingly high despite the subsidized rate a lot of countries offer for religious establishments (Abideen, 1997). The reasons that have been identified towards the high energy usage are- (i) unsuitable building design, and (ii) inefficient energy management profile (Azmi et al., 2021). Simulation studies show that with a suitable envelope thermal design, as much as 26% of energy can be conserved; while improving the HVAC operational strategy and system efficiency can reduce the energy usage by 36% (Budaiwi et al., 2013). With a combined optimization of design and operational profile, the researchers reported that as much as half of the energy could be conserved for mosques in the context of Saudi Arabia. Thus, conclusion can be drawn that

most mosques that use high amount of energy due to employing HVAC may not be energy efficient and are wasting much of the energy that is being used.

A comparative analysis has been drawn in Figure 2.11 for mosque energy optimization experiments available in the literature. As an objective standard of comparison between the numerical analyses, the results have been expressed in terms of annual energy usage intensity (EUI), expressed in kWh/m².year. These parametric studies illustrate how the optimization of building and operational parameters may impact the energy efficiency of a mosque. Since the HVAC system is the most energy consuming aspect of a mosque building, it can be seen that optimization of the air-conditioning (AC) efficiency and operation timings for hot climates can easily reduce the energy usage by 30 % (Samiuddin, 2014) to nearly 50% (Al-Shaalan et al., 2014). On the other hand, components of the building envelope such as insulation of walls and roofs, shading etc. can also reduce energy requirements as it improves the thermal performance and lowers the thermal load. It must be noted that the studies mentioned in this figure portray idealistic scenarios which may not be feasible in real-life circumstances due to structural or financial constraints. A detailed discourse of the contributing factors and optimization of mosque energy efficiency is beyond the scope of this discussion and can be found in the published journal article attached in Appendix A (Azmi et al., 2021). A systematic approach for the energy audit of mosques is necessary to assess the design factors and operational characteristics affecting the energy usage pattern (Abdou et al., 2002). This can lead to conclusions about building components or energy management policies that are responsible for the high energy usage of mosques. Based on such studies, further investigations can be done, and suitable measures can be taken accordingly towards increased energy efficiency.



Figure 2.11: Energy optimization studies for mosques found in the literature.

2.3.4 Thermal Performance of Mosque Buildings

As it can be seen from the previous section, the HVAC systems are the largest consumer of energy in mosques (Al-Homoud et al., 2005b). Furthermore, it has been found from multiple studies that building envelope is the biggest contributing factor towards the thermal load of mosques (Al-Homoud et al., 2009). In hot climates, the mosque building envelope is nine times more responsible for heat gain than the combined impact of occupant load from human beings, and equipment load from lightings and fixtures (Budaiwi, 2011). For external load or skin-load dominated buildings like mosques, external climatic conditions contribute greatly to the thermal load of the interior (Azmi et al., 2021). Thus, the thermal performance of the envelope dictates the thermal load for the building, which subsequently affects the energy efficiency for air-conditioned mosques and occupants' thermal comfort for naturally ventilated mosques. The components of envelope thermal design for a mosque have been discussed previously in literature (Azmi & Ibrahim, 2020), as shown in Figure 2.12. In addition to these, the building orientation, location and surroundings also play a role in the thermal performance of a building. The thermal performance of mosque buildings can be improved with effective thermal designing that includes using suitable materials, having the right construction details, and in general, through applying passive design approach. Optimizing the different attributes and characteristics of building components can allow for suitable thermal designing of the building, yielding optimum thermal performance. A comprehensive literature review on the thermal performance of mosque buildings has been published as a journal article (Azmi & Ibrahim, 2020) which is provided in Appendix B. Detailed discussion and analysis of all the findings available in literature is not viable to include in this section and can be found in the

published article. Nevertheless, a brief overview is provided here in the context of the objectives of this research.

ENVELOPE THERMAL DESIGN CONSIDERATIONS FOR A MOSQUE

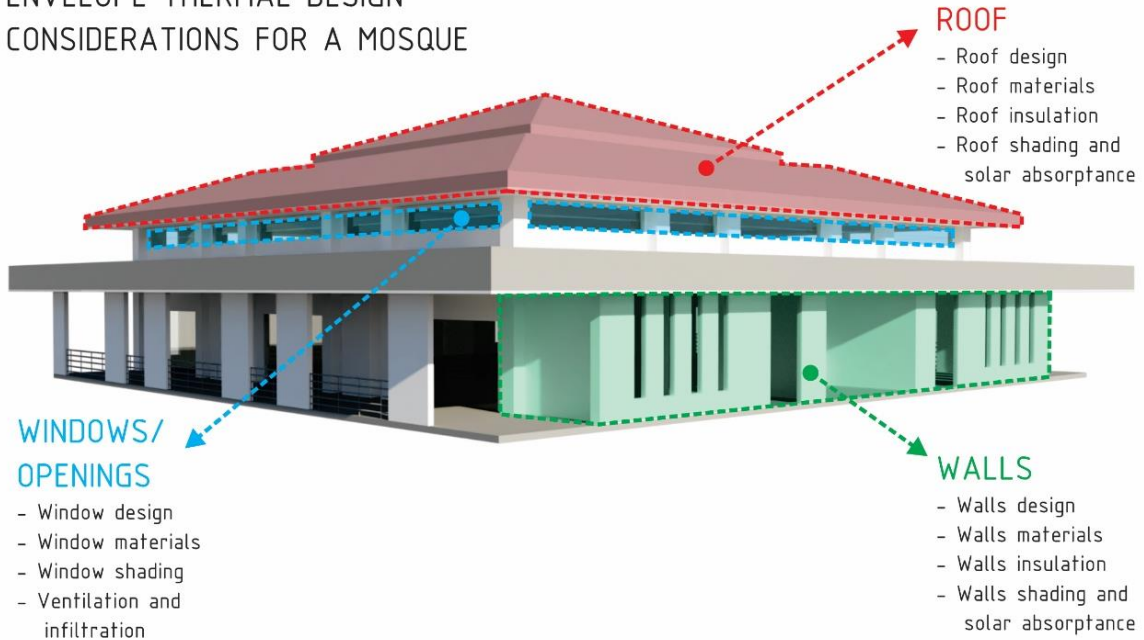


Figure 2.12: Example of the envelope thermal design components for a typical medium-sized mosque in Malaysia (Azmi & Ibrahim, 2020).

For hot climates, roofs are one of the most critical design components and contribute the most to the thermal load due to constant exposure to the sun (Faghih & Bahadori, 2011). Research shows that roofs with suitable insulation (Budaiwi, 2011) and lower solar absorptance materials (Al-Homoud, 1999) ensure lower cooling load in mosques. However, where human thermal comfort is concerned, the overhead space due to multiple volume prayer halls can be an added benefit in mosques (Tang et al., 2006). This space works as a thermal buffer zone as air is a bad conductor for heat and protects the occupants from the heat gained through the roof (Asfour & Gadi, 2007). Additionally, heated air moves upwards in convection currents, ensuring that the lowest portion closer to human-level is comparatively cooler (Gagliano et al., 2012). Since mosque halls usually have a large height,

the contribution of the roof towards the MRT of the occupants is also lower as the angle factor is smaller compared to the nearby walls. Similar to the roofs, walls with better insulation are favourable for hot climates to reduce the heat gain from the exterior (Al-Homoud, 2009). Walls with external buffers in the form of balconies or porticos (Cook, 1999) perform much better thermally as the shading protects the walls from direct solar heat gain. When an exposed wall retains the thermal energy and later radiates it to the interior, it can create thermal discomfort in the occupants even when the air temperature is cooler, especially during *Maghrib* and *Isha* prayers. This thermal lag of the walls can also be taken advantage of by utilizing night-time flushing of the heat to reduce indoor temperature (Hameed, 2011). Windows in mosques serve the purpose for providing visual comfort as well as for daylighting requirements. However, for naturally ventilated mosques, windows are also a means for cross ventilation which is important for human thermoregulation and thermal comfort of the occupants.

Typically, naturally ventilated mosques are supposed to have an indoor temperature similar to the outdoor ambient temperature (Sugini et al., 2017). Correspondingly, the vacant time in between the prayers for air-conditioned mosques should also have a similar temperature to the outdoors. However, because of residual heat from the mosque building structure and nearby built-up areas as well as lack of proper ventilation, the indoors remain much hotter with high humidity build-up (Azmi & Ibrahim, 2020). Many field studies have found that the indoor ambient temperature is 2-5 °C higher in mosques for both HD (Al-ajmi, 2010, Asfour, 2009) and HH (Bakhlah & Hassan, 2012, Nordin & Misni, 2018) climatic settings. Researchers have attributed this to the poor thermal performance of the mosque buildings (Mushtaha & Helmy, 2017) as well as residual heat from the occupant load (Khalil et al., 2013). Studies have also found that the MRT is 3-5 °C higher than the

ambient temperature in air-conditioned mosques (Samiuddin, 2014), and can be as much as 5-6 °C higher in naturally ventilated mosques (Soegijanto & Yohana, 2004). Even much later after sunset during the *Isha* prayers when the outdoor temperature was lower, the indoor temperature remained more than 2°C higher (Khalil et al., 2013), which can be attributed to the thermal lag effect of the building envelope. In one survey it was found that the congregants expressed thermal discomfort during the *Isha* prayers but were satisfied with the thermal environment during the *Fajr* prayers (Hussin et al., 2014), yet the air temperatures were very similar in both scenarios. While there was no explanation or insight for such findings provided by the authors in this paper, it can be inferred that with all other factors being the same, it must have been the high MRT due to the heated building structure which had caused the thermal discomfort in the occupants.

Since mosques are operated intermittently, it requires a high level of energy for the HVAC systems to maintain thermal comfort conditions during each operation phase. Thus, the thermal design of the building, which is influenced by many design decisions, greatly influences the energy usage of a mosque (Al-Homoud, 2009). Inadequate or unsuitable building thermal design allows the building to retain heat from the solar gain causing residual heat build-up in the interior. This consequentially increases the amount of energy consumed by the HVAC units since the system needs to be designed with more capacity and requires longer running times (Budaiwi et al., 2013). In a study carried out in Saudi Arabia, it was found that improving the thermal performance of the mosque envelope through applying insulation to the walls and roof could reduce the energy consumption by more than 25% (Budaiwi, 2011). Although Figure 2.11 in Section 2.3.3 indicates how HVAC system optimization can be the biggest energy saving means, proper building design can ensure that thermal comfort can be achieved by passive and low-cost approaches. Optimizing envelope

thermal design improves indoor thermal conditions and ensures better thermal comfort even without the need for HVAC systems. Subsequently, suitable thermal performance of the building also reduces energy usage when HVAC systems are needed for thermal control as lesser cooling loads require reduced operation timing and smaller machine sizing (Azmi & Ibrahim, 2020). Thus, in order to maintain thermal comfort with sustainable energy consumption at the occupancy stage, proper thermal design of the mosque envelope is of utmost importance and should be considered at the earliest design phases.

2.3.5 Optimizing Thermal Comfort in Mosques

The function of the mosque is well-defined, and prayers can be classified as a sedentary activity with a minimum metabolic rate. The other subjective factor of thermal comfort- clothing insulation, is also of a similar value as it is generally dictated by the religious requirement for clothing during prayers (Hussin et al., 2015). Therefore, thermal comfort in mosques is largely dependent on the ambient indoor thermal quality resulting from the four objective environmental parameters (ASHRAE, 2013) that are dictated by the building design. Keeping the specificities of the thermal comfort models aside, it can be argued that suitable building design is the most important consideration in the optimization of thermal comfort in mosques. As seen in the previous section, due to the poor envelope thermal design of the mosques, the thermal comfort of the occupants must be met by utilizing HVAC systems. As mosques have intermittent occupancy levels at different intervals throughout the day, the HVAC system is turned on intermittently. On one hand, such intermittent operational profile for these systems can be a contributing factor towards the high energy usage and equipment deterioration. On the other hand, despite the high energy usage, in the absence of a proper envelope thermal design, the HVAC system may still fail to ensure a suitable comfort temperature range due to the short operation time (Al-Homoud

et al., 2009). Yet, extended operational schedule beyond the prayer timings just to meet the thermal comfort needs of such a low occupancy level becomes wasteful in terms of energy. Thus, a careful balance must be struck between the thermal comfort requirements and the energy expended to maintain such an indoor environment.

Optimization of thermal comfort in the context of mosque buildings has mainly been focused on HVAC system optimization to reduce energy consumption. The operational parameters and management profile of HVAC are dictated by the end-users at the post-occupancy level and these factors are outside the scope of work and beyond the control of the designers. However, researchers have put forward their recommendations to help achieve better comfort conditions at reduced energy consumption. Suggestions include precooling of building mass to help absorb the cooling load so that thermal comfort during prayers can be easily achieved within a short period (Yüksel et al., 2020). There have also been suggestions for an intelligent automated operational profile for the HVAC so that thermal control can be maintained as per occupancy level (Hussin et al., 2020a). Some researchers suggest modulating the air distribution volume (Samiuddin & Budaiwi, 2018) while others recommend suitable air speed and throw (Hussin et al., 2020b) to reduce localized thermal discomfort. Improving the air changes per hour (ACH) (Jaafar et al., 2017) or optimization of the number of units (Khalil et al., 2013) of the HVAC system to strike a balance between comfort conditions and energy requirements are topics discussed in the literature as well. A prevalent theme that can be noticed in these above-mentioned studies is that all focus on optimizing different parameters of the HVAC system for better comfort conditions. As mentioned in Section 2.2.2, HVAC systems deal with the air temperature and relative humidity aspects of thermal comfort. However, considering all the four environmental

factors holistically, including the MRT and air speed, would yield the best possible optimization of thermal comfort.

While HVAC system optimization focuses on active means of thermal control, building design optimization is a passive approach towards enhancing thermal comfort. Yet studies from the ‘building design’ category mentioned in Section 2.3 focus only on the overall thermal load when discussing building design parameters (Azmi & Ibrahim, 2020). Thus, most research aimed at optimizing the building thermal performance focuses on lowering the cooling load gained through the building envelope (Hameed, 2011, Asfour, 2009). While reducing the thermal load can reduce HVAC operation timing and sizing, it not necessarily addresses the other aspects of thermal comfort, especially the oft-overlooked aspects of air speed and MRT. Hence, this category of studies is also directed at HVAC system optimizing as the end goal and largely ignores considering other aspects of thermal comfort. Furthermore, research that considers ventilation as a variable to be optimized, does so in the form of ACH required in the context of indoor air quality (IAQ), applicable mainly for air-conditioned mosques (Mushtaha & Helmy, 2017). As detailed out in 2.2.2, MRT and air speed can have a huge influence on the thermal comfort of the occupants of hot climates. Especially in the context of mosques, where the occupants are in close proximity during prayers, MRT and air speed can have an even bigger significance towards the thermal perception of the occupants. Thus, optimizing the thermal comfort would require addressing all the contributing factors, holistically.

2.4 Mosques in Malaysia

In Malaysia, matters pertaining to mosque infrastructure and management are overseen by the Department of Islamic Development Malaysia known as *Jabatan Kemajuan*

Islam Malaysia (JAKIM). According to the 2020 year-ending statistics of JAKIM, there are a total of 24,722 mosques in Malaysia (JAKIM, 2019). As per the government classifications, mosques are classified into three categories- large, medium and small; the description and statistics are provided in Table 1.1 below. It is to be noted that this classification is at par with other studies found in the literature (Abdou et al., 2005), and hence, the capacity range has been taken from there.

Table 2.1: Types of mosques in Malaysia.

Category	Definition and Description	Capacity of Users	No. of Mosques (Malaysia)	No. of Mosques (Sarawak)
Large mosques	Landmark mosques or large mosques owned by the states.	~ over 1500	256	15
Medium mosques	Referred to as <i>Jamii'</i> (Communal) mosques, where the daily and Friday prayers are held.	500-1500	6,904	374
Small mosques	Referred to as <i>surau</i> where only the daily prayers are held. Can be a freestanding building or as a part of other buildings.	~ less than 500	17,562	389

2.4.1 Overview of Mosque Research in Malaysia

Among the 92 papers thoroughly studied for the purpose of this research, 28 articles are on Malaysian case study mosques. However, these studies are comparatively recent and have been conducted in the last 10 years (Figure 2.13). The research papers can be classified into three types depending on their methodology:

(i) Discussion papers: These are narrative papers that qualitatively discuss and analyse the characteristics of one or several mosques without any on-site quantitative data collection. While these papers can prove to help identify design trends or indoor

environmental scenario of mosques, it does not propose improvement measures or solutions to existing problems based on scientific methods.

(ii) Field studies: These include field surveys and on-site data collection with the results and analysis expressed as quantitative data. The outcomes of the research are usually graphically represented, with comments and suggestions for improvement measures.

(ii) Numerical experiments: Experiments that carried out parametric simulations based on the case study model and tested different design scenarios to achieve a solution. The research output is in the form of a probable optimized scenario as a response to the research question posed.

Out of the 28 publications in the context of Malaysia, 6 are discussion papers, 19 are field study articles yet only 3 are numerical experiments (Figure 2.13). The list of the articles, along with details such as publication year, research type, research focus etc. are included in Appendix C in a tabular form.

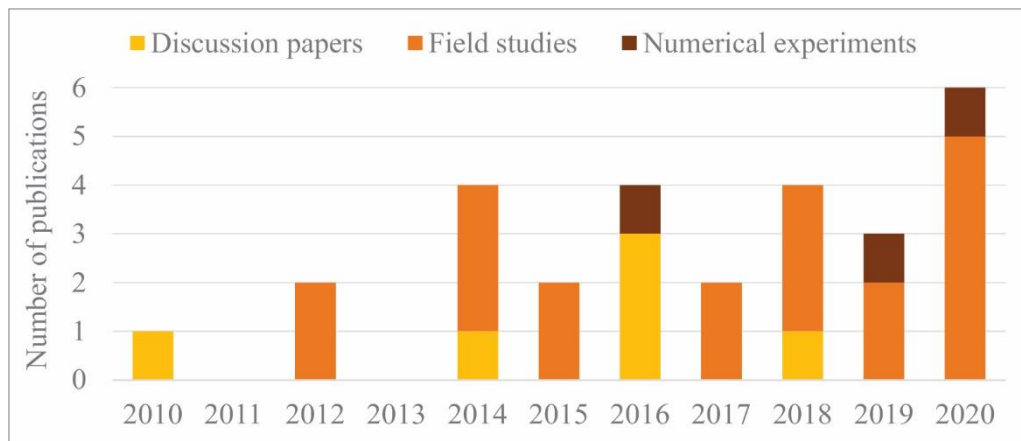


Figure 2.13: Mosque research publications in the context of Malaysia.

There have been discussion papers and field studies undertaken for case study mosques across Malaysia in Penang (Bakhlah & Hassan, 2012), Sarawak (Ibrahim et al.,

2014), Selangor (Nordin & Misni, 2017), Kuala Lumpur (Abdullah et al., 2016), Putrajaya (Ariff et al., 2012), Perak (Omar et al., 2018), Melaka (Maarof, 2014), Johor (Ghaleb, 2017). A survey conducted across multiple states found that about 70-80% of mosques are fully air-conditioned while the rest are sometimes operated with natural ventilation aided with mechanical fans, depending on the occupancy level and ambient temperature (Eusof et al., 2015). There have also been articles on Cyberjaya Mosque (Aziz, 2016) which is the only Green Certified, Platinum-rated mosque in Malaysia. In this mosque the HVAC system is operated only during high occupancy timings such as *Jumuah* prayers or *Eid* prayers. Field studies have compared between different types of roof materials (Nordin & Misni, 2017), roof shapes (Maarof, 2014), opening type (Nordin & Misni, 2018), façade design (Abdullah et al., 2016), commenting on the suitability of the designs in the context of Malaysia. It is to be noted that all these papers are discussion papers or field studies commenting on the different aspects of mosques and drawing a comparison between them. There are four thermal comfort field surveys carried out in Malaysia- two of them are in Penang (Hussin et al., 2018a, Hussin et al., 2015) while one each in Melaka (Maarof, 2014) and Johor (Azmi & Kandar, 2020). The two mosques in Penang are fully air-conditioned mosque with one of them having retrofitted HVAC system at a previously naturally ventilated mosque. The case study mosque in Johor is a naturally ventilated mosque while the one in Melaka is operated in mixed mode. In all four cases, comfort temperature range was found to be above the recommended ASHRAE level of 23-27 °C, even as much as 4° higher (Hussin et al., 2015).

There have been only three parametric numerical analyses that have been carried out in the context of Malaysia. Two of them are on the naturally ventilated, medium-sized Masjid Al-Jawahir in Johor where CFD was used to determine the best configuration and placement of exhaust fans on the western wall (Noman et al., 2016), or on the roof (Kamar et al., 2019).

Findings show that mechanical exhaust fans promote forced ventilation which allows for air circulation within the hall as it causes movement of air that was otherwise stagnant. The fans remove the heated air from the interior that had risen due to the convection current, causing fresh cooler air to enter through the lower level openings which allow up to 3 °C reduction in the temperature. However, it must be noted that these two studies did not consider solar radiation and focused only on the airflow volume and air speed as an objective variable of the study. Being a naturally ventilated mosque, the energy usage was not taken into consideration as well. The other numerical study (Hussin et al., 2020b) was conducted for the air-conditioned Penang State Mosque, which is a large mosque according to the categories mentioned in Section 2.4. In this study, researchers optimized the air distribution strategies for the HVAC system using CFD. Findings show that comfort conditions could still be achieved at 27 °C set-point temperature, which was 5 °C more than the usual set-point of 22 °C. This increase of thermostat temperature at constant air volume allowed for 32% energy savings. Alternatively, reducing the air supply velocity from 6 m/s to 3 m/s with a constant temperature of 25 °C allowed for 16% reduction in energy. In this study as well, the MRT was taken to be equivalent to the air temperature in order to simplify the numerical simulations.

2.4.2 Thermal Comfort Requirements

Malaysia is situated near the equator and has a year-long hot season with a high amount of daily and yearly solar radiation (Azmi et al., 2017). This causes the building structure to retain heat for a long time, influencing the MRT of the interior. Furthermore, since the *Qiblah* wall of Malaysia is located at the north-west 292° compass direction, it receives direct solar radiation from the afternoon sun. Even during low occupancy periods, the congregational prayers are held close to this wall. Although the majority of interior solar

gain occurs through the windows (Cannistraro et al., 2015), the walls can store the heat for a long time, gradually releasing it to the interior. The heated *Qiblah* wall can greatly impact the MRT, and consequentially, the thermal comfort of the occupants at proximity to the wall. Furthermore, the added humidity factor for HH climates of Malaysia greatly influences the thermal comfort level of the occupants. Hence, in order to evaluate the thermal comfort conditions of the occupants and optimize building parameters for better thermal comfort, all the factors of thermal comfort must be addressed holistically. As it has been previously mentioned in Section 2.2.2, modulating the MRT to enable easier thermoregulation or providing localized air speed to increase the comfort temperature levels may be a more sustainable and economic way to enhance thermal comfort conditions compared to the energy intensive HVAC systems. During high occupancy periods in mosques, the radiant heat from the nearby congregants would add to the MRT while localized comfort ventilation may not be possible because of the closely packed group of people. Therefore, such passive or low-cost means of optimizing thermal comfort may be adopted for low occupancy daily prayers while reserving the operation of HVAC systems for *Jumuah* prayers only.

2.5 Summary and Research Gap

As of 2019, there are over 4 million mosques worldwide (Deloitte, 2019). Due to the functional requirements of a large space operated at intermittent occupancy timings, a lot of energy is wasted maintaining the indoor thermal environment while often the comfort requirements are not met. In recent years there has been a rising interest in academia on the research of mosque buildings focusing on improving thermal comfort conditions while optimizing energy efficiency. Figure 2.14 shows the location of the case study mosques of the studied literature. As it can be seen, most research has been carried out for case study

mosques in Saudi Arabia and Malaysia, which are representatives of the HD and HH climates, respectively.

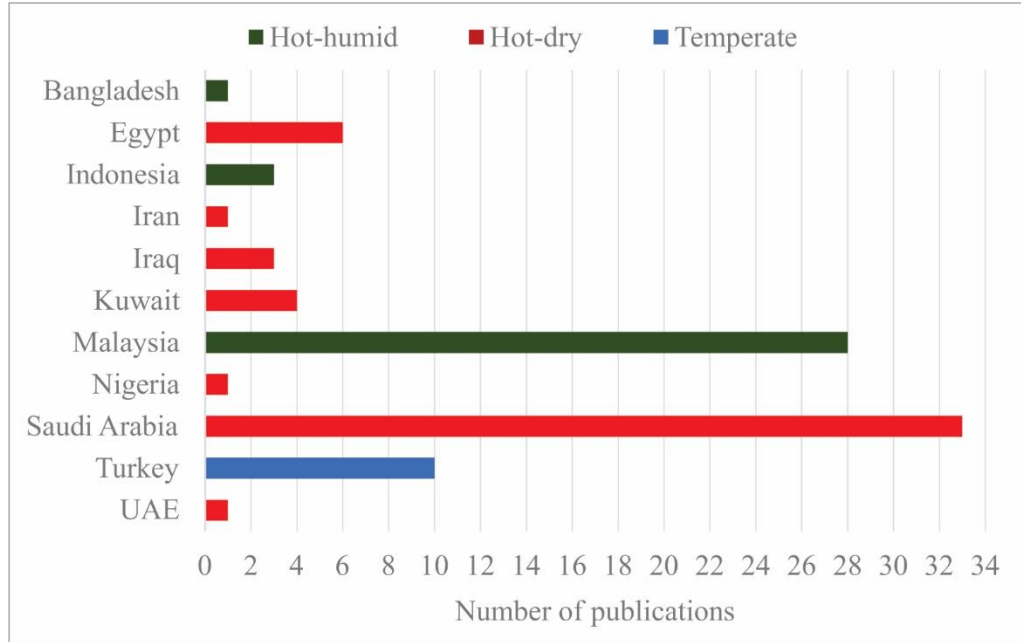


Figure 2.14: Country-wise location of case study mosques.

Further classification into the methodology of the papers from these two countries, expressed in percentage (Figure 2.15), shows that there have been very few numerical experiments in the context of Malaysia. The majority of the numerical studies discussed in the subsections of Section 2.3 have also been carried out in the Middle East in the context of HD climate. However, Malaysia has a high humidity rate which can greatly impact the thermal comfort of occupants. Hence, the challenges in attaining thermal comfort in HH climates are vastly different from HD climates.

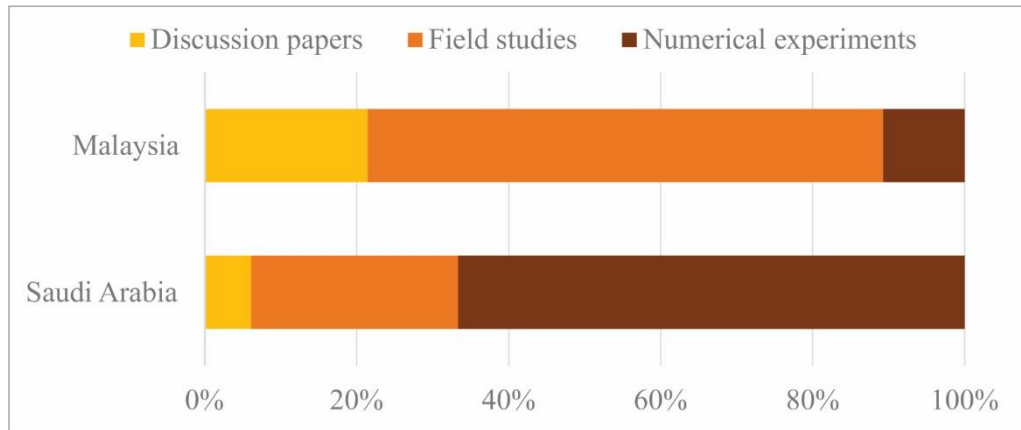


Figure 2.15: Research methodology for case study mosques in Malaysia and Saudi Arabia.

In addition to the high humidity, the *Qiblah* wall located at the north-west side of the mosque for Malaysia is susceptible to high solar gains. Therefore, in approaching the passive design and comfort strategies, the air speed and MRT are important considerations for the thermal comfort calculations. Through the parametric studies of the *Qiblah* wall design in conjunction with ventilation strategies, thermal comfort conditions can be enhanced for the occupants. This would minimize the dependency on HVAC systems, especially during low occupancy daily prayer timings, resulting in sustainable energy consumption. It is hypothesized that for prayers that are not during the daytime (i.e., *Fajr*, *Maghrib* and *Isha*), optimized design parameters can eliminate the need for mechanical intervention. For other prayers which have high ambient air temperature (*Dhuhr* and *Asr*), or during high occupancy periods (*Jumuah*), such passive design strategies may not be enough to meet the comfort needs. Nevertheless, better thermal performance of the building ensures lower thermal load contributed through the building envelope which helps lower energy consumption for the active HVAC systems.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter discusses the stages of this study and elaborates on the methodology undertaken to fulfil the research objectives. The research project has five phases- (i) literature review, (ii) data collection, (iii) numerical modelling, (iv) parametric studies, and (v) analysing results. The findings and conclusions from phase one, literature review, have already been discussed in the previous chapters. Figure 3.1 depicts a flowchart for the remaining four stages where it is further divided into multiple subtasks. It must be noted that while the figure depicts the phases linearly, the research procedure is an overlapping and iterative process. The following sections discuss, in detail, the various aspects of the research methodology carried out for this study. Where necessary, comments are provided on the justification in light of the objectives of the research. Additionally, the hindrances faced while carrying out the research process are also mentioned wherever appropriate. The chapter ends by providing an overview of the research methodology and highlighting how the objectives have been fulfilled in the procedure.

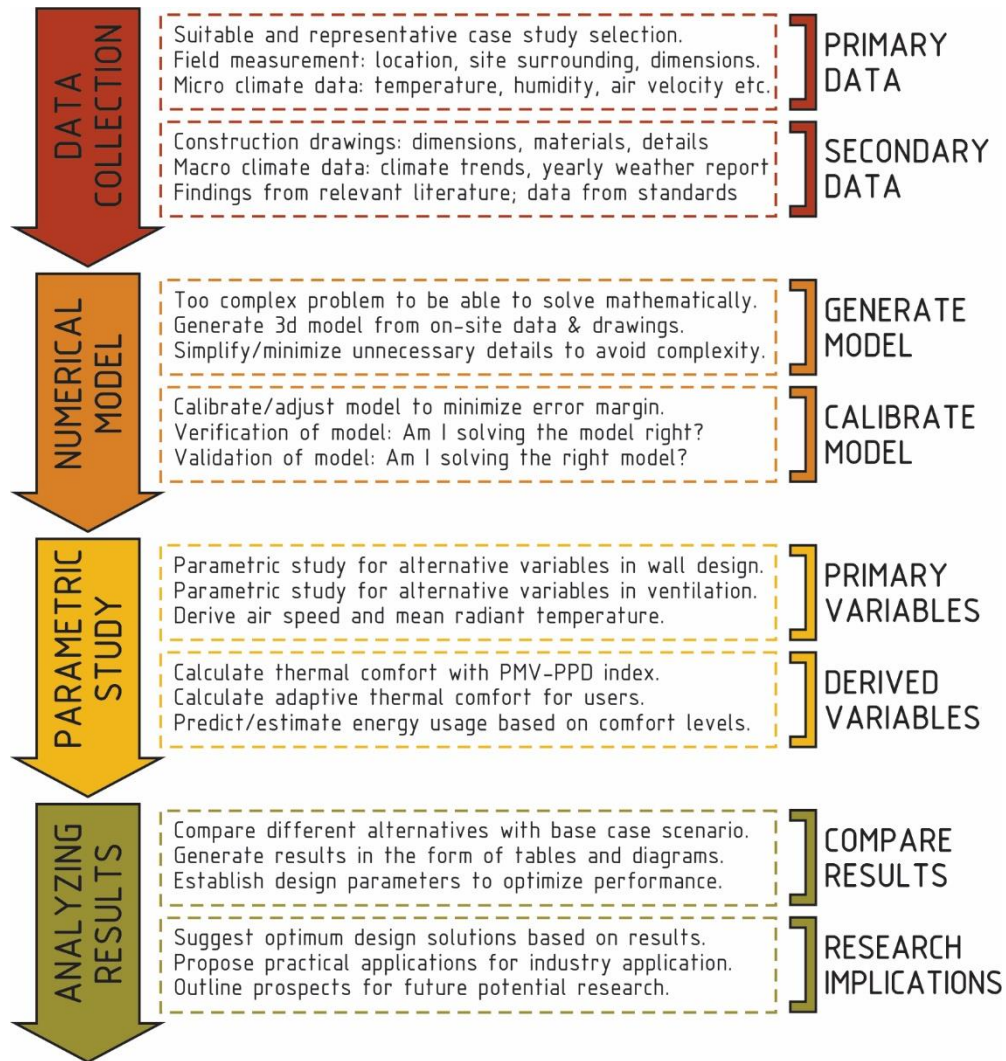


Figure 3.1: Flow chart of the methodology of research.

3.2 Study Decisions

Before proceeding with the research, some study decisions had to be made with regard to the case study mosque and selection of suitable simulation software. This section discusses the procedure and justifications for the selection.

3.2.1 Case Study Selection

The different types and categories of mosques in Malaysia have been highlighted in Section 2.4. A suitable representative of the typical Malaysian mosque needed to be selected

in carrying out this research. The case study mosque would be located in Kuching, Sarawak for ease of data collection and would fulfill the following requirements:

i) Medium-sized mosque catering to daily and Friday prayers: As stated in the objectives, this research aims to lower the need for HVAC interventions through the modulation of building design parameters, especially during lower occupancy periods. The smaller mosques that accommodate only the daily prayers often have a full capacity during the prayers. Hence, operating the HVAC system for those timings is justified as the energy is not being wasted to cool empty portions of the mosque. Both medium and large mosques have variable occupancy patterns with high occupancy during *Jumuah* and a significantly lower occupancy during the daily prayers. However, large mosques are often of monumental scales which would be resource-intensive to simulate numerically. Additionally, as a symbol of iconic design, large mosques have various design styles which may not make the results and findings universal. Since medium sized mosques are more common in Malaysia, a case study of such a prototype would be representative of the typical Malay mosques.

ii) Situated at a comparative less dense urban setting: Urban mosques may be subjected to additional heat gain from the reradiation of the built-up areas of the surrounding context. In order to minimize the effects of external elements and only focus on the mosque building design, mosques situated in areas with less urban density would be suitable. Such a case study would allow for unbiased testing of the environmental factors that play a role in the thermal comfort of the occupants.

iii) One large prayer hall with the auxiliary spaces situated separately: Although some mosques may have a mezzanine level, only mosques that are single-storied will be considered. Typically, medium sized mosques have a multiple volume prayer hall to

maintain the aspect ratio of the space. Moreover, preference will be given to where the prayer hall is a single standing structure with the auxiliary and service spaces located at separate wings. These criteria will help identify and solve for the most critical design elements of the prayer hall.

The suburb of Batu Kawa in Kuching was selected as a suitable location for the case study mosque. A google search indicated a total of six mosques or free-standing *surau* buildings within the area (Figure 3.2). After preliminary inspection of the sites, it was found that three of those were only for daily prayers; one was closely situated with other buildings in the compact neighbourhood while the other had auxiliary spaces immediately next to the main prayer hall. Only *Masjid Darul Ibadah* (indicated in a red box in the figure) was found to be fulfilling all the requirements mentioned above (Figure 3.3). As an added benefit, this mosque is commissioned and maintained by *Tabung Baitulmal Sarawak* which is a government-funded organization established by the *Jabatan Agama Islam* (Department of Islamic Religious Affairs) of the Sarawak state government. Hence, access to the design drawings and electricity bills was possible with necessary clearance and permissions. Details on the design of this case study mosque are discussed in subsequent sections.



Figure 3.2: Field survey of mosques in Batu Kawa, Kuching, Sarawak.



Figure 3.3: Outside view of selected case study mosque, *Masjid Darul Ibadah*.

3.2.2 Software Selection

A detailed discussion of the different types of numerical tools used for the parametric analysis of thermal comfort and energy usage has been provided in Section 2.2.3. In order to avoid repetition, the scopes and limitations of BES and CFD softwares are not mentioned here. Nevertheless, the justification and suitability of the softwares in light of the space and occupancy of mosques is provided in this section. There have been different types of simulation softwares used for studies in the context of mosque buildings. A comparative

study is shown in Table 3.1 so as to identify the best suitable option that may help fulfill the objectives for this particular project. This table includes the pros and cons as well as examples of literature using the respective softwares in studying mosque building design. It can be seen that the predominantly used numerical tools are BES softwares like EnergyPlus, DesignBuilder, VisualDOE etc. These softwares assume that indoor air is perfectly mixed and has a uniform temperature. In real-life scenarios, that is not the case since the HVAC systems are intermittently operated in the mosques. Additionally, such softwares consider thermal comfort optimization in terms of HVAC usage parameters, and ventilation in the form of ACH of the HVAC systems. It may be noted that although most simulation softwares allow general modification of the occupancy schedule input, it does not specifically cater for the intermittent type operational schedule of mosques. Hence, while a BES tool may be useful in predicting and optimizing energy usage, it may not be suitable for thermal comfort analysis.

CFD softwares are more capable of quantifying and assessing comfort conditions in a passive system without HVAC, as it takes into consideration all the variables of thermal comfort. Since this study is focused on optimizing the thermal comfort of occupants without the intervention of active means of thermal control, using CFD software would be more suited to the objectives set for this research. CFD mathematically simulates fluid flow and heat transfer associated with human thermoregulation and calculates the thermal comfort of occupants as a result output. It also takes into account both shortwave and longwave radiations, which are important parameters for thermal comfort in HH climates. Amongst many available CFD tools, Autodesk CFD was chosen due to its interconnectivity to the building information modelling (BIM) software Autodesk Revit. BIM provides data for material properties that may be imported into the CFD program as an option. Hence, the

iterative process of designing, tweaking, and simulating can be smooth. Studies have shown that this software provides stable results, especially when simulating indoor conditions (Naboni et al., 2017b). Other research has shown that although Autodesk CFD may exhibit temperature discrepancies when simulated for long-term, year-round studies, it performed exceptionally well for diurnal simulations (Albatayneh et al., 2017). Additionally, this software provides options for dynamic thermal modelling (DTM) which predicts the way a building responds when subjected to external environmental factors. Hence, this software proved to be a suitable option for fulfilling the research objectives for this project. In addition to interoperability with Autodesk CFD, Autodesk Revit also serves as a baseline software tool for other BES programs such as Autodesk Insights, EnergyPlus etc. Therefore, further research may also be carried out in the future for this same case study mosque to analyse the HVAC usage optimization.

Table 3.1: Comparative analysis of simulation softwares.

Software	Pros	Cons	Examples
EnergyPlus	<ul style="list-style-type: none">• Free software.• Widely used.• Validated and accepted in academia and industry.	<ul style="list-style-type: none">• Complicated interface requiring technical knowledge.• Requires detailed input which might not be available during the initial designing phases.• Considers indoor as a uniform space without variation in air temperature.	(Samiuddin & Budaiwi, 2018) (Alabdullatief et al., 2016) (Al-Homoud et al., 2005a)
Ecotect	<ul style="list-style-type: none">• Easy to use interface.• Student version available.• Requires minimum input.	<ul style="list-style-type: none">• The product has been discontinued• Considers the indoors as a homogeneous space.• Does not calculate for natural ventilation.	(Mushtaha & Helmy, 2017) (Asfour, 2009) (Al-Shamrani et al., 2016) (Sugini et al., 2017)
Design Builder	<ul style="list-style-type: none">• Easy to use interface.• Detailed energy analysis.• Visual output and data analysis tools.	<ul style="list-style-type: none">• Paid software.• Calculates indoor as a homogeneous space.• Does not consider air flow and buoyancy for natural ventilation.	(Alabdullatief, 2017) (Alabdullatief et al., 2019) (Abdallah, 2019) (Bughrara et al., 2018)
VisualDOE	<ul style="list-style-type: none">• Easy to use interface.• Detailed energy analysis.• Visual output and data analysis tools.	<ul style="list-style-type: none">• Paid software.• Calculates indoor as a homogeneous space.• Does not consider air flow and buoyancy for natural ventilation.	(Al Anzi & Al-Shammeri, 2010) (Budaiwi, 2011) (Budaiwi et al., 2013) (Budaiwi & Abdou, 2013)

Table 3.1 continued

Others: BLAST EnerOPT eQuest PC-DOE	<ul style="list-style-type: none">• Each software code is designed for a specific type of research methodology and is best suited for that particular type of research.• All are BES softwares.	<ul style="list-style-type: none">• Usually paid softwares.• Designed for a specific type of study and not suited for general usage.• Not very user-friendly interface.	(Al-Homoud, 2009) (Hameed, 2011) (Al-Shaalan et al., 2014) (Mohammad and Khalid, 2014)
CFD (Commercial Ansys CFD software is the most commonly used)	<ul style="list-style-type: none">• Student versions available• Takes into consideration air flow and buoyancy effects for natural ventilation.• Takes into consideration variations in thermal comfort.	<ul style="list-style-type: none">• Complicated interface requiring technical knowledge.• Requires extensive knowledge of thermodynamics and fluid dynamics for correct interpretation of results.• Time-consuming and resource-intensive simulations.	(Khalil et al., 2013) (Noman et al., 2016) (Hussin et al., 2020b) (Mohammed et al., 2020)

3.3 Data Collection

Data collection involved primary data collected on-site as well as secondary data gathered from relevant literary sources, which have been referenced where appropriate. Extensive data collection was carried out for three months from February 2020 to April 2020. The main types of data that were necessary to carry out this study are as follows:

i) Measurement and construction details of the building in order to create an accurate computerized numerical model.

ii) Objective environmental data from the site as well as from meteorological sources for defining the simulation settings and the validation of the simulation results.

iii) Values for the personal and environmental factors influencing the thermal comfort of the occupants to assess the comfort conditions.

In addition to these, an energy audit was also carried out and the operational schedule was monitored to assess the probable energy savings that may be achieved through improving the comfort conditions for the occupants.

3.3.1 Field Measurements

Detailed physical measurements were taken on-site for the case study mosque. Supplementary information, such as detailed working drawings and construction information were obtained from the archives of the *Tabung Baitulmal Sarawak* office. The accuracy of the gathered data was cross-referenced with the engineers' construction drawings. The mosque compound is of a rectangular shape of approximately 75m x 180m and has a built-up area of 1060 m². The main prayer hall is ~500 m² in area and is oriented according to the *Qiblah* direction which is 292° NW for Kuching, Sarawak. The *Qiblah* axis

runs through the centre of the square prayer hall, with the *Qiblah* wall remaining exposed to the western sun (Figure 3.4). The design is symmetrical with two detached service wings on either side of the prayer hall housing the auxiliary spaces. The southern wing consists of the management office and storage while the northern wing contains the kitchen, toilets and ablution areas (Figure 3.5). However, since the mosque is maintained by the *Tabung Baitulmal Sarawak* office situated right next to the mosque, the management office remains unoccupied. More details on the existing design of the mosque and computer modelling will be discussed in Section 3.4.

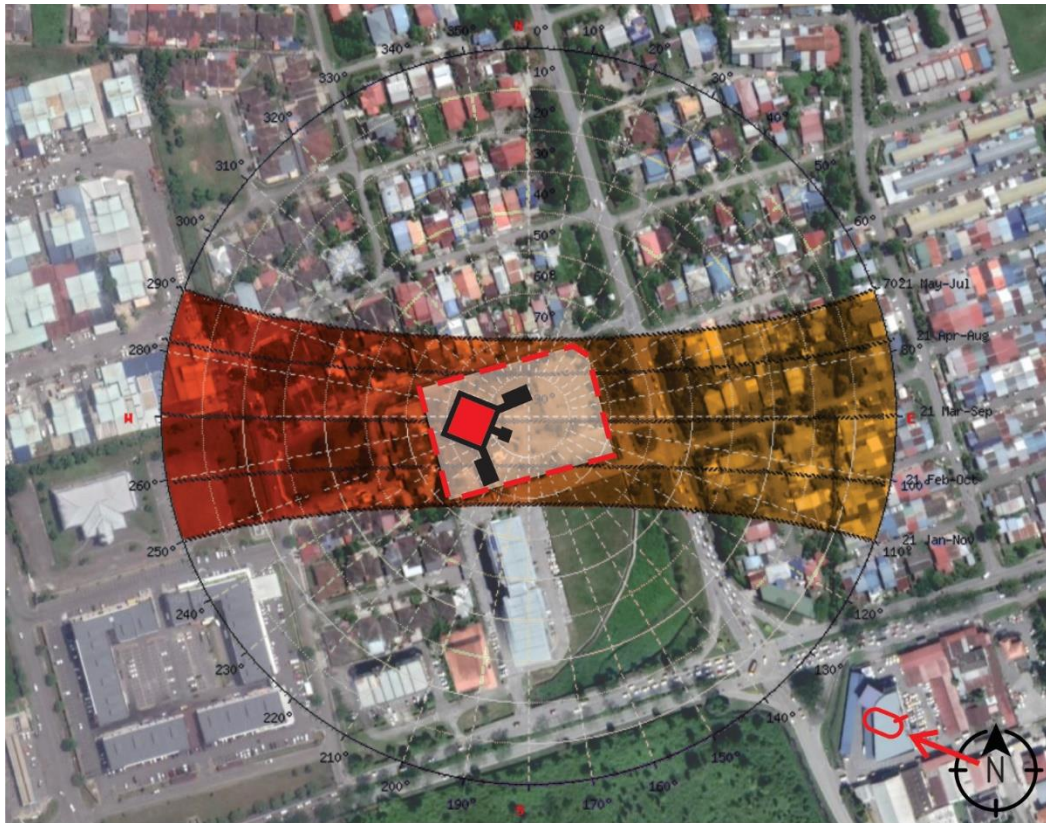


Figure 3.4: Yearly sunpath for the case study mosque, *Masjid Darul Ibadah* (located at 1.52° N, 110.32° E).



Figure 3.5: The main prayer hall with two service wings on either side.

3.3.2 Macro Climatic Data

For any environmental analysis, the climatic context of the building is the most important consideration. Yearly meteorological data provides the climatic backdrop against which design considerations are to be assessed. According to the World Meteorological Organization, the weather station in Kuching is identified as WMO # 964130. The data for this weather station can be accessed from the EnergyPlus website in the form of *epw* weather files (EnergyPlus, 2021). This is the most commonly used weather data file for building engineering purposes, which is funded and developed by the U.S. Department of Energy (DOE) (Crawley et al., 2004). For Malaysia, the available weather data is of a typical meteorological year (TMY), also known as historical weather data. Such files provide hourly data for the whole year that has been derived from the Integrated Surface Database (ISD) maintained by US National Oceanic and Atmospheric Administration (NOAA). It is considered to be one of the most authentic weather resources that reflect recent climate conditions and is recommended by ASHRAE for building performance and energy analysis (Crawley and Lawrie, 2015).

The data from the *epw* weather file was imported into the Climate Consultant software tool (Milne et al., 2009) to visualize the prevalent climatic conditions. Thereafter,

plots were generated to show the temperature, humidity and solar radiation conditions, which are provided in Appendix D. Additionally, a total of 8760 points for hourly temperature-humidity data was extracted for the whole year, which has been juxtaposed on the bioclimatic comfort chart developed by Givoni (1998) (Figure 3.6).

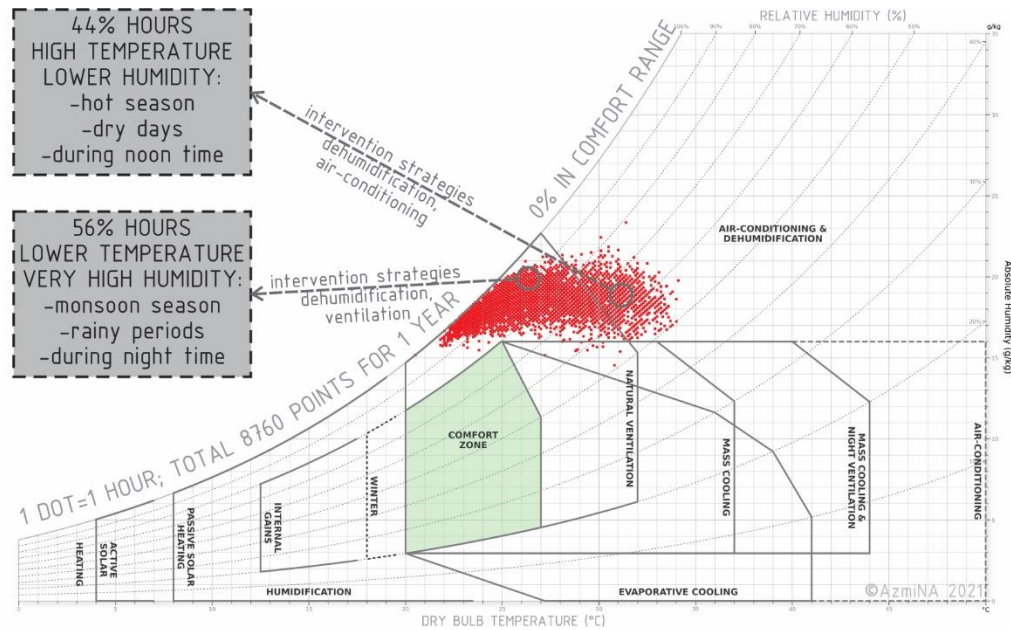


Figure 3.6: Psychrometric chart showing hot-humid climate conditions of Kuching, Sarawak.

The climatic diagrams in Appendix D show that Kuching has year-round hot weather where the temperature generally remains within the range of 22-34 °C. Year-long high sky-cover and high humidity are also characteristic of this climatic zone. Hence, although situated near to the equator, the direct solar radiation is comparatively lower than the theoretical calculation due to regular cloud coverage. Timetable plots for both dry-bulb temperature and relative humidity show that generally, the trend is similar throughout the year. However, the temperature ranges are slightly higher from April to September, while the humidity ranges are higher from November to February. These two seasons are generally referred to as the hot and monsoon season, respectively. The above psychrometric diagram

also clearly depicts the characteristic properties of HH climates with high temperature and high humidity resulting in conditions constantly beyond the comfort zone. As mentioned previously in Section 2.2.2, enhancing thermal comfort in buildings of such climates is generally achieved through utilizing HVAC systems. The HVAC system lowers both the temperature and humidity, moving the temperature-humidity plot points within the comfort zone. On the other hand, modulating the air speed and MRT helps shift the comfort zone to the right of the figure, allowing for comfort conditions at higher temperatures and higher humidity levels. This is the inherent principle of designing passive systems, which is also a part of the objectives of this research. Further elaboration on how the comfort zone is shifted due to change in MRT and air speed will be discussed in the results chapter.

3.3.3 Micro Climatic Data

The previous section discusses the macro-climatic data for the city of Kuching. For studies conducted at building scale, micro-climatic information is also required for the specific geo-location. From Figure 3.7 it can be seen that the data collection period partly coincides with the monsoon season. During this season, the temperatures are lower, humidity is higher, and the high cloud coverage results in lesser sunhours. However, the numerical analysis will be carried out for the month of June, which is the hottest month of the year, to test for the worst-case design-day scenario. The equipment used for the data collection of the environmental parameters are depicted in Figure 3.8, along with the technical specifications. The inside surface temperature of the *Qiblah* wall was monitored while air temperature, humidity, and air speed data were collected for both outdoors and indoors. All data were collected at the recommended height of 1.0-1.2 m for human relevance. Initially for indoors, the data was collected for three points at the front of the prayer hall near the *Qiblah* wall and three points near the back of the hall. However, the readings for all the front

data points and the back data points were very similar. This is because thermal stratification of air happens vertically, and not horizontally, due to the buoyancy of air. Therefore, under natural ventilation conditions and no forced or added ventilation, there is very less variation in the readings between the closely situated data points. Hence, data readings were continued to be collected at two points, one at the front and one at the back. Outdoor data was collected at a shaded area outside the prayer hall to ensure that the direct solar radiation does not influence the readings on the thermometer.

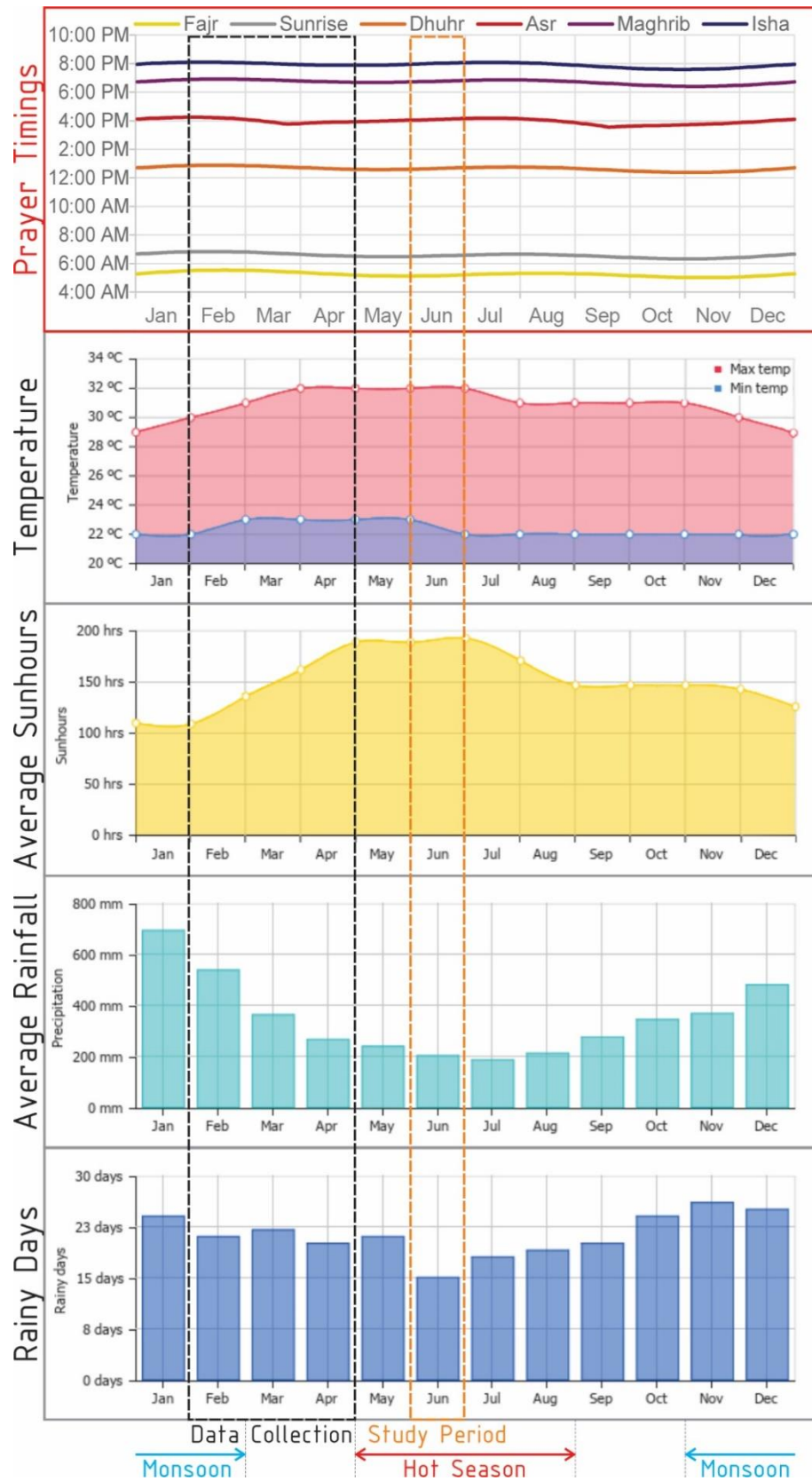


Figure 3.7: Yearly prayer timings and climatic conditions for Kuching, Sarawak.

TA 888 Hot-wire Anemometer	Testo 625 Thermo-hygrometer	FLIR E4 Infrared Camera
		
<u>Temperature Range:</u> -10 to +60 °C <u>Airspeed range:</u> 0.1 to 15.0 m/s <u>Error Margin:</u> ±5% of full scale reading	<u>Temperature Range:</u> -10 to +60 °C <u>Humidity Range:</u> 0 to 100% RH <u>Error Margin:</u> ±0.5 °C, ±2.5% RH	<u>Temperature Range:</u> -40 to 70 °C <u>Humidity Range:</u> 0 to 95% RH <u>Error Margin:</u> ±2% of reading

Figure 3.8: Equipment used in data collection.

From the continuous monitoring of the environmental factors, four distinct types of days were observed:

i) Type A: Hot day with no rainfall and minimum cloud cover. Temperature peaks during the afternoon when the humidity is at the lowest. Thereafter, the temperature falls, and humidity rises into the night.

ii) Type B: Hot day with no rainfall but regular cloud coverage, occasionally blocking direct solar radiation. Similar to Type A days, the temperature peaks during the afternoon but is typically less hot. The humidity is also lowest during the afternoon but not as low as Type A days.

iii) Type C: Hot day with rainfall towards the afternoon. The day starts typically as Type A or Type B. However, there is some rainfall during the afternoon when the humidity

rises and the temperature falls. After the rainfall, the temperature and humidity settle down but are less extreme than either Type A or Type B days.

iv) Type D: Heavy cloud coverage with occasional light or heavy rainfall throughout the day. The temperature remains much lower than the other days while the humidity is considerably higher and typically, always remains over 90%.

The temperature and humidity graphs of 23, 26, 22 and 27 April are provided in Figure 3.9 as representative days for the identified categories of Types A, B, C and D, respectively. It should be mentioned that these four types with a similar general trend were observed irrespective of monsoon or hot season. During wetter seasons, Type C and D days were prevalent while during April, Type B and C days were more common. It may be predicted that during June to August there would be more Type A and Type B days as the climate is drier during those months. It is worth noting that during the data collection period, the air speed of the outdoors was found to be nearly non-existent with erratic gusts that did not show any prevalent pattern. With extended balconies, the indoors would observe very little air movement only during seldom-observed, stronger airflow situations. Thus, a decision was made that testing the scope for natural ventilation as part of the second objective of this research would be done for 0 m/s air speed to examine for the worst-case ventilation scenario.

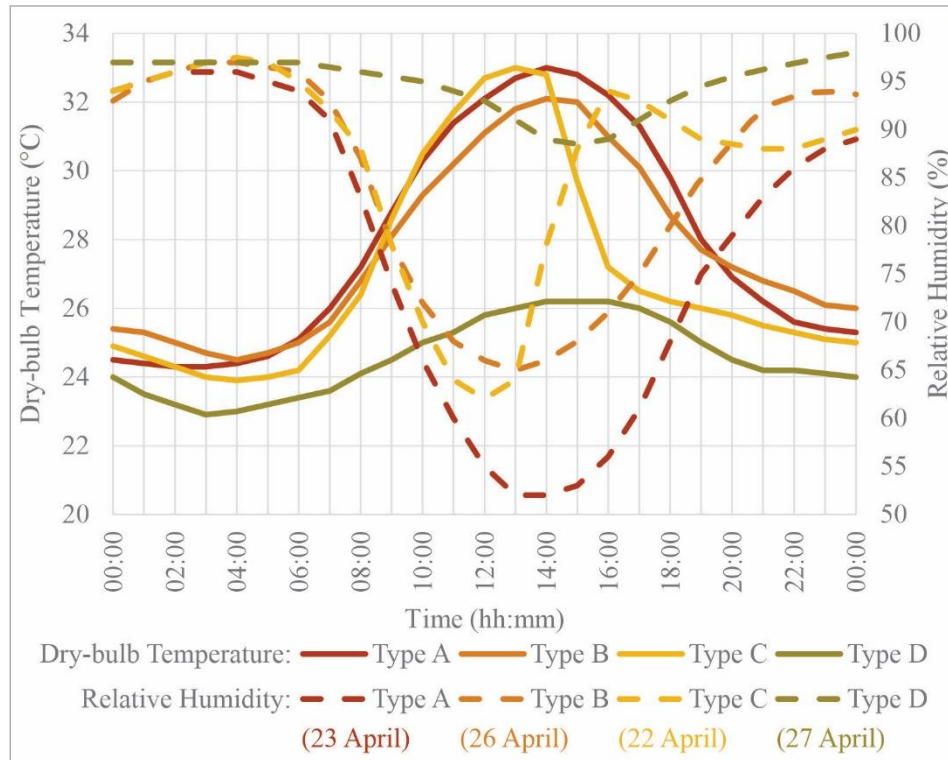


Figure 3.9: Identified four types of days for the Malaysian climate.

Figure 3.10 shows the wall surface temperature, outdoor temperature, and indoor temperature readings for 23 April, a Type A day scenario as identified above. This day can be considered as a worst-case design-day scenario for April. It can be seen that the temperatures of the indoor data collection points closely follow the outdoor temperature with very little variation between the front and the back portions of the mosque. The indoor humidity values are also very similar to the outdoor conditions, which is not shown to simplify the figure. It is interesting to note that from the late afternoon time, the indoor temperature remains higher than the outdoors. This is at par with findings from other literature discussed in Section 2.3.4 where the indoors of naturally ventilated mosques are hotter than ambient outdoor temperature due to residual heat build-up. The figure shows that the temperature gradually lowers during HVAC operation timings, and sharply spike back immediately after the system is switched off. Although there is a considerably lower

temperature for the prayer times, the HVAC system only helps reach the recommended comfort conditions during *Fajr* and *Isha* prayers for a hot day. It is worth repeating that this comfort range has been derived for a humidity level of 50%, as alluded to previously in Figure 2.5. However, for both *Fajr* and *Isha* prayers, the humidity level is significantly higher for the HH climates of Malaysia. The impact of such humidity levels will be analysed in the next chapter when assessing the thermal comfort conditions holistically.

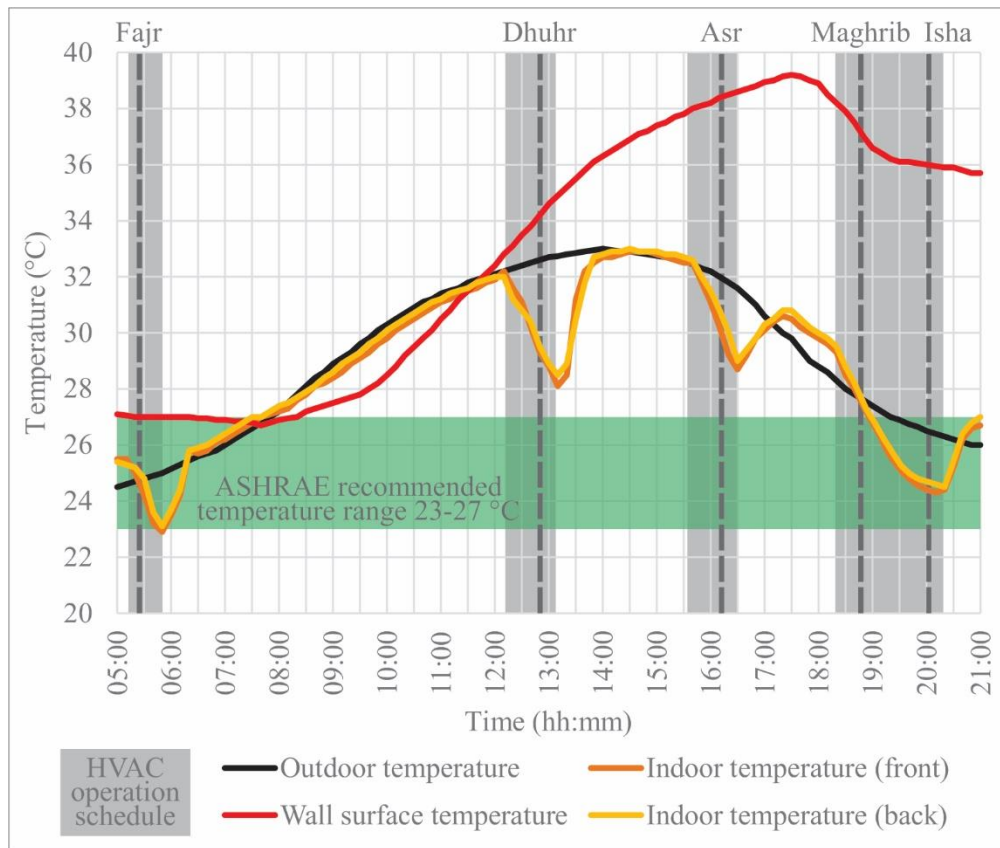


Figure 3.10: Field data for 23 April as a representative hot day for design considerations.

Since Malaysia is located near the equator, the prayer timings vary only slightly throughout the year as the days are of similar duration for such geolocation (Figure 3.7). Hence, a representative hot day of April would suffice for validation of the numerical model. In subsequent sections, the outdoor temperature values from this day (Figure 3.10) will be input for the numerical simulation settings. Thereafter, the numerical model will be validated

by comparing the simulated results with the readings from the two indoor data collection points. Afterward, the simulations will be run for a Type A day for the month of June to test the design alternatives for the absolute worst-case scenario of the year.

3.3.4 Occupancy Pattern

During the data collection period, the occupancy characteristics and operational profile of the mosque were monitored as well. Typically, mosque floor area per person is calculated at 1 m² both in literature (Al-Homoud et al., 2009) and according to standards (Malaysia, 2014). However, it was found that people generally stand in closely packed rows, resulting in an occupancy area of 0.7 m². A similar occupancy area was also seen in other literature (Alashaab and Alamery, 2018) where rows of congregants were considered. Hence, the occupancy percentage was calculated with respect to the existing practice. The clothing insulation and metabolic rate were assessed according to the ASHRAE guidelines (ASHRAE, 2017a) and were determined at 0.6 clo and 1.2 met, respectively. This is coherent with other thermal comfort studies carried out in the context of Malaysian mosques (Hussin et al., 2015). The occupancy timings and operational schedule are determined according to the prayer times which is dependent on the solar position. As seen in the previous section, the timings for the prayers vary within a small range of 15-25 mins throughout the year (Figure 3.7). However, instead of a fixed timing for operation, the schedule is maintained with respect to the beginning of each prayer time when the *adhaan* (call to prayer) is given. The timing for the congregational prayer as well as the operational schedule of the HVAC system is calculated with reference to this time and is maintained meticulously by the caretaker of the mosque.

Figure 3.11 shows the operational timeline for different facilities within the mosque along with the occupancy period calculated from the *adhaan* timing. Overall, the mosque operation schedule is calculated at approximately 4.5 hours daily, which is half of typical non-residential building types. It can be noticed that the standard protocol is to turn on the HVAC system well ahead of the congregational prayer time except for the *Fajr* prayers, which was alluded to in Figure 3.10. It must be mentioned that although *Maghrib* and *Isha* timings are shown separately in this figure, in reality, there is approximately one hour gap between the end of *Maghrib* and the beginning of *Isha* prayers. During this time, the HVAC system is not switched off and the total continuous duration for HVAC operation is just above 2 hours in total (Figure 3.10). This figure also depicts that the lights are turned off during the daylight prayers, i.e. *Dhuhr* and *Asr*, while the fans are turned off for *Fajr* and *Isha* prayers. Once again referencing the temperature readings from Figure 3.10, it could be seen that only during the *Fajr* and *Isha* prayers the temperature is within the comfort range as prescribed by ASHRAE. However, at such temperature conditions, an added air movement from the fans would induce a feeling of cold. Hence, the fans are kept switched off during *Fajr* prayers while the users habitually turn off the fans when the temperature gradually lowers after the *Maghrib* prayers.

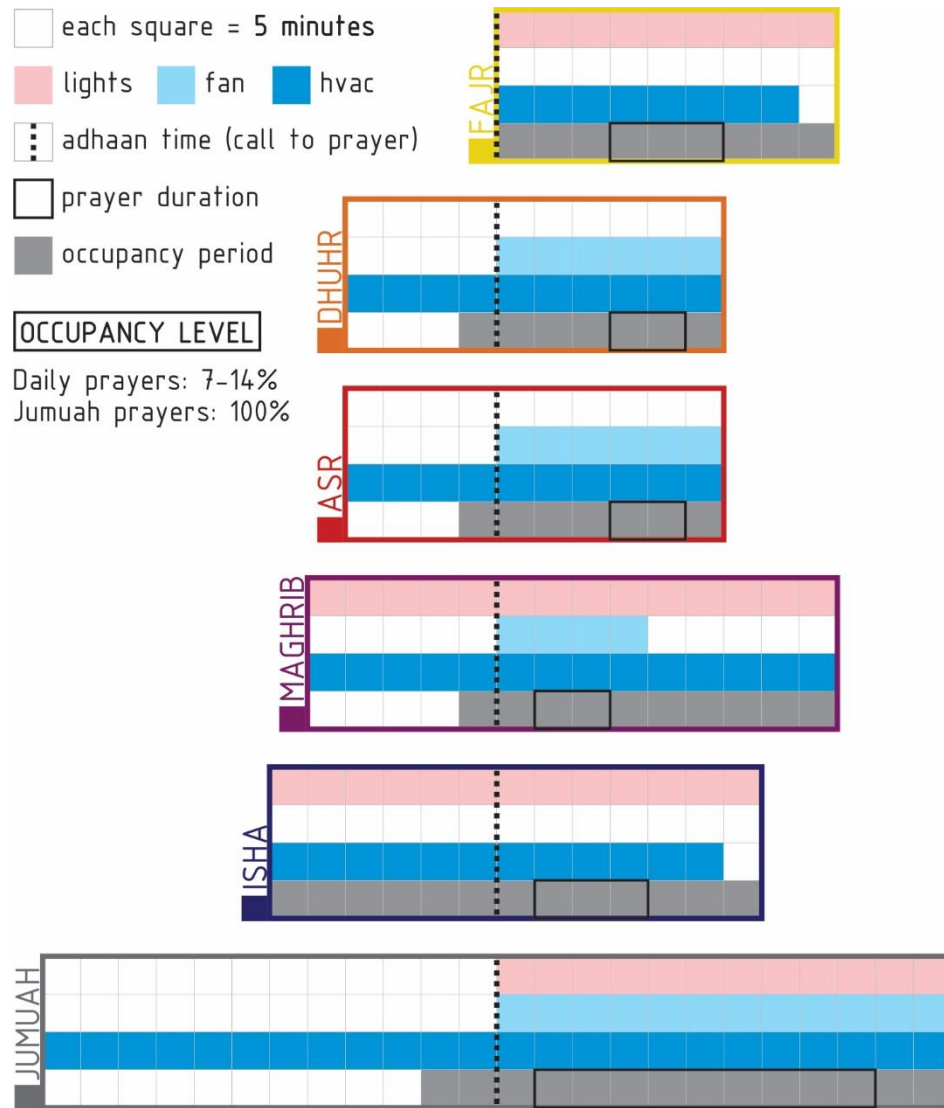


Figure 3.11: Mosque operational schedule and occupancy period.

3.3.5 Energy Audit

Continuous daily tabulation of electricity usage was done during the data collection period (Figure 3.12). This figure represents all types of days as classified in Section 3.3.3, for both the rainy season and the hot season. However, very little variation within the electricity expenditure was observed for all other days except Friday. This is because the HVAC system is operated according to a fixed schedule as outlined in the previous section, irrespective of the prevalent outdoor weather conditions. The energy usage is higher for

Fridays as the *Jumuah* prayers have full occupancy for longer times, and with additional fans operating during this period. Additionally, on some Fridays, or during occasional Saturdays there are extra community events such as lectures or wedding solemnization. The electricity usage is higher for the additional 1-2 hours of operation timing on those days. In addition to electricity usage monitoring, the past few years' energy usage information was also gathered to assess the electricity usage pattern. Further calculations on the itemized data usage, daily and monthly energy expenditure, as well as the yearly EUI, will be provided in the results chapter. Such analysis will help identify the relationship between mosque thermal comfort requirements and energy usage patterns, which is the first objective of this study.

Figure 3.12: Daily energy usage pattern for case study mosque.

3.4 Base Model Formulation

building at such a large scale. However, it could be seen that some minor design modifications were made which were different from the detailed drawings, such as, position of windows or dimensions of doors. In such instances, actual measurements were used whilst modelling. Figure 3.13 shows the 3D model of the prayer hall within the site boundary. It must be noted that the service wings on either side were excluded from the modelling as these structures do not impact the thermal comfort of the occupants during prayer times. Oftentimes in literature, CFD analyses are carried out with partial models of the case study where the findings are extrapolated from the results of such sections. However, this study is focused on the MRT component of thermal comfort, which requires modelling of the whole prayer hall for accurate calculations. The model also included the shaded balcony area which acts as a spillover space during high occupancy timings. This is due to the fact that the external shading of the balcony impacts the MRT of the interior and such modelling was necessary for realistic results. Henceforth in this thesis, only the main prayer hall with the accompanying balcony will be referenced for the numerical analysis.

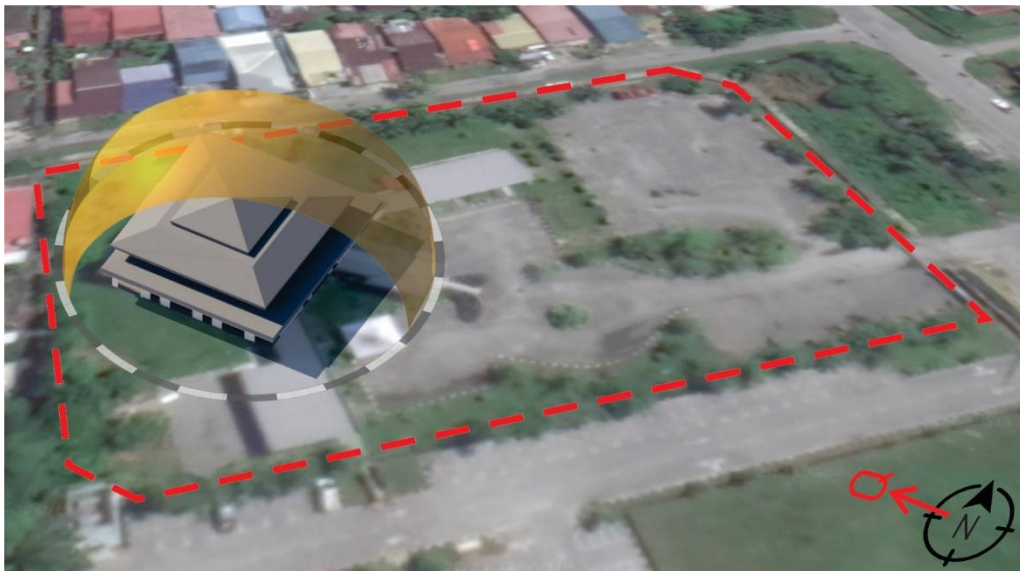


Figure 3.13: 3D model of the prayer hall showing orientation towards the *Qiblah* axis.

Figure 3.14 shows the isometric view of the mosque depicting the layout grid. The hall is a multiple-volume space with the highest point inside measuring at 9 m. This figure also illustrates the two data collection points at the front and the back. The modelling was done with one row of congregants, which is the most typical scenario for the daily prayers. The details of the roof inner-structure were not modelled, and each roof volume was considered as a single element. The roof structural components do not directly impact the thermal comfort of the occupants and hence, such a simplification will make the model less complicated. The equivalent thermophysical property for such simplified geometry will be considered in the material properties. The figure is provided in monochrome although Autodesk Revit allows options for material rendering. This is because the materials' settings and properties will be input in the Autodesk CFD software. The following subsections elaborate on the modelling process and different aspects of the base model.

minimal. The simplifications of such components in the 3D model are described below and illustrated in Figure 3.15:

(A) Lights were not included in the 3D model. There are a total 60 LED downlights of 24W in the mosque. Some hand calculations were done to determine the heating effect of such lighting fixtures at the distance of over 6 m from ground. Since the impact is negligible, the lighting fixtures were not modelled.

(B) Ornamentation and decorations such as wall hangings, clocks etc. were not modelled.

(C) Furnitures such as chairs, tables, small bookstands etc. were not modelled. Similarly, the *Mimbar* (pulpit) was not modelled as well.

(D) The ceiling was modelled separately to the outer roof massing (as shown previously in Figure 3.14). As the ceiling is in view range of the prayer area, it would impact the MRT of the occupants.

(E) Bookshelves were modelled as a niche in the wall, without the detailed components.

(F) Complex geometry such as door and window frames were removed from the model. The equivalent thermophysical qualities will be accounted for in the material properties.

(G) The fans were modelled as it would be a part of the simulation for ventilation purposes. However, the supporting stand and base were removed to reduce number of elements.



Figure 3.15: Interior of the mosque (top), and the simplification of the 3D Revit model (bottom) for simulation purposes.

3.4.2 Building Components' Information

Information regarding the types of materials and finishes were obtained from the working drawings of the building. Various building materials' information and detailed properties were obtained from industrial manuals, manufacturers' details, technical information datasheet for the respective brand and type of material used in the construction. These were cross-referenced with engineering handbooks (Thomas, 2006), ASHRAE fundamentals (ASHRAE, 2009), and building bylaws (Malaysia, 2006) to calculate the R value, U-value, and solar heat gain coefficient (SHGC) which are provided in Table 3.2. The properties of the building components should be represented accurately whilst modelling as these determine how much heat is stored or transmitted, and how long it takes the energy to reach the interior.

Table 3.2: Details for building components' configuration.

Building Component	Details	Notes
Roof	Steel roof structure with rafter and purlin to engineer's details and fitted with 0.47mm roofing sheet of aluminium/zinc alloy-coated steel. Interior includes double sided sisalation reflective layer and 300mm layer of lightweight rockwool of 40kg/m ³ density, supported with a layer of wire mesh.	Overall for roof + ceiling: R-value: 3.8 m ² k/W; U-value: 0.26 W/m ² k
Ceiling	9.5mm gypsum ceiling board of 1200mm x 500mm dimension supported with 3.2mm MS channel.	

Table 3.2 continued

Floor	300mm x 300mm glazed ceramic tiles with 10mm carpeting.	
Structure (Columns and beams)	Trabeated structure of 500mm x 500mm columns with 300mm x 600mm beams at level 1 and 300mm x 300mm beams supporting the roof; 13mm cement sand plaster on all sides and finished with paint.	
Wall	95mm single brick wall with 10mm cement sand plaster on either side and finished with paint.	R-value: 0.32 m ² k/W; U-value: 3.13 W/m ² k
Window (Fixed)	5mm clear tempered fixed glass with aluminium frame fitted onto 3mm MS plate.	SHGC 0.9 U-value: 5.4 W/m ² k
Window (<i>Qiblah</i> side)	5mm clear tempered fixed glass and tint film with aluminium frame fitted onto 3mm MS plate.	SHGC 0.7 U-value 5.4 W/m ² k
Glazed doors	10mm tinted tempered fixed glass in aluminium frame on MS channel to manufacturers details.	SHGC 0.5 U-value 5.3 W/m ² k

3.4.3 Assessment Parameters

Figure 3.16 depicts the 3D model of the prayer hall showing the sunpath for Kuching. The afternoon sun always faces the *Qiblah* wall at 292° as the solar azimuth for the sunset ranges from 247° - 294° . Figure 3.17 illustrates the 3D rendering and the actual picture of the case study mosque showing the *Qiblah* wall. As this wall is typically exposed to the overheated afternoon sun, it would greatly affect the conductive as well as the radiative heat gain of the interior. This research will parametrically assess the *Qiblah* wall performance for different alternatives through numerical analysis. After validation and verification of the calibrated model, different sets of simulations will be carried out focusing on the *Qiblah* wall configuration of the mosque. A suitable best-case and optimized scenario will be selected where the thermal gain is minimized through the building envelope of this side, resulting in better comfort conditions for the occupants.

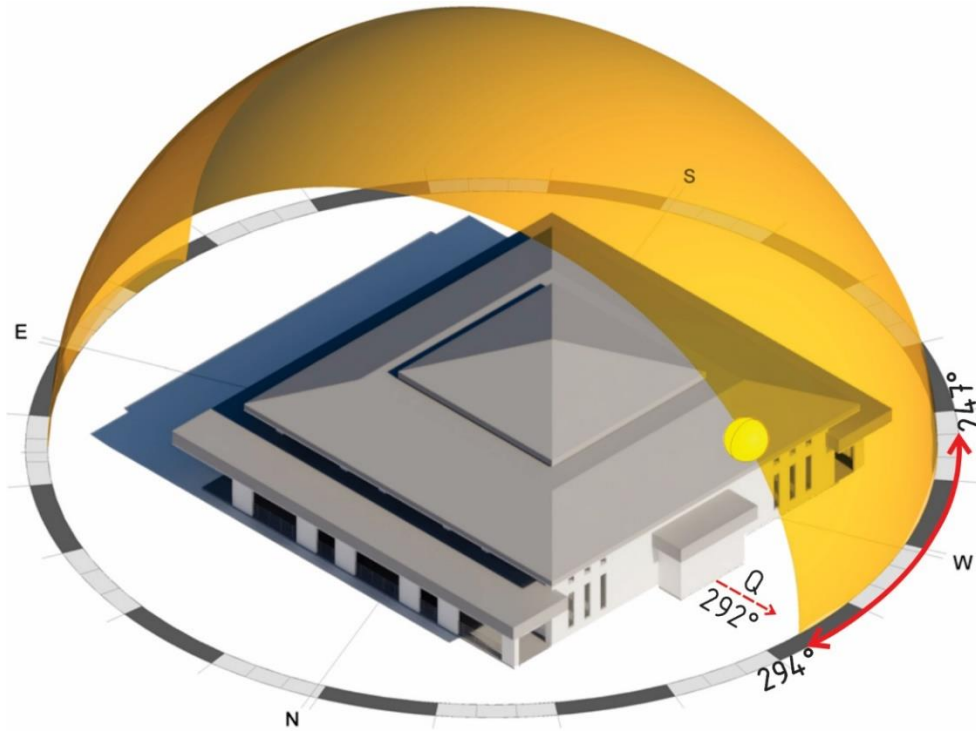


Figure 3.16: 3D model of the prayer hall with the sunpath.



Figure 3.17: 3D rendering and actual picture of the case study showing the *Qiblah* wall.

3.5 Numerical Simulation

Carrying out field experiments for the parametric study of building components is a costly and time-consuming process due to the scale of the involved components. In such instances, numerical analyses can provide a cost-effective approach for testing design alternatives in order to optimize the building components. Additionally, such analyses allow for carrying out simulations for different timings of the year as well as for different climatic and geographic conditions. Hence, for a large domain as in this study, and with so many parameters and variables involved, a numerical approach is the only feasible option. A numerical analysis is an iterative process to solve problems that are too complex to solve analytically (Figure 3.18). With the help of computer software, the parameters of the domain can be defined which is known as mathematical modelling of the physical problem. Thereafter, a set of solution criteria is defined in addition to coding the rules for the iterative

solving process. Figure 3.18 also relates the numerical solution procedure with the steps for solving thermo-fluid problems in a CFD platform. This figure is essentially showing the breakdown of phases (iii) and (iv) as described in Section 3.1.

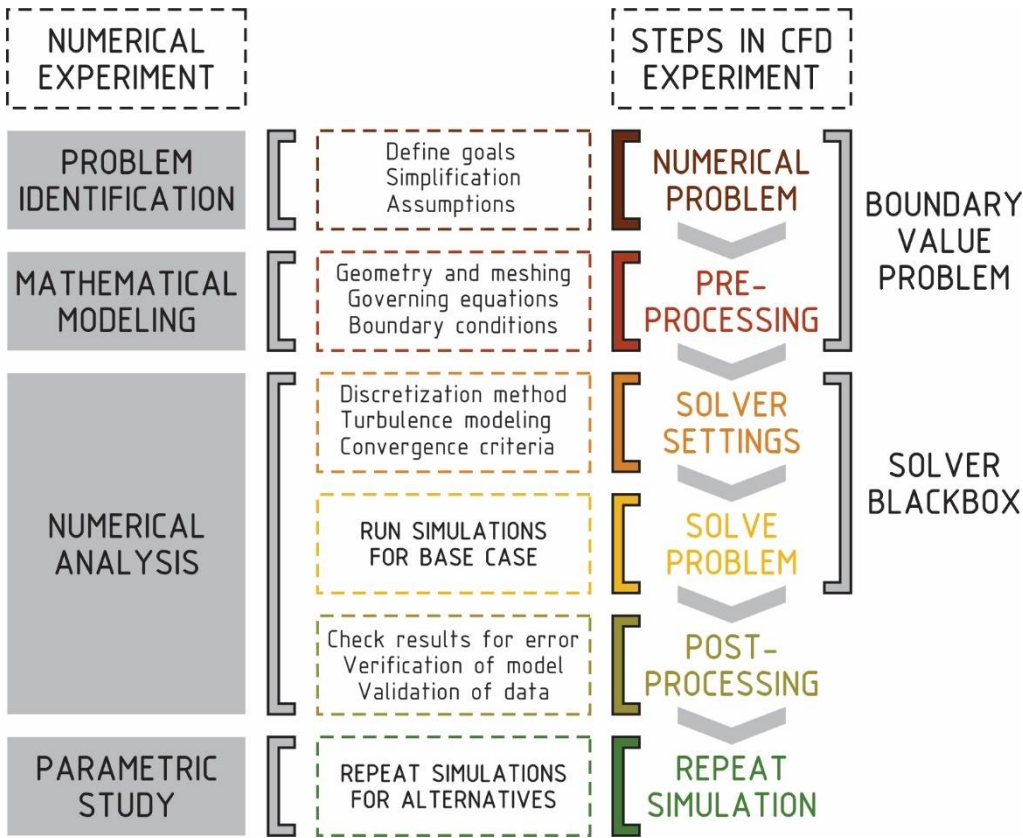


Figure 3.18: Process for numerical analysis.

Since Autodesk Revit and Autodesk CFD were chosen due to their interoperability, the created geometry described in the previous section can be directly imported into the CFD platform through a plug-in. However, this is a trial-and-error procedure where many criteria have to be ensured, such as no overlapping geometry, no small gaps, no unusual angled component etc. Having such geometry may cause the simulations to fail or produce wrong results. Hence, after importing the model, a thorough investigation has to be made to ensure the geometry is suitable for CFD simulations. If any inconsistency is observed, change can be made in the Revit platform, and the model re-imported into CFD. Thereafter, the different

parameters and solver settings are input in CFD, the details of which are elaborated in the following sections.

3.5.1 Model Geometry and Assumptions

For doing simulations involving solar loading and natural ventilation conditions, the external context of the building must also be considered to allow for DTM calculations. Hence, the ground and external air volumes are required to account for the reradiated and reflected heat of the surrounding. Autodesk best practice guidelines (Autodesk CFD, 2019) suggest a ground width of at least three to ten times the length of the building and the air volume height five to ten times the maximum building height. Depending on the setting of the surrounding context, the width needs to be on the larger side while more height is necessary for dominant wind speed conditions. The environment beyond this area may impact the outputs but would be negligible in terms of thermo-fluid modelling. The external volume should be cuboidal if there is any prevalent directional wind loading but can be spherical when such wind flow is not considered for the scenario. The contextual details within this external volume do not need to be modelled as the parameters for DTM can be input in the solar settings options, which will be discussed in Section 3.5.5. Since the case study building is situated in a less dense locality and the current analysis does not consider any high wind speeds, the modelling of the environment is done as illustrated in Figure 3.19. The recommended ground depth of 1 m is also modelled for DTM purposes.

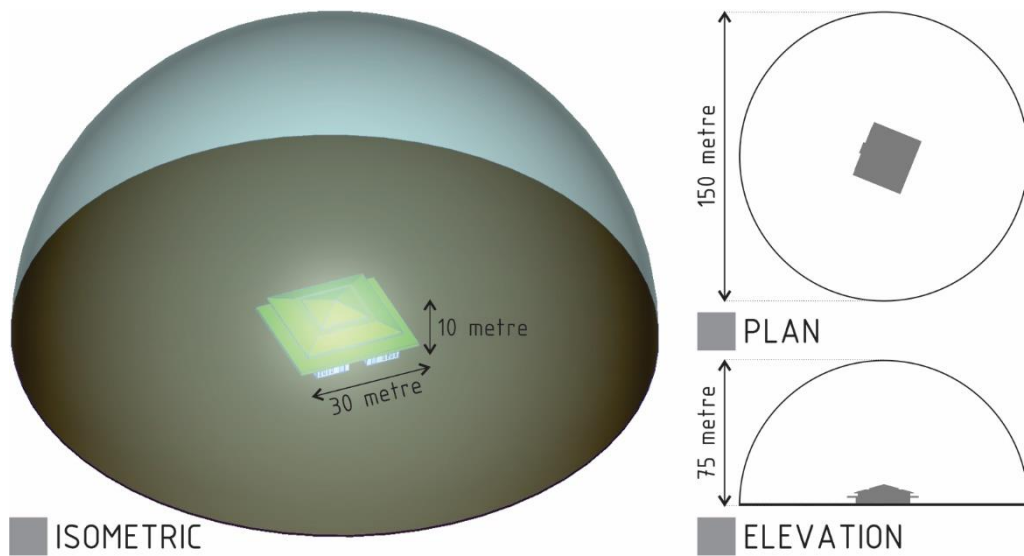


Figure 3.19: CFD model with ground volume and external air.

With the accompanying external ground and air volumes, the mathematical domain would be fairly large, making the simulations quite resource extensive. An overly detailed model requires a longer computational time and can often fail in the CFD software due to its complicated nature. Therefore, some further modifications needed to be made to remove or simplify the components that are not directly required to fulfill the objectives of this research. Some of these components were initially modelled in Revit, but later during the trial-and-error procedure of importing into CFD, it was deemed necessary to remove or simplify such components. Figure 3.20 compares between the case study building, the Revit 3D model, and the CFD model. The assumptions and simplifications are as below:

(A) The carpet and ground slab were not modelled separately. Rather, only one volume was modelled as the floor, which accounts for the overall thermophysical properties of both.

(B) The wall niche for bookshelves, which was modelled in Revit, was removed as it was insignificant for the thermal comfort of the occupants.

(C) Since this study will only be testing natural or mechanical ventilation by fans, the HVAC indoor units were removed. Positioned at more than 3 m height, these small volumes are not impactful for the thermo-fluid simulations.

(D) All glazed doors were modelled without the two middle panels, emulating opened doors for natural ventilation. In practice, these are left open in between the prayer times.

(E) Detailed model of humans was substituted with simplified geometry of 1.75m x 0.5m x 0.25m cuboids. The impact of breathing was ignored and only the standing position was considered. Although movement during the prayers can create slight turbulence, the significance of it for thermal comfort is negligible (Al Assaad et al., 2019).

(F) The columns and beams were removed, and the walls were represented as masses with no further details.



Figure 3.20: Interior of case study building (top), modelled in Revit (middle) and simplified model imported into CFD (bottom).

3.5.2 Material Properties

The materials were assigned, and properties were set up accordingly in the CFD interface. The BIM data from Revit as well as the default settings for materials in Autodesk CFD were validated against industry standards (CIBSE, 2013) and guidebooks (ASHRAE, 2009). In most cases, the setup was found to be aligned with empirical data in both the Autodesk softwares. Except for air, the scenario environment for all the solid materials was set as fixed, implying that the thermophysical properties of those materials will stay constant throughout the analysis. However, the air is set as a variable which is an appropriate setting for natural convection scenarios and is used elsewhere in the literature (Egger, 2013). Such settings take into account the movement of the fluid due to the density gradients created by thermal stratification, where the density varies according to the ideal gas equation of state. For this analysis, the air is considered to be a thermally transparent medium with 1.0 emissivity, and the default viscosity is set at 1.82×10^{-5} kg/ms. The emissivity of the sky and cloud cover has been accounted for in the solar settings which will be discussed later. Figure 3.21 depicts the CFD model with the assigned materials while Table 3.3 provides the material properties.

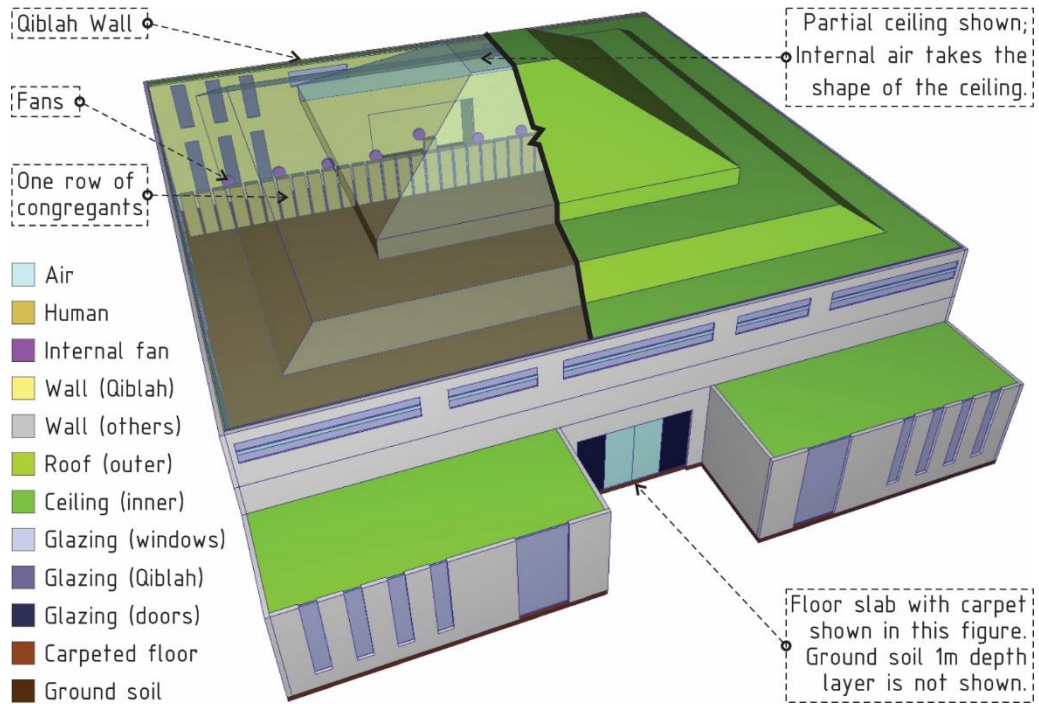


Figure 3.21: Materials specified in Autodesk CFD.

Table 3.3: Material properties.

	Thermal Conductivity, k (W/mK)	Density, ρ (kg/m ³)	Specific Heat, C_p (J/kgK)
Air	2.56×10^{-2}	1.17	1004
Heavy concrete	1.37	2300	920
Cement plaster	0.57	1300	980
Brick	0.77	1750	800
Insulation	0.03	100	1030
Light concrete	0.20	600	850
Plasterboard	0.17	800	980
Soil	1.2	1550	890
Tempered glass	1.1	2500	850

3.5.3 Governing Equations

Within the above-discussed domain, the thermo-fluid problem is defined by governing equations. The equations for the mathematical model are based on the three fundamental laws of conservation for physical properties of fluids:

- i) Conservation of mass
- ii) Conservation of momentum (Newton's second law)
- iii) Conservation of energy (First law of thermodynamics)

Mathematical formulations of these laws represent the fluid flow and heat transfer within a single-phase fluid. The conservation of mass and energy are mathematically expressed as continuity equation and energy equation, respectively. For incompressible fluids, the Navier-Stokes equation describes the motion of fluids and is derived through applying Newton's second law for fluid flow. Decomposing the equation into its time-averaged components for a non-laminar flow gives the momentum equations for the three directions of a 3D model. These substituted equations are also known as Reynolds-averaged Navier–Stokes (RANS) equations. The mathematical modelling of the current analysis is governed by, and can be solved with, the continuity equation, momentum equations, and energy equation as given below:

Continuity equation,

Equation 3.1

$$\frac{\delta \rho}{\delta t} + \frac{\delta \rho u}{\delta x} + \frac{\delta \rho v}{\delta y} + \frac{\delta \rho w}{\delta z} = 0$$

X-Momentum equation,

Equation 3.2

$$\begin{aligned}\rho \frac{\delta u}{\delta t} + \rho u \frac{\delta u}{\delta x} + \rho v \frac{\delta u}{\delta y} + \rho w \frac{\delta u}{\delta z} \\ = \rho g_x - \frac{\delta p}{\delta x} + \frac{\delta}{\delta x} \left[2\mu \frac{\delta u}{\delta x} \right] \\ + \frac{\delta}{\delta y} \left[\mu \left(\frac{\delta u}{\delta y} + \frac{\delta v}{\delta x} \right) \right] + \frac{\delta}{\delta z} \left[\mu \left(\frac{\delta u}{\delta z} + \frac{\delta w}{\delta x} \right) \right]\end{aligned}$$

Y-Momentum equation,

Equation 3.3

$$\begin{aligned}\rho \frac{\delta v}{\delta t} + \rho u \frac{\delta v}{\delta x} + \rho v \frac{\delta v}{\delta y} + \rho w \frac{\delta v}{\delta z} \\ = \rho g_y - \frac{\delta p}{\delta y} + \frac{\delta}{\delta x} \left[\mu \left(\frac{\delta u}{\delta y} + \frac{\delta v}{\delta x} \right) \right] \\ + \frac{\delta}{\delta y} \left[2\mu \frac{\delta v}{\delta y} \right] + \frac{\delta}{\delta z} \left[\mu \left(\frac{\delta v}{\delta z} + \frac{\delta w}{\delta y} \right) \right]\end{aligned}$$

Z-Momentum equation,

Equation 3.4

$$\begin{aligned}\rho \frac{\delta w}{\delta t} + \rho u \frac{\delta w}{\delta x} + \rho v \frac{\delta w}{\delta y} + \rho w \frac{\delta w}{\delta z} \\ = \rho g_z - \frac{\delta p}{\delta z} + \frac{\delta}{\delta x} \left[\mu \left(\frac{\delta u}{\delta z} + \frac{\delta w}{\delta x} \right) \right] \\ + \frac{\delta}{\delta y} \left[\mu \left(\frac{\delta v}{\delta z} + \frac{\delta w}{\delta y} \right) \right] + \frac{\delta}{\delta z} \left[2\mu \frac{\delta w}{\delta z} \right]\end{aligned}$$

Energy equation,

Equation 3.5

$$\begin{aligned}\rho C_p \frac{\delta T}{\delta t} + \rho C_p u \frac{\delta T}{\delta x} + \rho C_p v \frac{\delta T}{\delta y} + \rho C_p w \frac{\delta T}{\delta z} \\ = \frac{\delta}{\delta x} \left[k \frac{\delta T}{\delta x} \right] + \frac{\delta}{\delta y} \left[k \frac{\delta T}{\delta y} \right] + \frac{\delta}{\delta z} \left[k \frac{\delta T}{\delta z} \right] + q_v\end{aligned}$$

The nomenclature for the symbols has been provided at the beginning of the thesis.

These above-mentioned equations are coupled equations as all five equations need to be

solved simultaneously to solve the energy transfer within a fluid flow domain. Only very basic problems can be solved analytically for such non-linear, coupled partial differential equations. For other instances involving complex scenarios such as the current study, computer-based numerical procedures are the only practical option to solve these equations. The software converts these non-linear governing equations into a finite number of linear algebraic equations which it solves iteratively. Further details of the numerical methods for solving thermo-fluid problems in Autodesk CFD will be discussed in Section 3.5.5.

3.5.4 Boundary Condition

The governing equations defining the fluid flow of the mathematical model are solved for a given set of boundary conditions. These parameters characterize the domain in which the thermo-fluid simulations are to be carried out in CFD. As a thumb rule, the more assumptions and simplifications made in the model geometry, the more boundary conditions need to be defined to adequately translate the existing physical scenario into a mathematical model. Alternatively, as is the case for this analysis, an elaborate model requires only the basic boundary conditions to be defined to solve the governing equations within the domain. Given below are some considerations in setting up the boundary conditions. A summary of the boundary condition inputs is also provided in Table 3.4.

- Ambient air temperature is the outdoor observed temperature that is climate dependant and can be set according to the field study data or macro climatic data.
- As the air was set as a variable material, the density would vary, and hotter air would rise due to buoyancy. The pressure boundary condition for air was set at 0 Pa to enable the buoyancy effect to take place.

- Since air speed of 0 m/s was chosen to test for the worst-case ventilation scenario, no velocity boundary conditions were assigned. Additionally, because the external volume of air was modelled, it was not necessary to assign a film coefficient boundary condition to represent the convective heat transfer between solids and the air.
- In order to account for the radiative heat transfer, most researchers only assign a surface temperature boundary condition (Ghaleb, 2017, Hussin et al., 2020b). However, since the hypothesis of this research is that the *Qiblah* wall is adversely affected by solar radiation, it was imperative that solar modelling be done. To provide accurate solar radiation values Autodesk CFD has an option of enabling the solar radiation solver in the radiation settings. This provides a real-time boundary condition for the solar heat flux, the details of which will be discussed in Section 3.5.5
- Ground temperature at 1 m was set at 27 °C as was observed for the site in a previous experiment (Muhammad et al., 2016). At this depth, the ground temperature does not vary diurnally or with seasonal changes in Malaysia. This is also why it is recommended to model a 1 m depth ground volume for DTM in Autodesk CFD.
- The observed human activity level of 1.2 met corresponds to $\sim 70 \text{ W/m}^2$. For the average human body surface area of 1.7 m^2 , the total heat generation equals 120 W. This is representative of the metabolic rate of the occupants during prayer times which was assigned to the volumetric human components.

Table 3.4: Boundary conditions.

Boundary condition	Value	Applied to
Ambient air temperature	Climate dependent	Face of the external air mass
Air pressure change	0 Pa	Face of the external air mass
Solar radiation	Time and location dependent	Radiation settings
Ground temperature	27 °C	Bottom surface of the ground mass
Human heat generation	120W	Human body volume

3.5.5 Numerical Approaches

The previous four sections outline the boundary value problem as indicated in Figure 3.18. The physical model has been translated into a mathematical model defined by governing equations and boundary conditions. This model will be solved in the commercially available CFD solver from Autodesk Incorporated to obtain the numerical solution. A student license was obtained which allows for free access to the software as well as cloud simulating credits which helped in running complex simulations. A solver is called a blackbox (Figure 3.18) as the process remains behind the codes, whereby wrong settings could result in a completed simulation but with erroneous results. Hence, it is of utmost importance to understand and identify the components of a solver coding. This section outlines the details of the numerical approaches used by CFD in general, and the Autodesk CFD code in particular. Thereafter, the following three subsections will discuss the specifics concerning this study. The various aspects of the CFD solver, which is provided in

meticulous detail, can help future researchers replicate the methodology and reproduce similar experiments.

Discretization: As mentioned in Section 3.5.3, the non-linear, coupled partial differential equations need to be converted into a set of linear algebraic equations to solve it numerically. The CFD solver does so through a process called discretization whereby the continuous model geometry is divided into smaller elements or control volumes. Autodesk CFD uses the finite element method (FEM) for the discretization of the continuous problem domain and converts the governing equations into algebraic equations to be solved numerically at the nodes of each of these elements. There are other methods of discretization utilized by other softwares but the FEM provides flexibility in modelling any geometric shape which is useful for building engineering analyses. The domain discretization process generates a set of discrete cells; the combined discrete spatial domain is known as the grid or mesh. The continuous resultant parameters, such as temperature, velocity etc. are characterized by the value at the nodes of each cell element, and the values between the nodes are determined through polynomial interpolation.

Meshing: In three-dimensional models, most mesh elements in Autodesk CFD are tetrahedral which is a four-sided, triangular-faced element. A meshed geometry containing such types of elements gives the most accurate results (Ramponi and Blocken, 2012). Nevertheless, the accuracy of the numerical solution highly depends on the mesh quality of the discretized geometry. A more detailed mesh with smaller elements, and consequentially more equations to be solved, will require longer processing time but yield better results. Discretization error or numerical error occurs from unsuitable meshing which may result in inaccurate outputs. This can be solved through a grid convergence test or grid independency

test to ensure that the solution is less sensitive to the meshing, and approach the continuum solution. Further details for the sensitivity analysis of the meshing will be provided in the subsequent sections.

Pressure-Velocity Coupling: Pressure-velocity coupling refers to a numerical algorithm that uses a combination of the continuity and momentum equations to derive an equation for pressure in the fluids. For simulations involving natural ventilation and buoyancy-driven convection current, this derivation scheme for solving the pressure component is particularly important. For low-speed incompressible fluids, Autodesk CFD uses the pressure-based solver utilizing SIMPLE-R (Semi-Implicit Method for Pressure Linked Equations- Revised) approach to determine pressure-velocity coupling which is commonly used for CFD applications.

Advection Scheme: The advection scheme determines the numerical method of propagating results of surface elements through the solution mesh. Autodesk CFD uses several variants of the streamline upwind discretization schemes to model the advection terms. Advection scheme 5, which is termed Modified Petrov-Galerkin, is a second-order upwind scheme that has been proven as a stable method for similar studies (2019). This method gives results that are accurate to two decimal places and helps avoid numerical diffusion error that is associated with tetrahedral meshing.

Turbulence Modelling: Turbulence modeling is the construction and use of a mathematical model to predict the effects of turbulence within the fluid flow. The k -epsilon is a two-equation model which is one of the most common turbulence models. A two-equation model includes two transport equations to represent the turbulent properties of the flow which helps simulate mean flow characteristics for turbulent flow conditions. This

approach takes into account the historical effects like convection and diffusion of turbulent energy. In most indoor environmental analyses, a standard k -epsilon model can provide satisfactory results (Zhai et al., 2007, Farea et al., 2015). Other building engineering studies using the Autodesk CFD software (Egger, 2013, Davis, 2016) as well as similar analysis carried out for mosques in other software settings (Hussin et al., 2020b, Ghaleb, 2017) have used this turbulence modelling. Hence, for this study, k -epsilon was chosen as the turbulence model.

Radiation: Autodesk CFD uses a diffuse grey body radiation model where direct shortwave radiations, as well as the indirect and diffused longwave radiations, are and taken into account. The radiation model computes true view factors of every part of the model within the visible range for each element of the mesh. It does so by projecting an image of the surrounding element faces onto a sphere centering the element. This projection of a spherical bitmap of the surroundings is used to calculate the exact view factors, which is as accurate as the pixel resolution of the bitmap. Therefore, the solid angle proportions are maintained and reciprocity of the view factors between every face of every part is ensured in the solver. This is a very resource-intensive procedure but allows for a high level of accuracy and a rigorous energy balance for radiation calculations. CFD also gives an extremely accurate MRT where it is calculated as a weighted temperature where the weightage is how much view space a certain face is taking up as viewed from each element.

Solar Modelling: The procedure for solar radiation analysis is the same as the normal radiation simulations in Autodesk CFD. To include solar radiation, the solver assumes a dome over the domain which represents the sky where the view factors between this sky dome and every element determine its solar loading. The solar radiation amount is

determined according to the position of the sun which is dependent on the time of day, and the geographical location. The solar radiant flux is calculated using the equation as below:

$$q_{\text{solar}} = \text{Solar_Constant} * [\sin(\text{Solar Altitude}) + 0.25 * \sin(2 * \text{Solar Altitude})] \quad \text{Equation 3.6}$$

The solver obtains the altitude of the sun from the verified database of the US National Oceanic and Atmospheric Administration (NOAA). This value is dependent on the latitude and longitude of the geolocation which has to be provided in the solar settings. The Solar_Constant is set at 910 W/m² by default which indicates a sky with no pollution or cloud cover, and no nearby obscuring objects such as trees or other buildings. However, this value is to be adjusted in the radiation settings depending on the observed radiation, taking into account the cloud coverage, as well as the nearby objects that block the direct or indirect radiation of the sun. A Solar_Constant of 600 W/m² was found to give radiation values that reflect the historically reported radiation range for Kuching (Figure 4, Appendix D). This approach to solar modelling gives a precise radiation heat flux value as it is applied for the exact solar position instead of an averaged radiation boundary condition which is the norm for most research found in the literature. In the context of transient analyses, the sun is changing its position constantly, and the angle of incident radiation changes as well. The Autodesk CFD solar modelling helps in DTM as the solver recalculates the above equation for each time-step of the simulation resulting in accurate solar loading.

Convergence: Solving a model numerically requires concurrently solving the linearized governing equations to be applicable for all the elements within the domain. Each simulation run is known as an iteration whereby the software approximates the values and solves the equations. Based on the error rate from the previous run, a new iteration is run

with a more accurate approximation. A residual is the measure of the local imbalance of a conserved variable in each control volume; the lower the residual value is, the more numerically accurate the solution. Continuous reduction of residuals compared to the previous stage allows for the error margin in solutions to approach near zero. With each iteration, the difference between the residual quantities decreases, and the result converges towards a stable solution. In reality, for a set of equations in a complex problem as this analysis, the residual is never zero but may be within a tolerance level depending on the accuracy required of the solution. When residuals are within an acceptable threshold value and the equations have converged, the results can be considered as reliable. In Autodesk CFD the Automatic Convergence Assessment can be enabled which stops iterations when the residuals are within a specified tolerance level, or the solution no longer changes with subsequent iterations. The default setting for the convergence criteria is retained whereby it is set to 1% variation of solution imbalances compared to the residual at the previous stage, which appropriate for most analyses (Autodesk CFD, 2019).

Errors: Although a simulation is numerically well converged, it does not necessarily imply that the setup of the model or solver is correct. Convergence of a simulation merely indicates that the solver has come up with an acceptable solution to the discretized set of equations, and the error margin in the solution is within a tolerable threshold. Nevertheless, there may be errors within the numerical model itself or in the process of interpreting the physical model to a mathematical model. Verification of the model and validation of the simulation is necessary to minimize these errors, the guidelines of which can be found in the literature (Zhai et al., 2002). As a thumb rule, it is recommended to pose the following two questions for a CFD model (ASHRAE, 2017b); the answers to these can help eliminate the errors through the process of verification and validation, respectively:

i) “Is the model being solved right?”: This questions whether the solution procedure for the mathematical model is rigorous. Verification of the model is a sensitivity analysis to check for the robustness of the numerical model. In CFD the verification is known as grid independence test or mesh sensitivity analysis. Since discretization converts a set of non-linear differential equations into a matrix of linearized algebraic equations, there always remains a chance of numerical error in this approximation. Typically, the behaviour of the variables within each cell can be assumed linear with the smallest of elements. A consistent numerical method will approach the continuum representation of the equations and zero discretization error as the number of grid points increases and the size of the grid spacing tends to zero. As the mesh is refined, the solution should become less sensitive to the grid spacing and approach the continuum solution. However, the finer the mesh is, the more algebraic equations need to be solved in the matrix which would increase the resource usage by manifolds. Verification is the procedure to increase the number of elements to a certain extent that with further refining of the mesh the solution no longer changes. At this point, the numerical or discretization error may be considered as minimized and that the solution is independent of the particular mesh created.

ii) “Is the right model being solved?”: This question checks whether the mathematical modelling of the physical problem has been done accurately. For numerical models, the level of confidence is determined by the level of accuracy which is established by comparing the results with reliable data. Testing of results against field data or findings from other numerical analyses is necessary to validate the model before carrying out parametric studies. For small-scale studies, the accuracy can be evaluated with existing literature of a similar setup. For larger models with multiple variables such as the current research, the results need to be validated with data from field experiments.

3.5.6 Simulation Settings

The mesh and the solving parameters that are chosen largely impact the speed and efficiency of the simulations, especially in complex problems such as this analysis. The mosque building along with the exterior air and ground volume was meshed, representing the computational domain for the CFD analysis. For such a large domain, it is important to refine the mesh in regions where more precise results are needed while using a coarser mesh in regions of lesser importance. This can yield accurate results without overburdening the analysis with too many calculation nodes. The automatic mesh sizing tool of Autodesk CFD was used to generate the mesh (Figure 3.22). This intelligent meshing creates orthogonal cells with a low level of skewness between the elements to ensure good mesh transitions. Additionally, a fairly uniform aspect ratio and volume ratio is maintained within the constraints and size of the domain. Thereafter, the mesh was regionally refined for the interior of the mosque building with a special focus on the *Qiblah* wall along with its surrounding context as these are the examining parameters for this research.

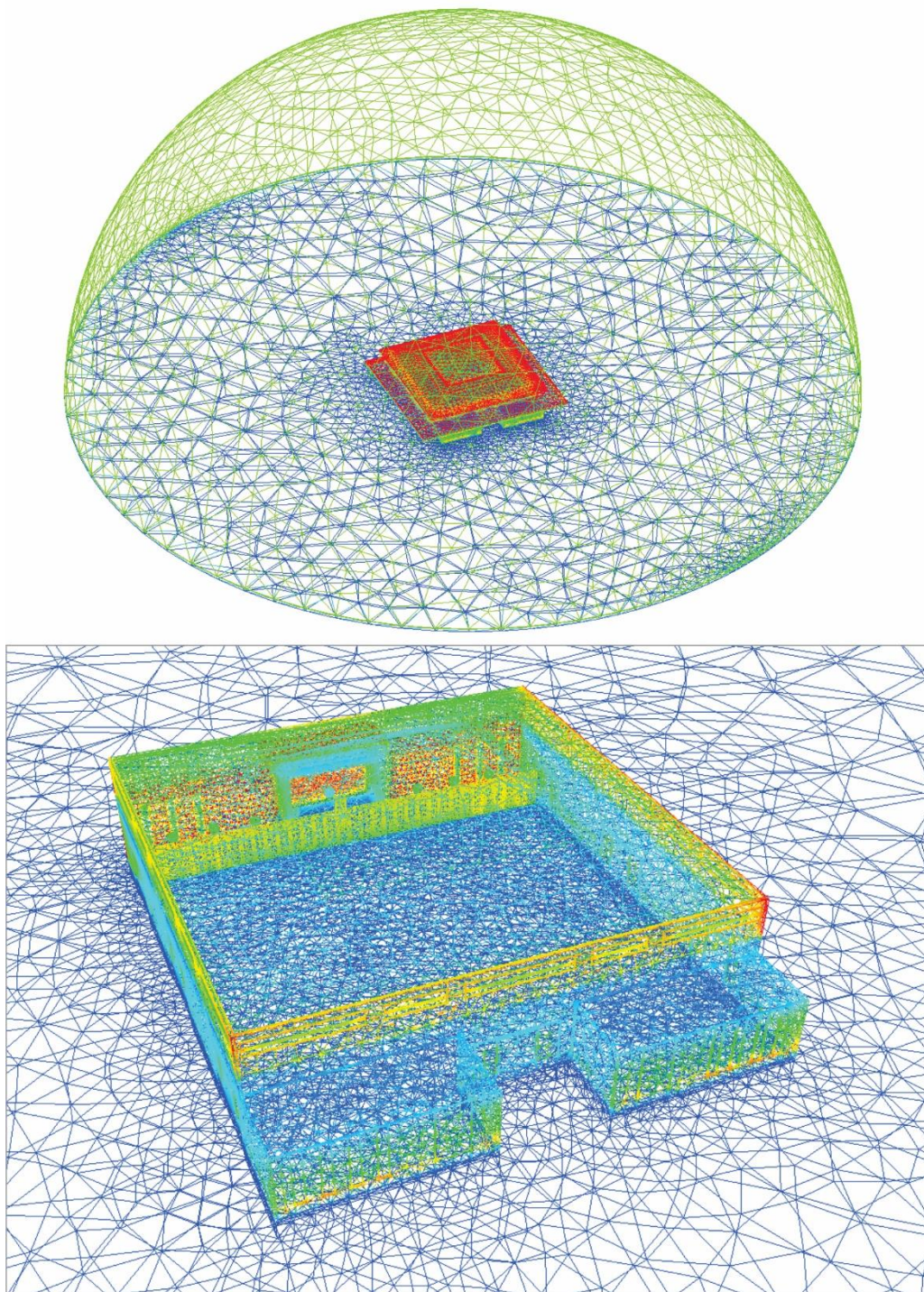


Figure 3.22: Exterior (top) and interior (bottom) meshing.

Any thermo-fluid analysis can be performed as transient or steady-state. A transient analysis accounts for time-dependent effects calculated within the specified time limit, whereas a steady-state analysis provides the converged solution for a particular point in time.

In analysing the current problem at hand, it was decided that steady-state simulations would be run for each prayer timing as those are the only occupancy periods in the mosque. Since the congregational prayer time lasts for only 10-15 minutes, it can be safely assumed that the variation within that period will be insignificant and the beginning of the prayer time can be a suitable representative time for each prayer. Nevertheless, for the solar radiation effects to be considered, a diurnal simulation also needed to be run to capture the effects of the solar loading on the *Qiblah* wall. A DTM with transient analysis is a suitable method to obtain precise results for the energy stored within the thermal mass or reradiated to the surroundings. In literature, it was found that transient solar analyses with heat and flow enabled would mostly diverge or show error (Albatayneh et al., 2020). This is understood as transient flow analysis requires very small time steps and the solution needs to be converged within each time step. This unnecessarily increases the file size and the required computer capacity by manifolds even for a small-scale model. Hence, it would be practically impossible to run a transient analysis for flow and heat calculations for a large domain as this numerical analysis.

Since the purpose of the transient analysis for the current problem is to determine the effects of solar loading, it was decided that the diurnal simulation would be run with only heat settings enabled. A 60 sec time step proved to be suitable as it is substantial for energy calculations (Albatayneh et al., 2015), and 1440 time steps for a 24-hour analysis would not make the simulations resource extensive. Autodesk CFD calculates the residuals for each time-step in the transient analysis, whereby an inner iteration of 10 was sufficient for heat transfer calculations (Davis, 2016). The radiation properties were provided in the solar radiation solver settings (Figure 3.23), where:

- (A) The latitude and longitude for the site in Kuching were provided.
- (B) The gravity vector and compass directions were defined accordingly.
- (C) The date and time were set for solar altitude and azimuth calculations.
- (D) The ambient reference temperature was input as a piecewise linear function for the case study day of 23 April (Figure 3.10). This value is necessary for the DTM.

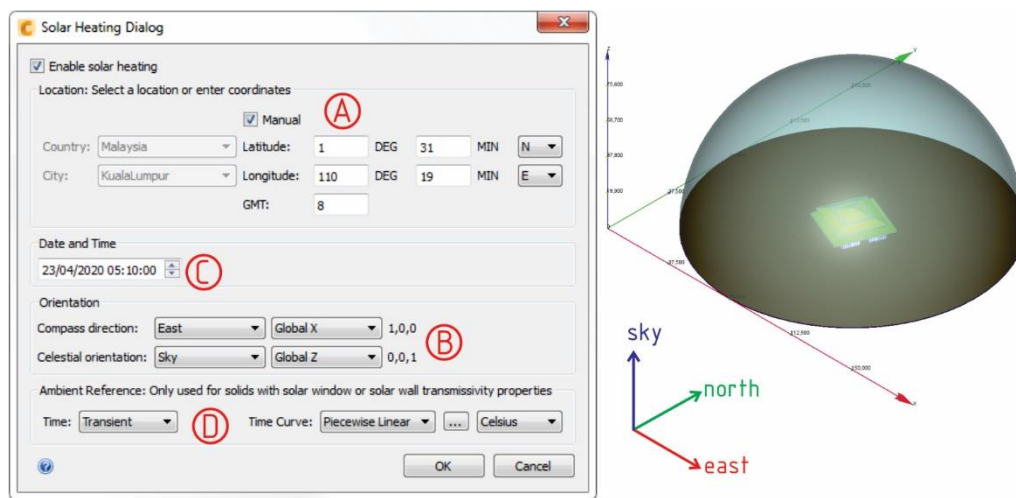


Figure 3.23: Solar settings in Autodesk CFD.

Thereafter, with the resultant quantities of the heat analysis, steady-state simulations were run for the beginning of each prayer time with only flow settings enabled. This ensured that the time-dependent heat component of the model was conserved while solving the flow equations. The iteration number for the steady-state analysis was set to 1500 with the Automatic Convergence Assessment set up for intelligent solution control. As the solution normalizes and becomes more accurate, the plot lines stop changing and the convergence lines are horizontal because it has reached a steady-state solution (Figure 3.24). Most simulations converged within an 1100-1300 iteration range with residuals that were sufficiently close to zero. All CFD simulations were initiated on a desktop PC with an Intel

Core i3-2100 3.10 GHz processor, 16 GB DDR3-1333 MHz RAM, and 4 GB DDR NVIDIA GeForce GT 630 graphics memory. However, running a large radiation model, especially with solar loading would require an immense amount of memory for transient analyses, as discussed in the previous section. In reality, even with such a high configuration computer, the analyses did not finish after 48 hours. Hence, the simulations were run on the Autodesk cloud solver with the free cloud credit provided within the student subscription. Including the upload and download time, it took approximately 12-14 hours to finish each simulation for the transient or steady-state analysis.

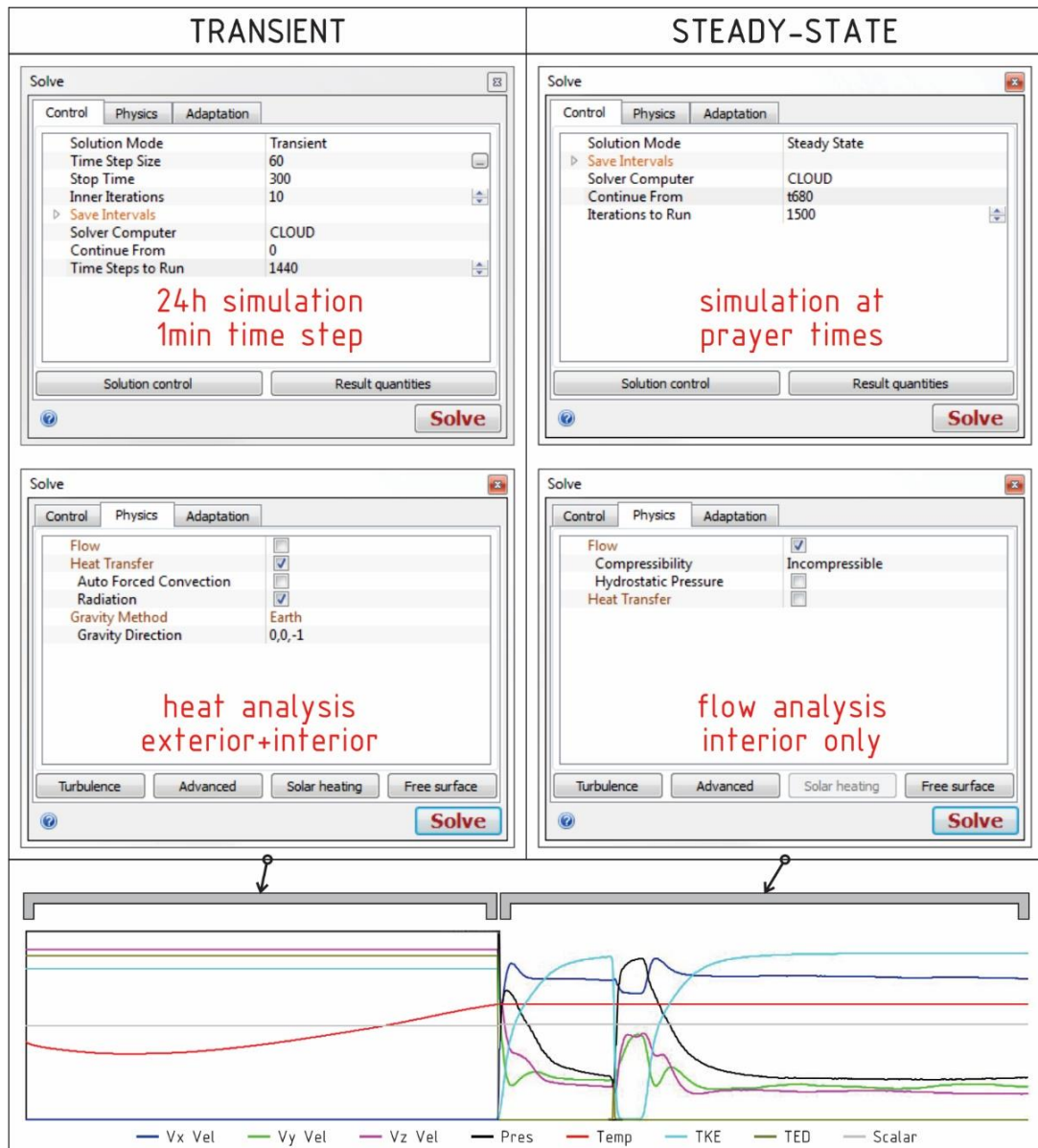


Figure 3.24: Transient (left) and steady-state (right) simulation settings.

3.5.7 Model Verification

Model verification helps achieve a rigorous mathematical model which is suitable for further parametric analysis. The first form of verification is called a sanity check in CFD terminology, whereby a preliminary visual assessment is carried out to check whether there are any anomalies or inconsistencies in the model. This also includes checking the surfaces to ensure that the meshes are not jagged or too coarse. For environmental analyses, it needs

to be checked whether the temperatures and flow patterns are realistic. Figure 3.25 depicts the simulation result image showing the various inspections that were done for the initial sanity check. It must be noted that a sanity check proves that the results are realistic but does not indicate whether they are accurate for the mathematical model defined by the boundary conditions and governing equations. Hence, the next step in verification is to check the robustness of the meshing by performing a grid convergence test. By refining the mesh and reducing the discretization error, grid independence can be achieved for the mathematical model. Autodesk CFD provides options for adjusting the volumetric mesh refinement factor that parametrically alters the mesh size and in consequence, the number of elements. Since this study involves a large computational domain, mesh sensitivity analysis was carried out for the temperatures at two points (Figure 3.26). An element count of approximately 3.9 million was chosen as the final mesh count as the results remain unchanged with further refining of the grid.

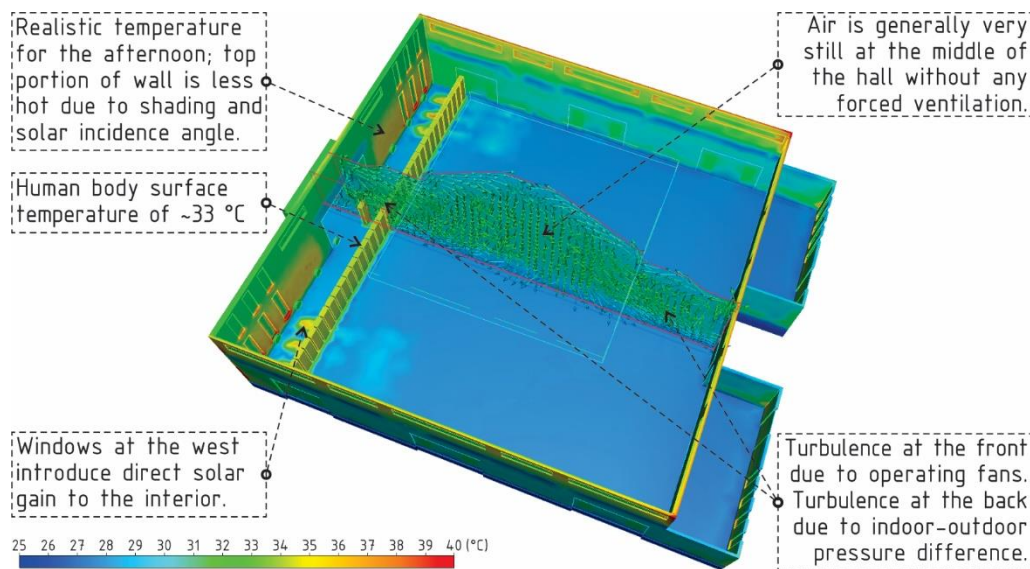


Figure 3.25: Sanity check for verification.

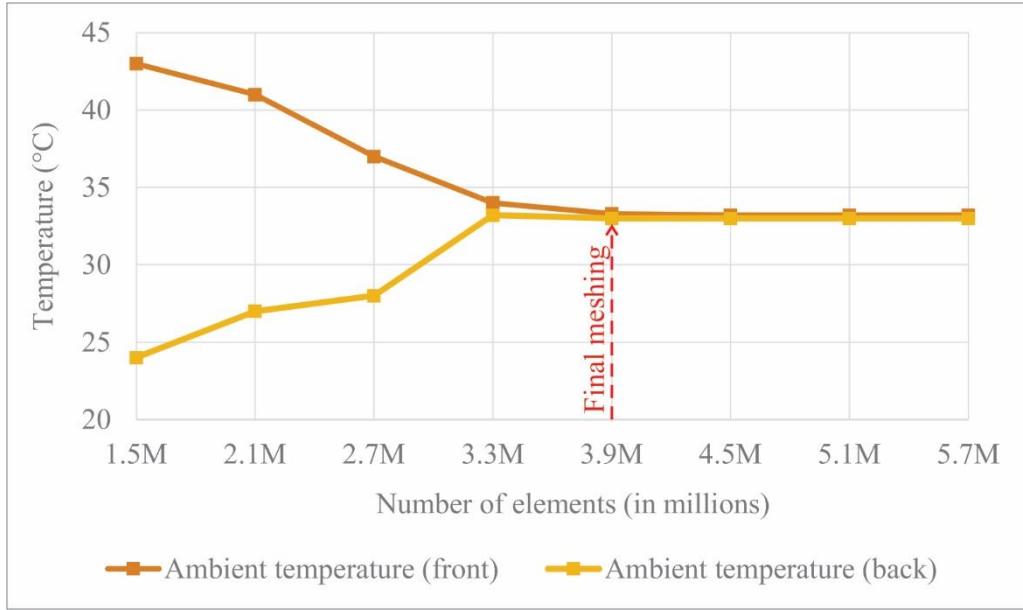


Figure 3.26: Grid independence test.

3.5.8 Model Validation

Model validation ensures that the numerical model accurately represents the physical model. A meticulous setup of the boundary value problem, as is done in this research, can ensure that the mathematical model is well-formed. Nevertheless, simulation results should be compared with the gathered field data to ensure that the results are realistic. In this analysis, the numerical model has been validated against the solar radiation values as well as the indoor temperatures and wall surface temperature. The historically recorded direct solar heat flux for the month of April varies between 600-650 W/m² during *Dhuhr* time and 300-350 W/m² during *Asr* time. Since a very hot day has been taken as a case study, the values would be towards the higher side, which can be observed in Figure 3.27. This is also the typical radiation amount for Malaysia, as indicated in Figure 4 of Appendix D. In Figure 3.28, the simulated temperature results for the data collection points (previously shown in Figure 3.14) and wall surface temperature were compared against field data. It can be seen that the data points from the simulation give very similar results to the measured data, with

not more than 5-8% variation. In CFD settings this can be considered a very robust setup (Ghaleb, 2017).

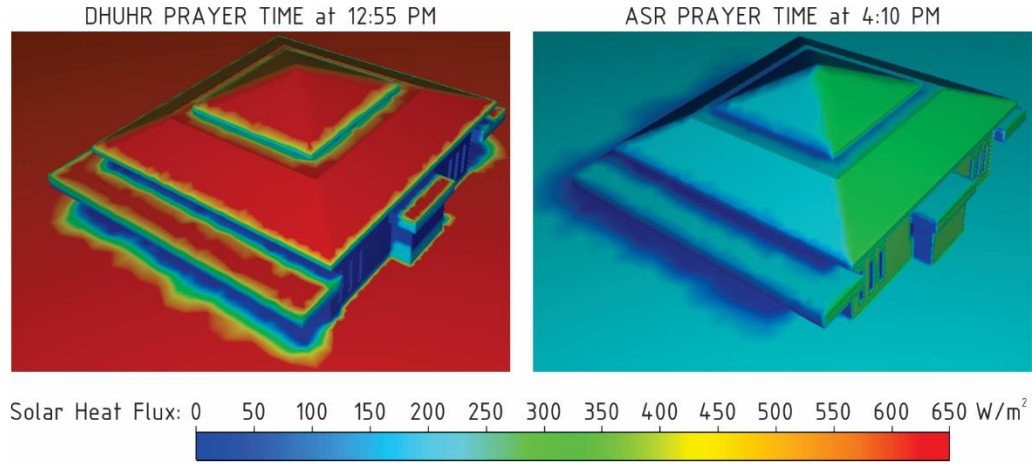


Figure 3.27: Solar radiation values during Dhuhr and Asr prayers on 23 April.

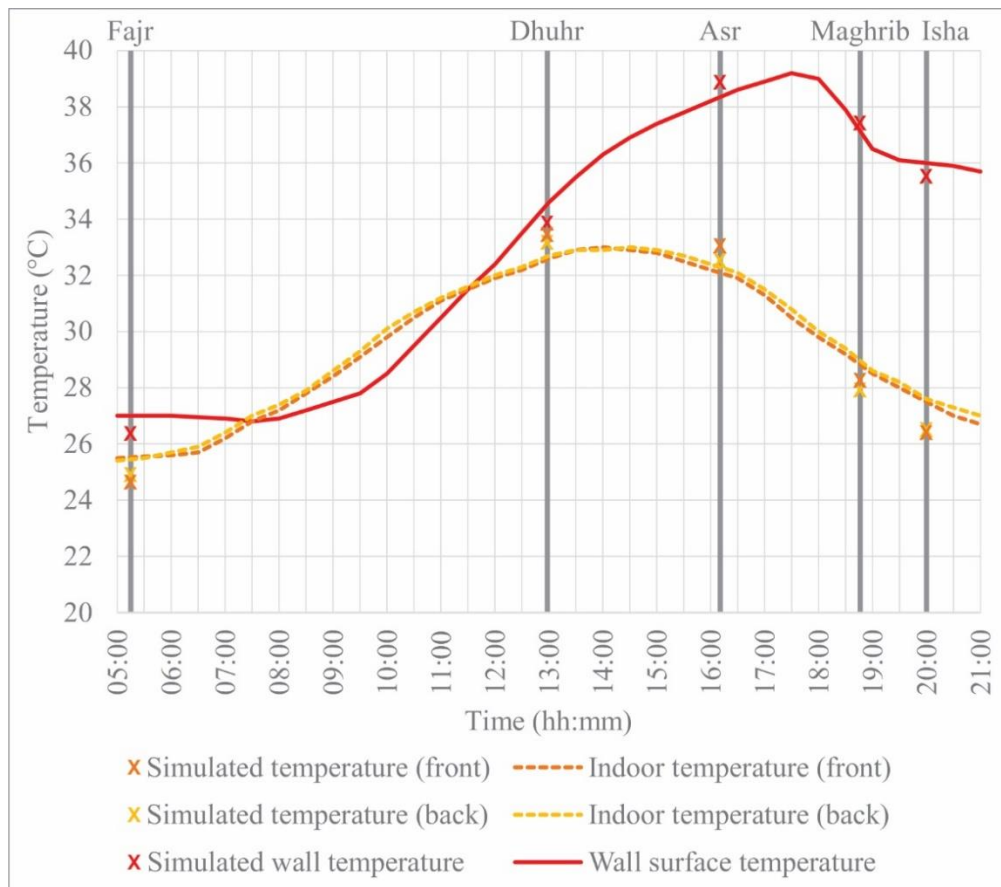


Figure 3.28: Validation with measured data.

3.6 Parametric Study

With the verified and validated model, the next step is to proceed with testing the hypothesis through parametric analysis. Although the case study model was validated with data from April, the study period would be the hottest and driest month of the year, June. The four types of days, as classified in Section 3.3.3 can be observed in the temperature plot for the whole month of June (Figure 3.29). However, there is a prevalence of Type A and Type B days for June as the month has only 15 days of rainfall on average, while over the year Kuching witnesses rainfall for more than 70% of days.

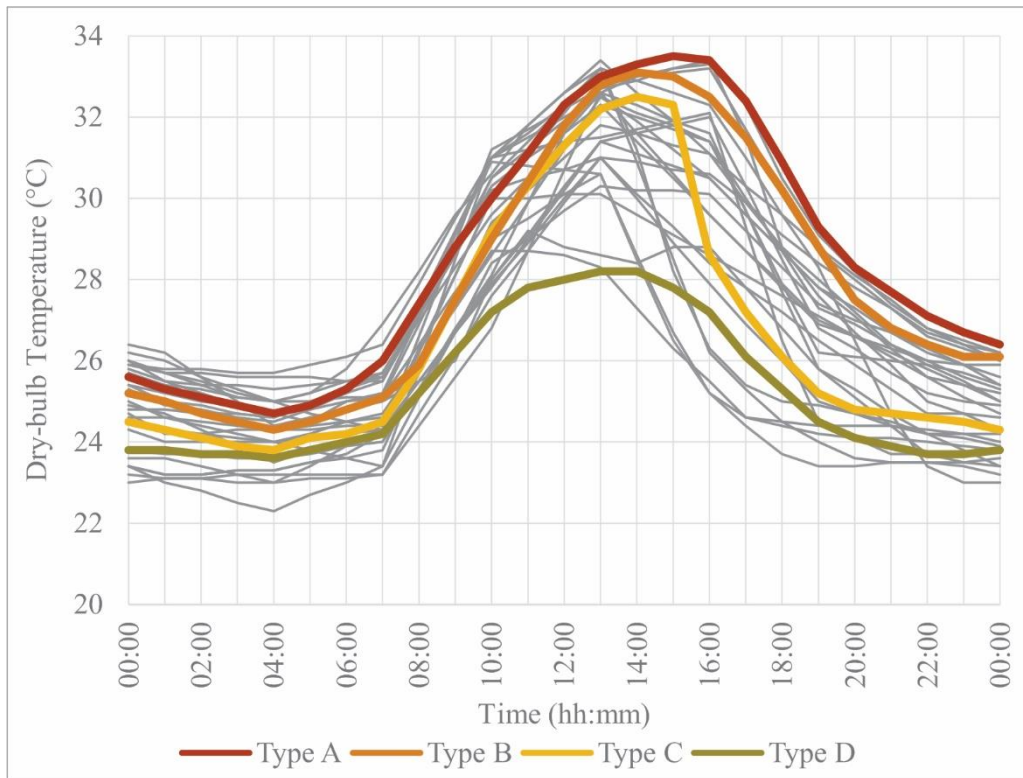


Figure 3.29: Temperature plot for June depicting the four types of days.

From the above plot, the hottest day of the year, 13 June, was selected as the suitable date for parametric studies. Optimizing thermal comfort conditions for the prayer timings with a peak temperature would mean that thermal comfort can be achieved for the other less

extreme days as well. Figure 3.30 provides the temperature-humidity plot for the selected design study day. This data would be provided in Autodesk CFD as a boundary condition for the transient DTM of the mathematical model. Additionally, the figure also provides the timings for the prayers, at which point the steady-state simulations will be run. The parametric study will be carried out by testing different design alternatives to derive a suitable solution that would allow for better thermal comfort of the occupants during the low occupancy periods without the need for utilizing the HVAC system. The subsequent sections highlight the design variables and the approach taken for the parametric analysis.

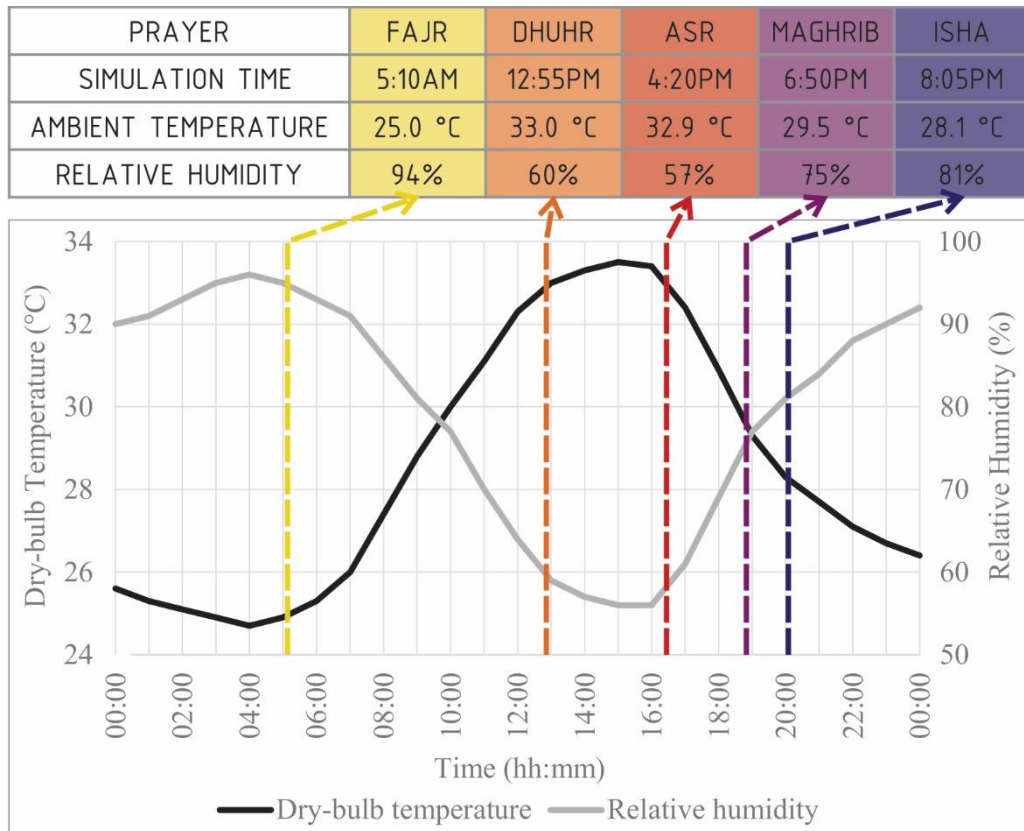


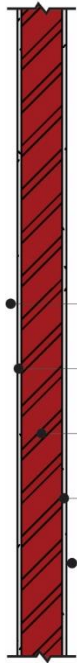
Figure 3.30: Selected design study day, 13 June.

3.6.1 Parametric Study of *Qiblah* Wall Design

The *Qiblah* wall is the most important design component for mosques in Malaysia in terms of solar exposure. The wall stores the solar energy which it later transmits to the

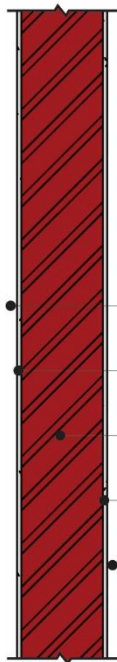
indoors. A total of four alternative cases, in addition to the base case scenario, were modelled and simulated for the parametric study. It must be noted that there is one other article in the literature that discusses wall optimization in the context of HD climates (Al-Shamrani et al., 2016). Yet, the proposed design alternatives in that study are purely hypothetical, which are neither constructionally feasible nor financially viable. However, while determining the alternative cases for this analysis, special focus was given to the available materials and industry standards in Malaysia, as well as general construction practice. This is to ensure that the outcome of this research is not only theoretically plausible but also practically applicable in the industry. Figure 3.31 illustrates the details of the design alternatives for this parametric study. The base case is a single brick wall with a very high U-value. Using a double brick wall in Wall 2 reduces the U-value, but the thermal mass increases as well. Walls 3 and 4 have an air cavity in between the double layers of the wall which hinders the heat transmission as air is a bad conductor of heat. However, Wall 4 has a non-loadbearing lightweight concrete block layer as the inner wall. The practicality of it is that the interior wall delays the heat being transmitted to the indoors without adding much to the thermal mass due to its aerated structure. Wall 5 is the same as Wall 4 with insulation filling up the wall cavity, ensuring a further barrier to heat transmission to the interior. It must be noted that whilst modeling the problem mathematically, it is assumed that the air motion inside the wall cavity is laminar.

WALL 1 (BASE CASE): Single brick wall



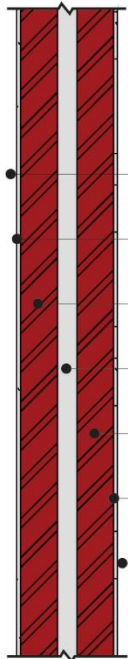
Layer Thickness and Material Type	Thermal Conductivity (W/mk)	R Value (m ² .K/W)
External surface air layer	-	0.04
10 mm cement plaster	0.57	0.02
95 mm clay brick wall	0.77	0.12
10 mm cement plaster	0.57	0.02
Internal surface air layer	-	0.12
TOTAL R VALUE		0.32
U VALUE = 3.13 W/m².K		

WALL 2: Double brick wall



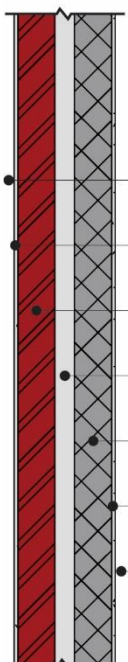
Layer Thickness and Material Type	Thermal Conductivity (W/mk)	R Value (m ² .K/W)
External surface air layer	-	0.04
10 mm cement plaster	0.57	0.02
190 mm clay brick wall	0.77	0.25
10 mm cement plaster	0.57	0.02
Internal surface air layer	-	0.12
TOTAL R VALUE		0.45
U VALUE = 2.22 W/m².K		

WALL 3: Double brick wall with air cavity

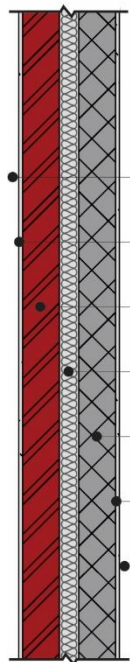


Layer Thickness and Material Type	Thermal Conductivity (W/mk)	R Value (m ² .K/W)
External surface air layer	-	0.04
10 mm cement plaster	0.57	0.02
95 mm clay brick wall	0.77	0.12
50 mm air cavity	-	0.17
95 mm clay brick wall	0.77	0.12
10 mm cement plaster	0.57	0.02
Internal surface air layer	-	0.12
TOTAL R VALUE		0.61
U VALUE = 1.64 W/m².K		

WALL 4: Double wall of brick and lightweight concrete blocks with air cavity



Layer Thickness and Material Type	Thermal Conductivity (W/mk)	R Value (m ² .K/W)
External surface air layer	-	0.04
10 mm cement plaster	0.57	0.02
95 mm clay brick wall	0.77	0.12
50 mm air cavity	-	0.17
95 mm lightweight concrete	0.20	0.48
10 mm cement plaster	0.57	0.02
Internal surface air layer	-	0.12
TOTAL R VALUE		0.97
U VALUE = 1.03 W/m².K		

WALL 5: Double wall of brick and lightweight concrete blocks with insulation

Layer Thickness and Material Type	Thermal Conductivity (W/mk)	R Value (m ² .K/W)
External surface air layer	-	0.04
10 mm cement plaster	0.57	0.02
95 mm clay brick wall	0.77	0.12
50 mm rock wool insulation	0.03	1.67
95 mm lightweight concrete	0.20	0.48
10 mm cement plaster	0.57	0.02
Internal surface air layer	-	0.12
TOTAL R VALUE		2.47
U VALUE = 0.41 W/m².K		

Figure 3.31: Design alternatives for parametric study.

3.6.2 Natural and Mechanical Ventilation

It was mentioned previously in Section 3.3.3 that the worst-case scenario of 0 m/s air speed was chosen to test out the natural ventilation scenario. The existing fans were modelled (Figure 3.21) to test out the scenario for mechanically enhanced ventilation without the utilization of HVAC systems. During natural ventilation simulation runs, these fans are considered switched off with a 0 m³/s volumetric air flow rate. For testing mechanical ventilation scenarios, a volumetric flow rate of 0.6 m³/s is assigned to denote that the fans were switched on. This value was calculated from the surface area of the fan and the air speed data obtained during the field inspection. Each simulation would be run both with values of the fans switched off and the fans switched on. It must be noted that the enhanced forced ventilation enables air movement helping with better thermoregulation of the human

body (Figure 2.4), which will be considered in the subsequent thermal comfort calculations. The air movement due to the fan does not, however, reduce or regulate the air temperature. Hence, no thermostat settings or temperature set-points were input in the CFD interface since the fans were set to be operated at existing ambient temperatures.

3.6.3 Thermal Comfort Assessment

Autodesk CFD calculates the thermal comfort of the occupants as a derived resultant quantity. In addition to that, thermal comfort calculations are also done in the CBE Thermal Comfort Tool (Tartarini et al., 2020) developed by the Centre for Built Environment, University of California, Berkeley. Both of these tools use the PMV-PPD equations as outlined in ASHRAE 55. However, it has been previously mentioned in Section 2.2.3 that the PMV-PPD scale may not be the most suitable option for naturally ventilated buildings in HH climates. Since this analysis is aimed at enhancing the comfort conditions without the need for HVAC interventions, it is imperative to analyse the thermal comfort of the occupants with respect to the adaptive scale as well. The assessment for adaptive thermal comfort is based on the operative temperature (OT) which is dependent on the air temperature, air speed, and MRT. Autodesk CFD also calculates the OT as a derived result from the simulation quantities of these factors. Table 3.5 outlines the values and sources for the six factors of thermal comfort. The personal factors and relative humidity are specified quantities that need to be input in the CFD result quantities dialog box. The remaining environmental factors are computed from the numerical analysis results based on the flow and heat transfer within the domain.

Table 3.5: Thermal comfort conditions.

Factor	Value	Obtained from
Metabolic rate	1.2 met	Field observation
Clothing insulation	0.6 clo	Field observation
Air temperature	Climate dependent	Simulation results
Relative humidity	Climate dependent	Weather data
Air speed	Climate dependent	Simulation results
MRT	Climate dependent	Simulation results

3.6.4 Comparison Between the Design Alternatives

A total of 50 simulation scenarios are carried out as the analyses are done for the five prayer times, with variances in the wall design and ventilation strategies (Figure 3.32). This is in addition to the initial diurnal transient heat flow simulations that were run for each wall design alternative. The centigrade scale will be used for comparison between the wall surface temperature, MRT, OT, as well as for comfort temperature calculations. From these, the neutral temperature and comfort ranges will also be derived as a comparison standard. Occupants' thermal comfort will be measured according to the ASHRAE recommended seven points thermal sensation scale for PMV, and in percentage for PPD. Results will be presented in the form of graphical diagrams as well as visual data from CFD simulations such as contour diagrams, flow diagrams, etc. The energy implications for the optimized design scenario will also be briefly discussed.

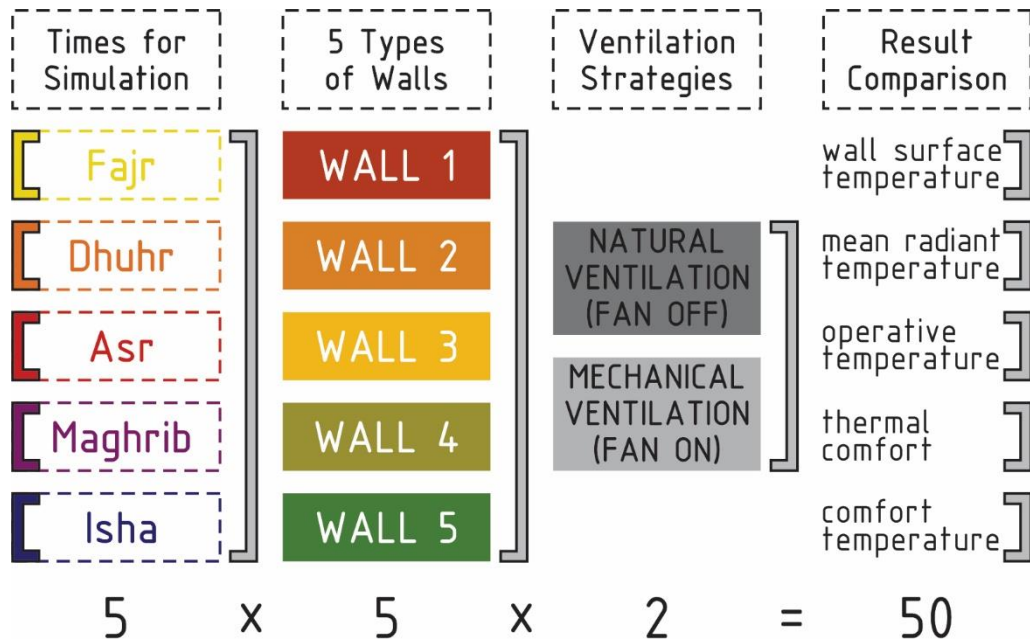


Figure 3.32: Total number of simulations run for the numerical analysis.

3.7 Summary

An overview of the selection procedure for a suitable software and case study mosque in accordance with the objectives of this research has been provided at the beginning of the methodology chapter. Thereafter, the procedure and means of obtaining both primary and secondary data have been presented. Next, the mathematical modelling and numerical simulation procedures have been discussed in meticulous detail so that similar studies can be easily conducted or replicated by other researchers. With a complete setup of the numerical model which has been rigorously validated and verified, parametric simulations have been carried out. The aspects of MRT and air speed for thermal comfort have been studied by simulating the *Qiblah* wall design alternatives and ventilation strategies, respectively. Results have been generated from the simulation runs which will be discussed in the following chapter. The first two objectives of this research have been fulfilled by analysing the findings from the field study data while the simulation outputs have helped in meeting the remaining two objectives.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, the results from the field study as well as numerical analysis are presented. The chapter begins by analysing the current scenario for thermal comfort and the energy consumption of the mosque. The following sections examine the findings from the simulations carried out on the validated model, in terms of *Qiblah* wall design and ventilation strategies. The impact of an optimized design solution on the comfort temperature range and the energy implications of such proposed solutions are also explored. Results are presented in the form of CFD-generated graphics as well as a comparison of the alternatives through graphical diagrams. Finally, the chapter concludes by discussing and evaluating the findings of this study with respect to the objectives set at the beginning of this research.

4.2 Base Case Scenario

As seen in Section 3.3.3, the indoor temperature and humidity closely follow the outdoor values due to a large number of openings along the perimeter of the prayer hall. Despite utilizing the HVAC system, the comfort temperature could only be achieved during the *Fajr* and *Isha* prayers for a case study hot day (Figure 3.10). This section further analyses the comfort conditions, and the subsequent energy implications, of the existing base case scenario.

4.2.1 Thermal Comfort

The collected data points were plotted on the Givoni bioclimatic chart which considers both the ambient temperature and the relative humidity, which is important for HH

climates. Figure 4.1 depicts the data points during all the prayer times, both with and without HVAC, for the hot month of April. Though the temperature is within recommended limits during *Fajr* and *Maghrib* prayers, it can be seen that the indoors barely reach comfort range as the humidity is too high. On the other hand, for daytime *Dhuhr* and *Asr* prayers, the humidity is comparatively lower, yet the temperature is not decreased sufficiently by the HVAC system. The recommended comfort zone is attained only during *Isha*, where the HVAC unit would have operated continuously more than 1.5 hours before the congregational prayers. In all other cases, the operation of HVAC 30-45 mins prior to the prayer time proves to be insufficient in terms of providing comfort. Nevertheless, the plot points are all shifted due to the removal of both the sensible and latent load, reducing the temperature and humidity, respectively. Yet with the high temperature and high humidity of the HH climates, intermittent short-spanned operation of the HVAC system is not sufficient to bring the temperature-humidity data points within the comfort levels.

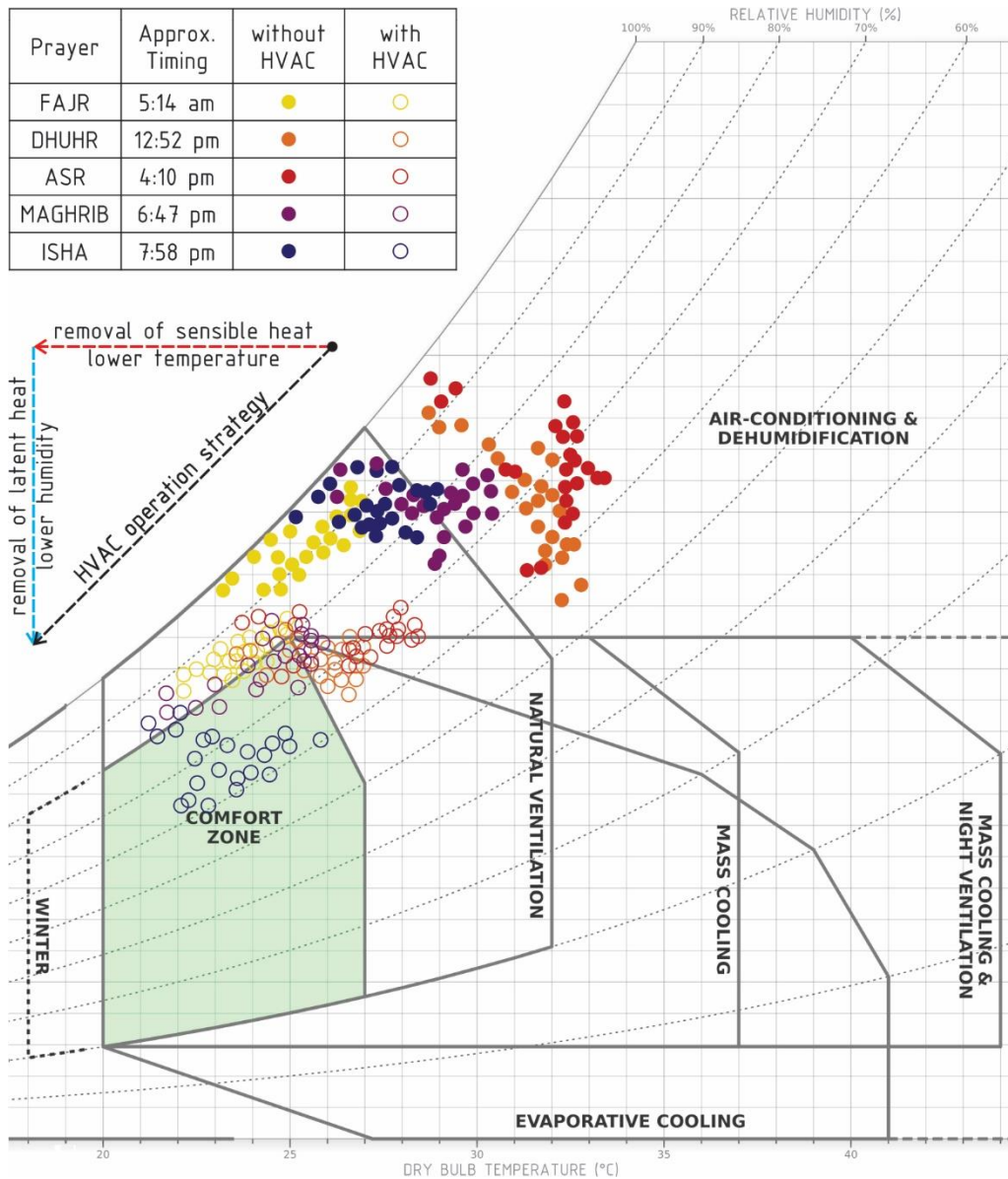


Figure 4.1: Current comfort conditions of case study mosque.

It must be noted that in this bioclimatic chart by Givoni the MRT is assumed to be equal to the air temperature and air speed is considered to be near-zero. However, due to the proximity of congregants during prayer times, and the *Qiblah* wall being exposed to the heated sun, the MRT is an important considering factor for the mosques of Malaysia. In such instances, the PMV may give a more holistic overview of the comfort conditions as it takes into account all the contributing factors. Although adaptive comfort scales are considered

more appropriate for hot climates, it is most suited to natural ventilation scenarios. Since the case study mosque operated HVAC for all prayers, the PMV-PPD index would give a better approximation of thermal comfort. Figure 4.2 gives the PMV and PPD range for all the prayer timings in April following the operational schedule currently in practice (Figure 3.11). It should be mentioned that there were six cases of Type D days with low temperature and heavy rainfall that have been excluded from the plot as those would skew the general results. From the figure, it can be noticed that even with HVAC in operation, the PMV and PPD remain mostly outside of the acceptable range for thermal comfort. For *Asr* and *Maghrib* prayers, none of the recorded instances were within the comfort levels. Comparing the bioclimatic chart to the PMV-PPD diagrams indicate that MRT could be the contributing factor for such a scenario.

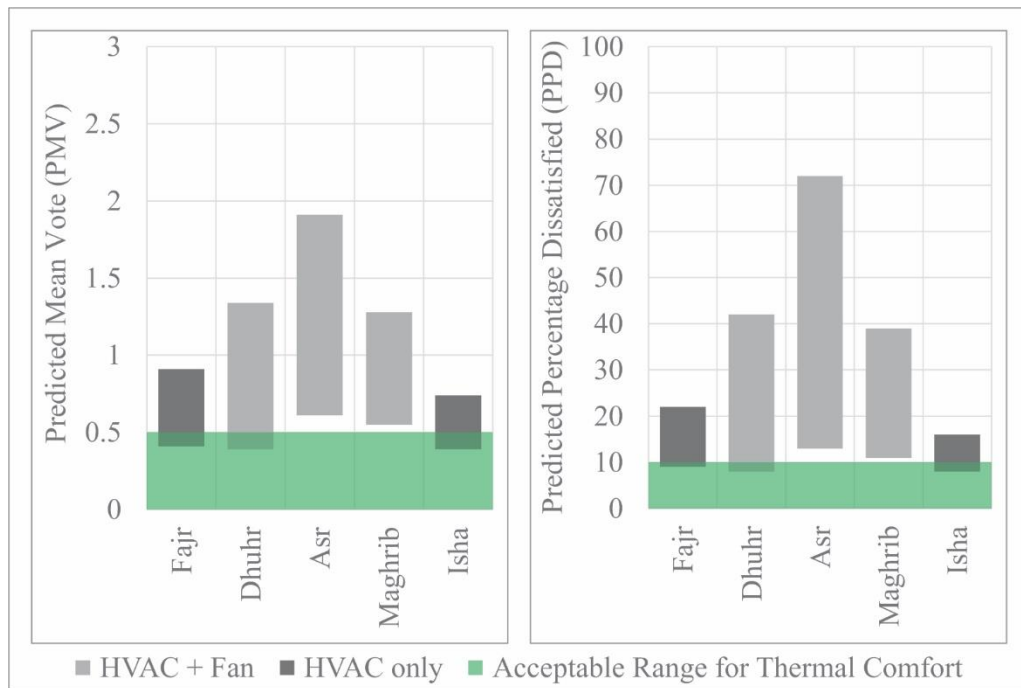


Figure 4.2: PMV (left) and PPD (right) ranges for the prayers in April.

4.2.2 Energy Usage

As the operational schedule of the mosque remains fixed irrespective of the prevalent outdoor weather conditions (Figure 3.11), the daily energy usage does not vary much. Figure 4.3 shows the itemized electricity usage in terms of kWh, as well as a percentage, for the data collection period. The daily values are an average for all days except Fridays while the monthly values reflect the additional usage for Fridays and any other social gatherings. From the energy bills of the whole year of 2020, the monthly energy usage is calculated at 6349.6 kWh which is coherent with the itemized data collected. The EUI for the year is calculated at 152.7 kWh/m².year, which is slightly lower than the energy usage for mosques in HD climates (Al-Homoud et al., 2009, Samiuddin, 2014) but at par with energy audits of medium mosques in Malaysia (Hussin et al., 2018b). However, considering that the mosque operation time is half of the typical non-residential buildings, the EUI is significantly higher than the recommended 135 kWh/m².year (Malaysia, 2007). It can be seen that the daily and monthly percentage of energy consumption for HVAC is over 94% which is higher than the results reported by other literature (Abdou et al., 2005, Abdallah, 2019). Considering the usage of both fans and HVAC as energy consumption to achieve comfort conditions, about 96% of the used energy is for maintaining the thermal comfort of the occupants. This is a large amount of energy being expended, especially considering the occupancy level and operational timings. Yet from the previous section it was observed that such a high level of electricity usage does not translate to suitable comfort levels for the majority of prayer times. Using passive and holistic means for achieving thermal comfort, as attempted in this research, may help lower the energy requirements of mosques.

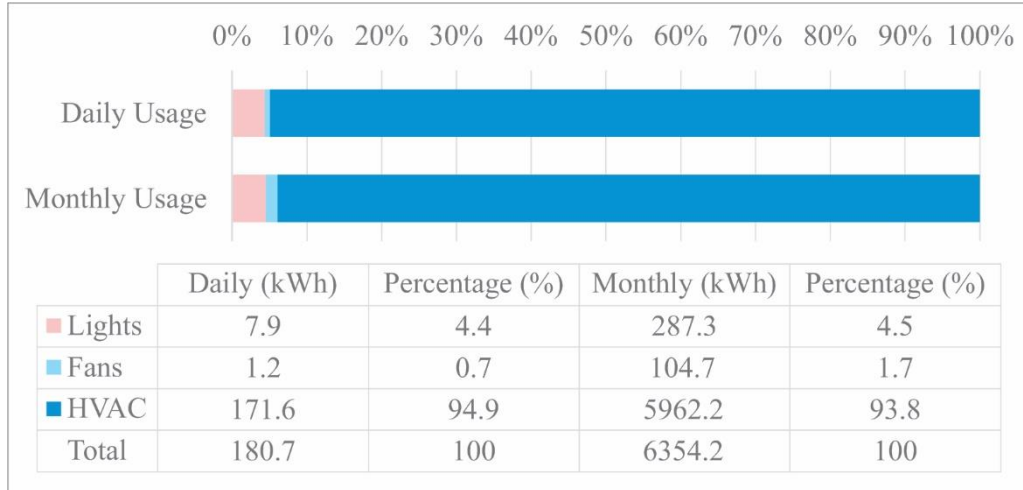


Figure 4.3: Daily and monthly energy end-use.

4.3 Effect of *Qiblah* Wall Design

Since the *Qiblah* wall is located towards the west in mosques of Malaysia, the absorbed solar radiation on the outer portion of the wall is conducted to the inside. Thereafter, the heated internal surface transfers the heat to the other nearby objects by radiation or through the air by means of convection. This largely impacts the MRT and, to a lesser extent, the air temperature components for thermal comfort calculations. The impact of different design alternatives of the *Qiblah* wall is discussed in this section. The change in performance due to the alternative design solutions are calculated with respect to Wall 1, the base case scenario.

4.3.1 Temperature Profile

The surface temperature for the *Qiblah* wall is presented in graph format in Figure 4.4 while the CFD-generated 2D and 3D diagrams are depicted in Figures 1 and 2 of Appendix E, respectively. The biggest impact of solar radiation on the wall can be seen for *Asr* and *Maghrib* prayers where the *Qiblah* wall is heated over 5 °C compared to ambient air temperature. During *Asr*, the sun is directly heating the wall while for *Maghrib* prayers the

sun has just set, but the wall still remains heated. Since Wall 1 is only of single layer brick, it immediately transfers the heat to the interior without much time delay. All of the alternative cases show a considerable reduction in the internal surface temperature of the wall. Wall 2, being a double layer brick wall takes longer to relay the heat and hence, can show up to 3.5 °C less surface temperature for *Asr* prayers. However, by the time for *Maghrib* prayers, the heat transfers to the interior, and only a 1 °C reduction is observed compared to the base case. Walls 3 and 4 both have air cavities inside them which work as a barrier to the heat transfer. Thus, for both the prayers, these two alternatives show a reduction of 12-14% heat gain. For the configuration of Wall 5, the inner surface temperature is reduced by 6.0 °C and 5.7 °C for the prayers of *Asr* and *Maghrib*, respectively. In this wall configuration, the insulation filler layer acts as an additional hindrance for heat gain through the wall.

The *Dhuhr* prayer is during the midday when the sun has not yet reached the western part of the sky that faces the *Qiblah* wall. Hence, the wall remains at a similar temperature to the air temperature as the main thermal gain of the wall happens from the radiative gain due to direct solar radiation. Nevertheless, the wall would already begin to gain heat from this time of the day owing to the indirect and reflected radiation from the external environment. Because of the considerably larger width of Wall 2, and air or insulation gaps for Walls 3-5, the thermal lag ensures that the alternatives show lower temperature during *Dhuhr* time. For both *Fajr* and *Isha* prayers, the base case wall remains about 2-3 °C above the ambient temperature due to residual heat from the day. However, Wall 2 performs worse in the case of *Fajr* as the high thermal mass does not allow it to dissipate heat entirely as compared to other scenarios. Overall, the optimum configuration of Wall 5 outperforms all other alternatives for all the prayer timings. It should be noted that the usage of lightweight

concrete blocks as the interior wall material for Walls 4 & 5 work twofold in preventing heat transfer through the wall. On one hand, the aerated construction material has pores containing air which works as an additional insulating barrier. On the other hand, due to lower thermal mass the wall does not store heat for later periods in time.

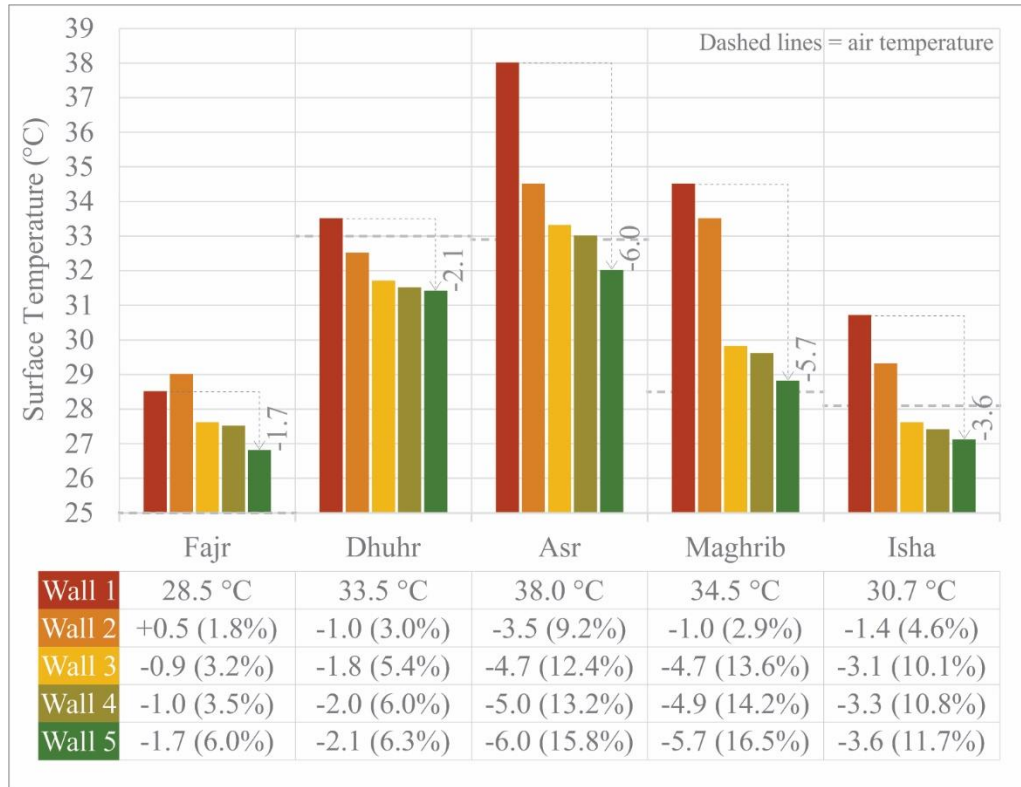


Figure 4.4: Surface temperature of the *Qiblah* wall.

4.3.2 MRT Profile

The heated wall transfers heat to the interior in the form of longwave radiation contributing to the MRT component of thermal comfort. The MRT at the congregant distance is shown in Figure 4.5 for the different alternatives studied. Apart from *Dhuhr*, all other prayer times have MRT which is 1-3 °C higher than the ambient temperature for the existing base case scenario. In literature, the MRT is generally considered to be equal to the air temperature. Even standardized indices, psychrometric charts, and recommended comfort

ranges are determined based on this premise. Yet as hypothesized in this research, the proximity to the *Qiblah* wall does cause a higher MRT which is detrimental to thermal comfort. Since the human body is less perceptive to radiative heat exchange, a higher MRT can create immense discomfort in the occupants. Thus, they may be keen on running the HVAC for longer times or prone to set the thermostat at lower temperatures, without being aware that it is the high MRT, and not the air temperature, which is causing the discomfort. Figure 3 of Appendix E shows the 3D view of the entire prayer hall depicting slight variations for the different alternatives tested in this study. However, this is because only the *Qiblah* wall was taken as a variable in this study and all other components are constant. Therefore, the difference in surface temperature of the wall, as shown in the previous section, will be most evident on the nearby solid objects to the *Qiblah* wall, namely the occupants. Hence, a visible impact can be found for the perceived MRT on the human bodies for the row of occupants standing in a congregation (Figure 4, Appendix E).

Similar to the case for surface temperature, the biggest decrease in MRT can be seen for *Asr* and *Maghrib* prayers. Both Walls 3 and 4 show a considerable difference for the MRT of occupants, showing a decrease of 3.2 °C for *Asr* and 2.7 °C for *Maghrib*. However, Wall 5 shows the optimum scenario of being able to reduce MRT by over 10% which is 3.7 °C and 3.2 °C lower than the base case for the two prayers, respectively. For *Isha* and *Dhuhr*, the change is also notable at 2.0 °C and 1.5 °C reductions in MRT, respectively. For all prayer times, any of the alternative walls performed better than the existing wall structure. However, comparing Wall 2 with Wall 3, which is practically the same wall configuration with and without a cavity, a significant difference can be noticed. Hence, it is safe to assume that for the *Qiblah* wall, an insulative barrier might prove to be helpful. In the industry, it is a common practice to use insulative walls only where air tightness is required for the HVAC

system efficiency. However, with the difference in the MRT as observed in this analysis, it can be understood that a wall with a low U-value may be of substantial benefit for even naturally ventilated mosques. It is interesting to note that within a scenario, the occupants standing in the middle portion have lower MRT gradients (Figure 4, Appendix E), as they have a greater distance from the western wall due to the *Mihrab*. This prompts a future discussion as to whether a buffer space between the *Qiblah* wall and the congregants might prove to be an easy solution in providing better comfort conditions.

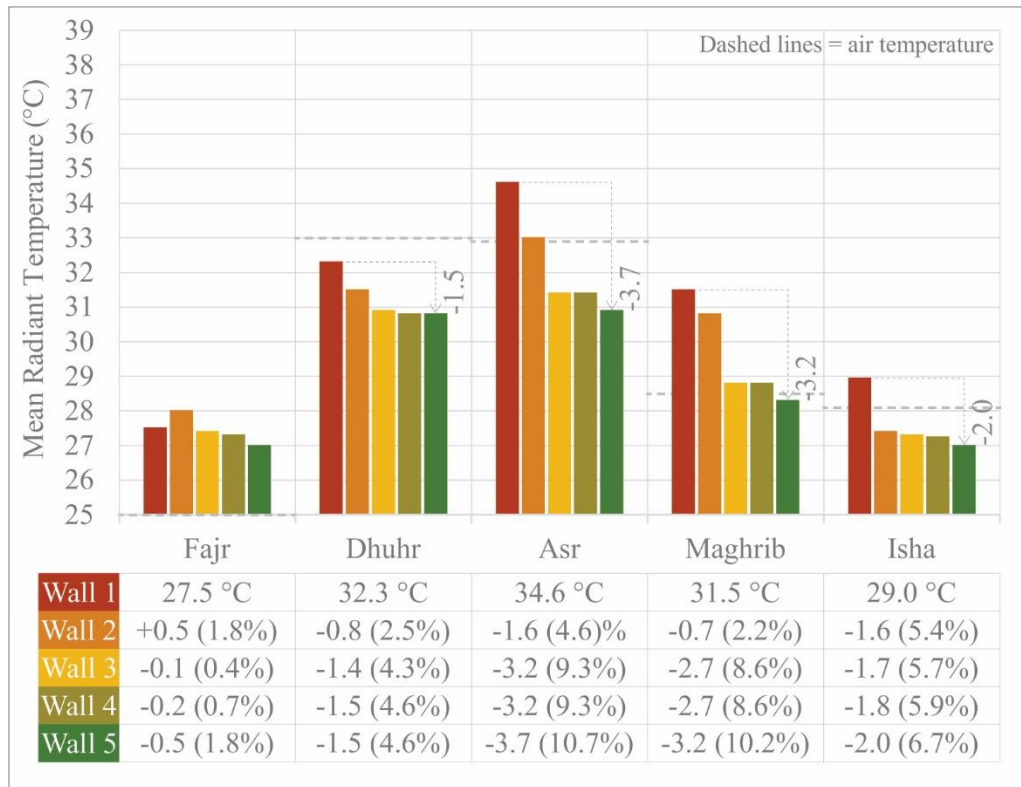


Figure 4.5: MRT at the row of occupants.

4.3.3 PMV-PPD Index

A reduction in the MRT perceived by the occupants will significantly improve the thermal comfort conditions. The results for PMV and PPD are shown in Figures 4.6 and 4.7, respectively. The 3D images of CFD simulation outputs for the row of occupants are

depicted in Figures 5 and 6 of Appendix E, respectively. As expected, it can be seen that for the existing building, the worst-case scenario is during *Asr* prayers, with the situation at *Dhuhr* following closely. This is due to the fact that the ambient temperature during these prayers on a hot day is very high. Even during the other three prayers, the PMV and PPD remain quite high as the analysis was carried out for the hottest day of the year. With Wall 5 configuration, up to 0.6 points and 0.5 points can be reduced for PMV index in *Asr* and *Maghrib* prayers, showing a reduction of 21% and 24% respectively. This translates to a decrease in PPD by more than 11% for *Asr* and 35% for *Maghrib*. It is worth mentioning that the correlation between surface temperature and MRT, and the subsequent relation between MRT and PMV-PPD values are not linear. Hence, the amount of reduction in PMV-PPD is not proportional to the decrease in wall temperature or MRT. Therefore, although the reduction of MRT is not as significant for *Isha* prayers, the corresponding PMV and PPD reduction are 17% and 26%, respectively. This indicates that at a lower air temperature, a reduced MRT can have a greater positive impact on the thermal comfort of occupants. Nevertheless, even for the best-case scenario, the changes are not sufficient to ensure comfort conditions for any of the prayer times. Despite the significant decrease in MRT, the change in comfort levels is not enough and the PMV remains much higher than the recommended 0.5. This also proves that high humidity and high air temperature are both major factors for the thermal comfort of the occupants in HH climates.

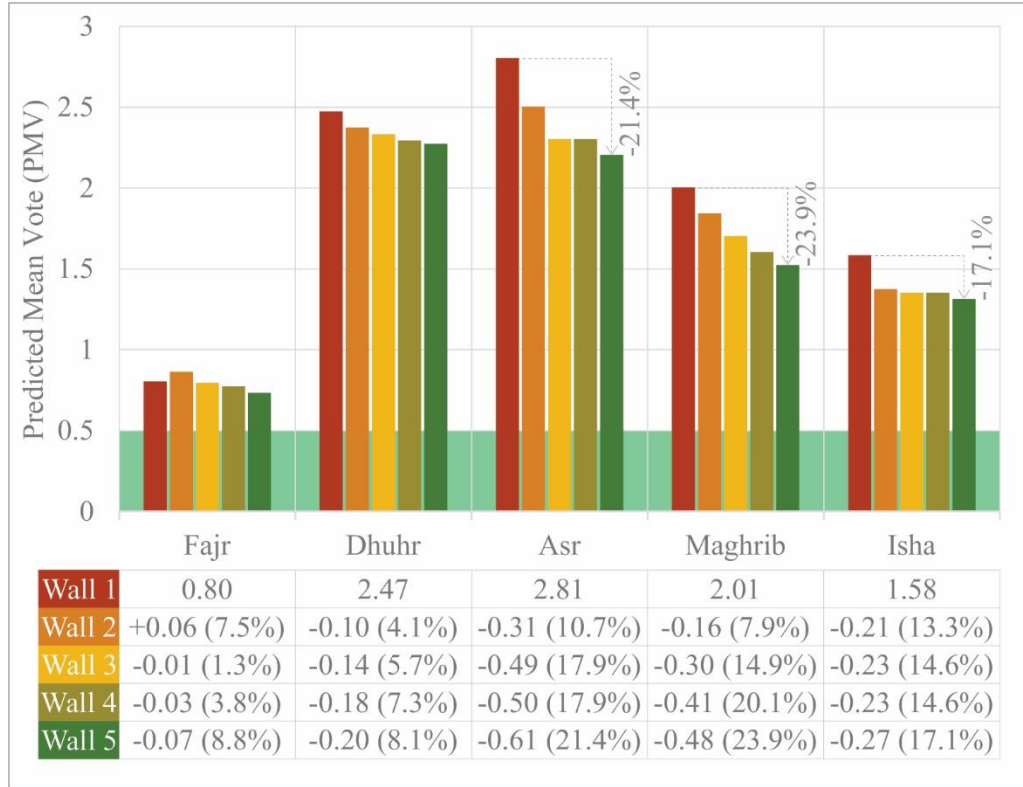


Figure 4.6: PMV at the row of occupants.

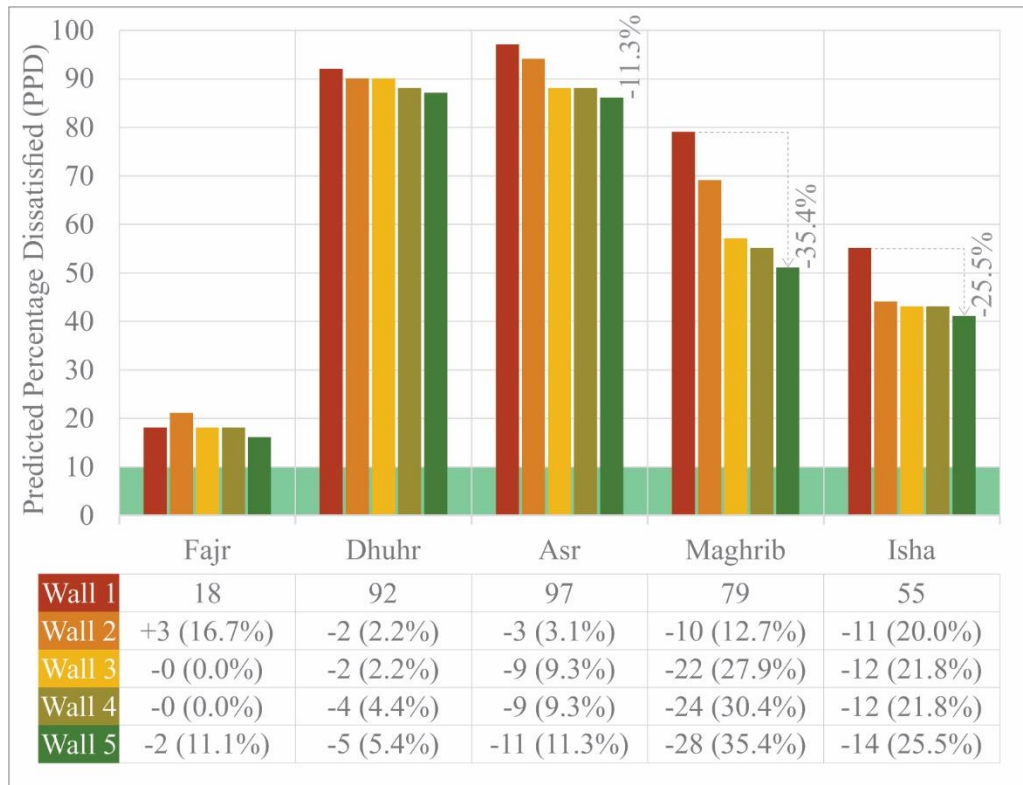


Figure 4.7: PPD at the row of occupants.

4.4 Effect of Ventilation Strategies

The diagrams from the previous section clearly show that thermal comfort cannot be achieved under natural ventilation conditions for the case study mosque. However, for this study, the air was considered nearly still, which is the worst-case ventilation scenario. In reality, there would be times when the natural air flow conditions may reach a comfortable level, but the results cannot be based on such unpredictable weather circumstances. An enhanced form of ventilation can be achieved by using mechanical fans as any air movement would give pleasant conditions for HH climates. This does not reduce the air temperature but helps human thermoregulation in terms of convective heat loss of the human body. Additionally, it removes the highly saturated air that is next to the skin, facilitating body temperature regulation through the evaporation of sweat. This section discusses how an added component of keeping the fans on during prayer times contributes to the thermal comfort of the occupants. The comparison for each design alternative would be given with respect to the same scenario having the fans switched off. It should be noted that with air movement, there would be a very slight change of wall surface temperature, and subsequent change in MRT, over the duration of the prayers. However, the steady-state simulations were run for a fixed time at the beginning of the prayers, and hence, no change in wall temperature or the MRT is observed for this analysis.

4.4.1 Velocity Profile

Figure 7 of Appendix E shows the visualizations of the air flow pattern for the different simulation cases. Since turning on the fan is a form of forced mechanical ventilation, there is hardly any variation between the scenarios. In all instances, the fan creates an air movement of approximately 1 m/s at the user level, which is congruent with the obtained field data. Due to the motion of the air, there is turbulence at the front portion

of the prayer hall which is dissipated, and gradually diminishes, as it progresses along the hall.

4.4.2 PMV-PPD Index

The PMV and PPD for the simulation scenarios with the fans turned on are given in Figures 4.8 and 4.9, respectively. Each percentage reduction is calculated with reference to the same design alternative with the fans switched off. 3D visualizations of the PMV and PPD are given in Figures 8 and 9 of Appendix E, respectively. For better comparison, both results with fans off and on are provided side by side for each design scenario. A remarkable drop in both PMV and PPD can be seen in all cases, including the base case scenario, ranging from 40% to as much as 80%. This proves the premise discussed in Section 2.2.2 that in HH climates an elevated air speed can be an effective approach to providing comfort conditions. Overall, it is possible to achieve conditions well within the comfort levels for *Fajr* and *Isha* while for *Maghrib* it is sufficiently close to the comfort range. Even during the peak daytime temperature at *Dhuhr* and *Asr*, there is a considerable decrease of approximately 40% in PMV and 50% in PPD. However, the most significant change can be seen for *Fajr* and *Isha* prayers where the temperature is lower compared to the other three prayer times. Thus, a conclusion can be drawn that an added air movement works best when the ambient temperature itself is low. It is interesting to note that for the base case of Wall 1, both *Fajr* and *Isha* reach comfort conditions of recommended PMV-PPD levels with the fan switched on. However, in practice, the fan is kept off during these times as the HVAC already lowers the temperature sufficiently within comfort levels. For existing mosques, this finding can be taken into consideration by encouraging the occupants to keep the HVAC turned off and fans on during these two prayer times to reduce energy consumption.

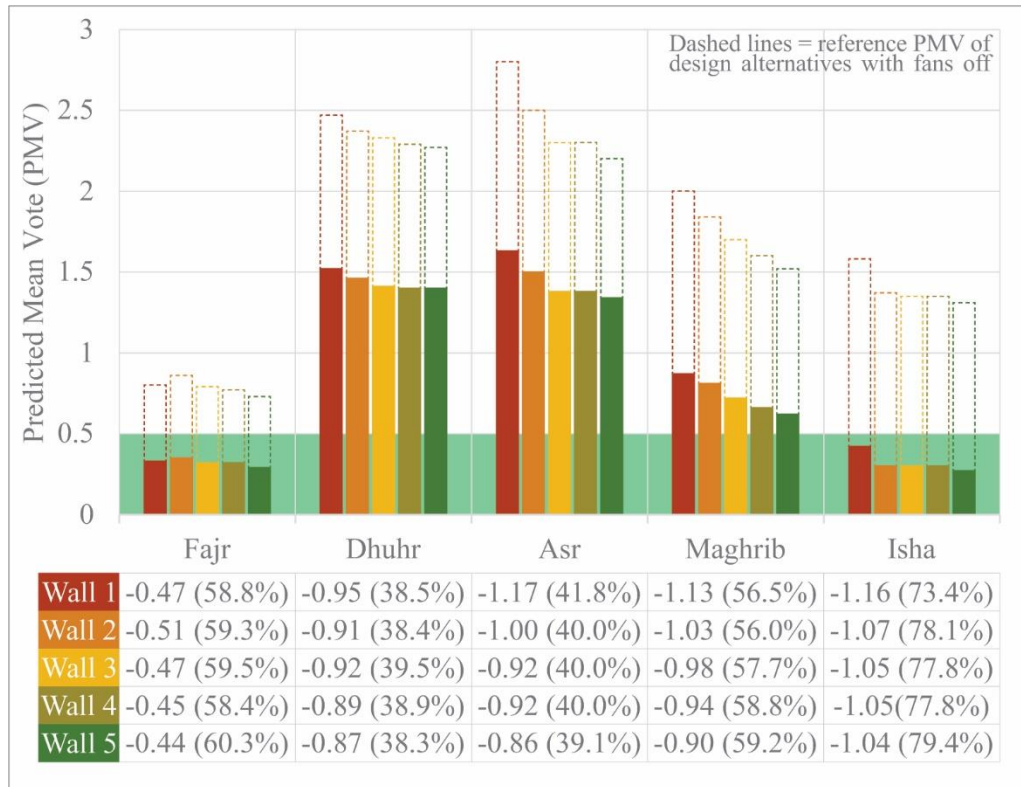


Figure 4.8: PMV of occupants with fans switched on.

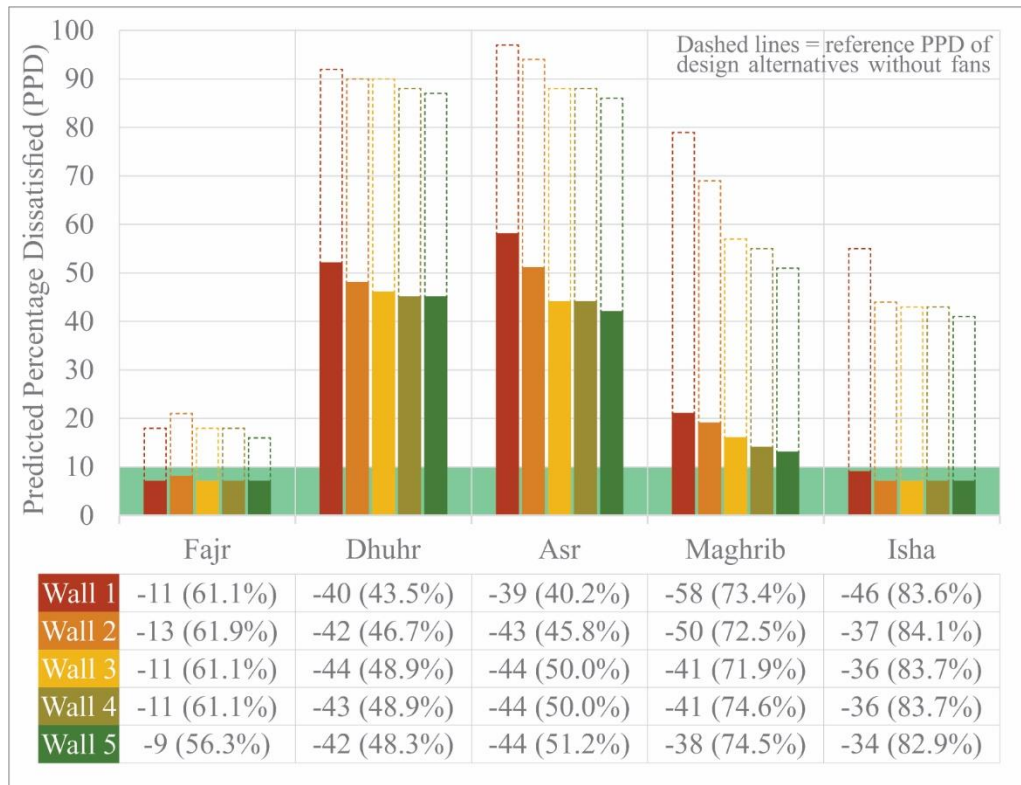


Figure 4.9: PPD of occupants with fans switched on.

4.4.3 Operative Temperature

The OT is dependent on the air temperature, air speed, and MRT. Hence, a decrease in MRT with better wall design results in a decrease in operative temperature as well. Whilst considering an air speed, the OT may decrease or increase depending on the ambient temperature and the surrounding context which may impact the air temperature. There is a continuous convective heat exchange between any solid and the air film next to the object. With fans operating close to the *Qiblah* wall, the increased air movement allows for more heat exchange between the wall and the surrounding air. When the wall has a high surface temperature, the heat from the wall is dissipated throughout the hall by means of the air flow, increasing the ambient air temperature. Hence for the existing Wall 1, operating the fan increases the OT of the occupants for the three later prayers of the day (Figure 4.10). In this instance, the air temperature is not changing due to the air flow but because of the heat from the wall being propagated by the fluid medium. The visualization can be seen in Figure 10 of Appendix E where the fan situated next to the heated west wall is blowing the hot air onto the congregants during *Asr* and *Maghrib* times. With the wall design being optimized, this problem does not remain for mechanical ventilation options. In fact, in cases where the MRT is lower than the ambient temperature, having a fan operating next to the *Qiblah* wall can have a cooling effect on the occupants by means of lowering the OT (Figure 11, Appendix E). Although this is a small change, the significance can be huge in terms of adaptive thermal comfort, which will be discussed in the next section.

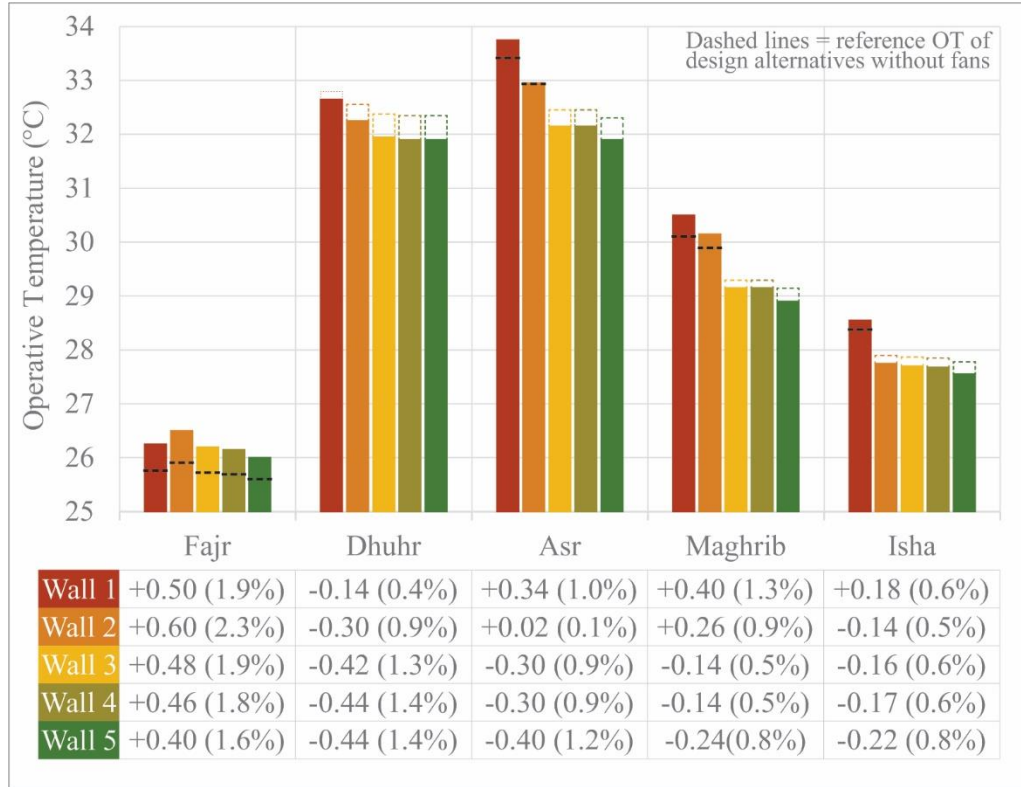


Figure 4.10: OT at the row of occupants.

4.5 Optimum Combination of Parameters

In Section 4.3 the comparison for each design alternative was made with the base case of Wall 1, while in Section 4.4 contrast was drawn between natural and mechanical ventilation options for each scenario. In this section, an overall evaluation is done to determine the optimum combination of parameters that provides better thermal comfort for the occupants. A comparative analysis is done to determine whether the comfort conditions can be met without the need for HVAC interventions; the subsequent implications of such measures are also discussed.

4.5.1 Thermal Comfort Conditions

From previous sections, it is apparent that Wall 5 proves to be the best design option for the *Qiblah* wall. Figures 4.11 and 4.12, depict the PMV and PPD, respectively,

comparing the results for Wall 1 and Wall 5, both with and without fans. This can help assess the improvement in thermal comfort levels that can be achieved in the best-case scenario compared to the existing design. The figures show that a PMV of under 0.5, and a corresponding PPD of less than 10%, are achieved for both *Fajr* and *Isha* prayers without utilizing the HVAC system. During the other three prayers, the comfort conditions also improve considerably, as the PMV index reduces by 43%, 52%, and 69%, respectively. However, such a decrease is not enough to ensure thermal comfort as the ambient temperatures are high during those times. Since air temperature is a major decisive factor for thermal comfort calculations, the high temperature during the *Dhuhr*, *Asr*, and *Maghrib* prayers is the biggest contributor towards discomfort. Therefore, HVAC would need to be operated on those occasions to reduce the air temperature and ensure the thermal comfort of the occupants. Nevertheless, it is to be noted that the numerical analysis has been carried out in the context of the worst-case scenario day, where the ambient temperature remains very high throughout the day. In reality, there would be many instances when the air temperature is much lower, requiring no HVAC intervention during those prayer times.

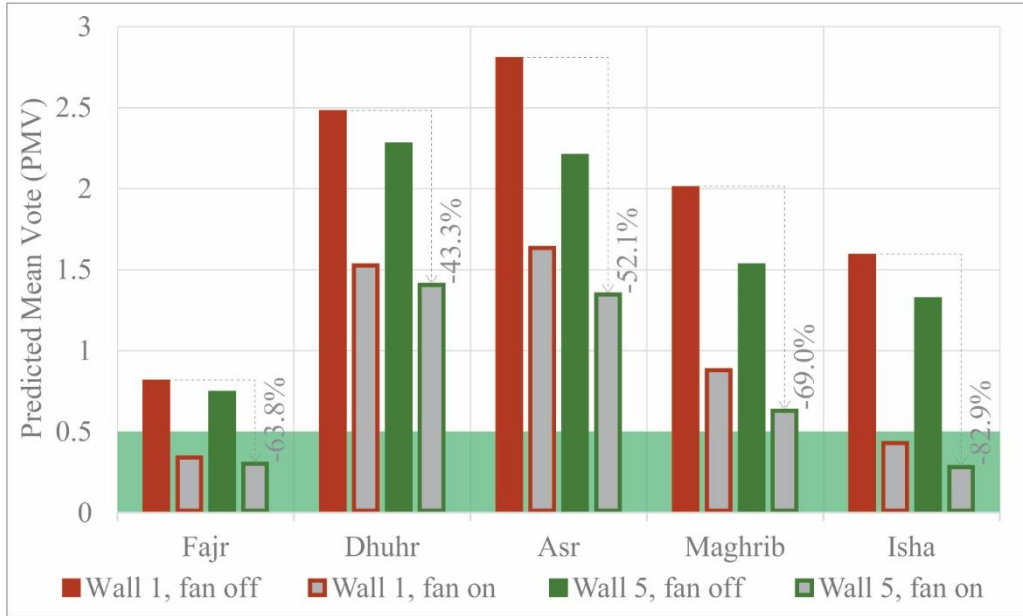


Figure 4.11: PMV of base case and optimum scenario.

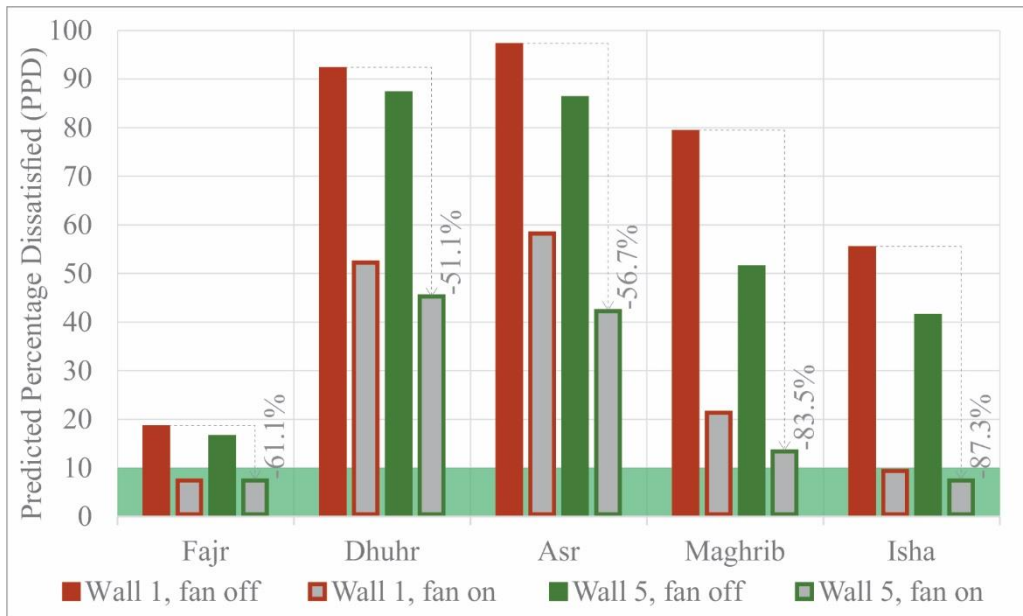


Figure 4.12: PPD of base case and optimum scenario.

While considering thermal comfort, adaptive comfort scales should also be taken into account as empirical data proves that it is more suitable for the hotter climates. The index is based on the OT (Figure 4.13), which is reduced by 2-5% in the best-case scenario for all prayers except *Fajr*. The slight increase of OT during *Fajr* is due to the thermal lag of the

wall which can be ignored as the ambient temperature is already low. The change in OT is not very significant because the air temperature remains unchanged as it was not a variable considered for this research. Nonetheless, plotting the OT in the adaptive thermal comfort model shows that this small change can bring the conditions from borderline to well within comfort ranges for both *Maghrib* and *Isha* (Figure 4.14). It is interesting to note that for *Maghrib* prayers, the PMV-PPD model gave a value just beyond comfort conditions, yet the adaptive model proves it to be within the recommended range. This comparison between the steady-state, PMV-PPD model and the empirically derived, adaptive model provides further evidence that people are more adapted to existing climatic conditions in hot climates. In this instance, it can be concluded that the high humidity conditions prevalent during *Maghrib* times contribute to the higher PMV-PPD values, which the occupants would be physiologically adapted to in reality. Similarly, the optimized values for *Dhuhr* and *Asr* are just outside comfort ranges in the adaptive model, yet the PMV-PPD calculations suggest severe discomfort for those prayer times.

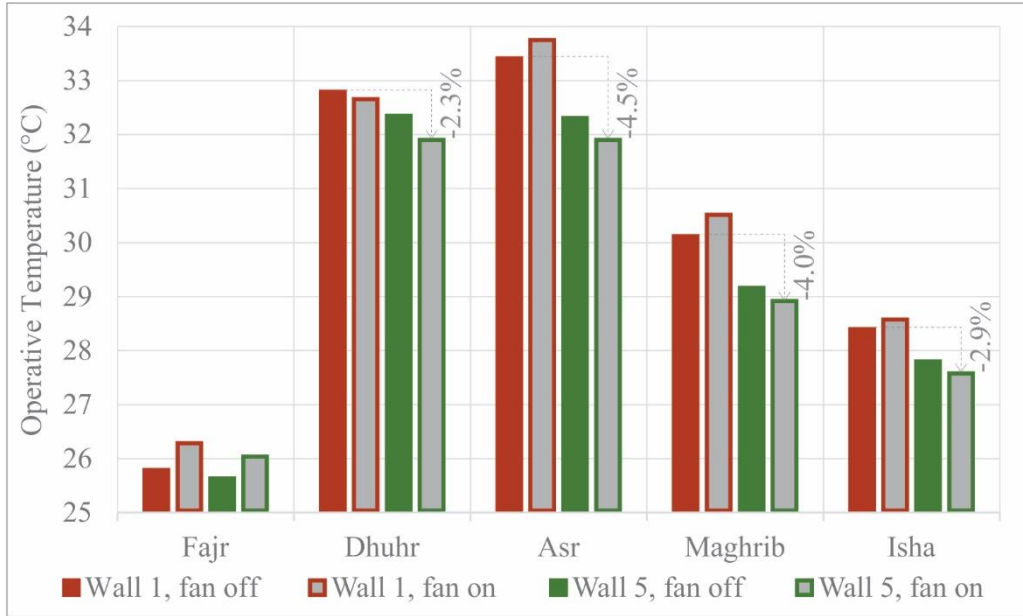


Figure 4.13: OT of base case and optimum scenario.

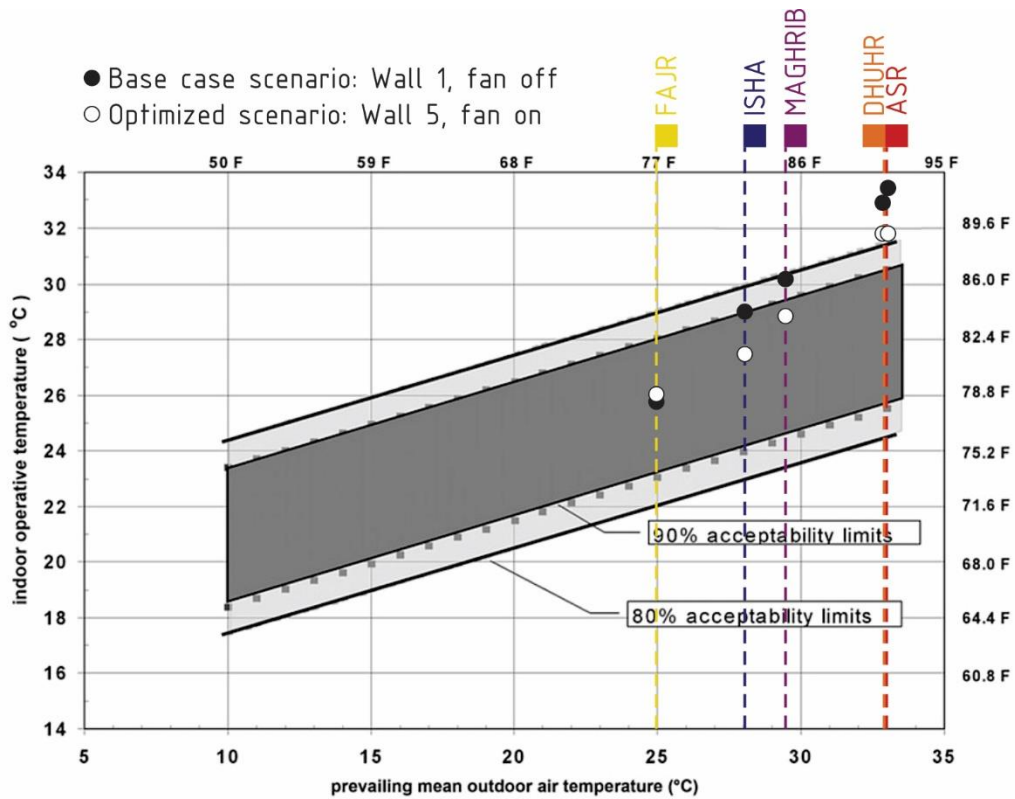


Figure 4.14: Adaptive thermal comfort levels for the optimized scenario.

4.5.2 Comfort Temperature

In Chapter 2 it was discussed how the ASHRAE recommended comfort temperature range is derived from a very limited set of values for the factors of thermal comfort (Figure 2.5). The values would, more often than not, vary widely from the presumptions in the context of hot climates. Yet, HVAC system designing in HD or HH climates is done according to the recommended set-point range prescribed by this standard. Using the HVAC for thermal control is an active design strategy that shifts the temperature-humidity data points within a psychrometric chart (Figure 4.1). On the other hand, passive design techniques shift the comfort range, enabling thermal comfort at conditions that are closer to the existing environment. An example is provided in Figure 4.15 to demonstrate the passive design principles for the various design scenarios tested in this analysis. For the *Asr* prayer time of the case study day when the temperature is 32.9 °C and the relative humidity is 57%, the following are the comfort conditions according to the PMV-PPD model:

(A) For the existing scenario with no mechanical ventilation, it would require a temperature range of 15-20.5 °C to ensure the thermal comfort of the occupants.

(B) With an optimized MRT by implementing Wall 5, the comfort range moves to the right, but the width remains unchanged. The new comfort temperature range is 17.5-23 °C, whereby a 3.7 °C drop in the MRT increases the neutral temperature by 2.5 °C.

(C) Introducing air movement to the base-case scenario through mechanical ventilation shifts the comfort range to the right, but also narrows it down. This is because localized thermal discomfort due to a draft is commonly associated with high air speed caused by the fans. The new comfort range is 22-25.5°C, which has a 3.5 °C width, as compared to the original width of 5.5 °C.

(D) Combining better *Qiblah* wall design with the ventilation strategies gives the optimum scenario of Wall 5 with fans on, which has also been discussed in the previous section. The overall optimized comfort range is 23.5-27 °C, where the upper limit, also known as the cooling set-point, is 6.5 °C more than the original scenario.

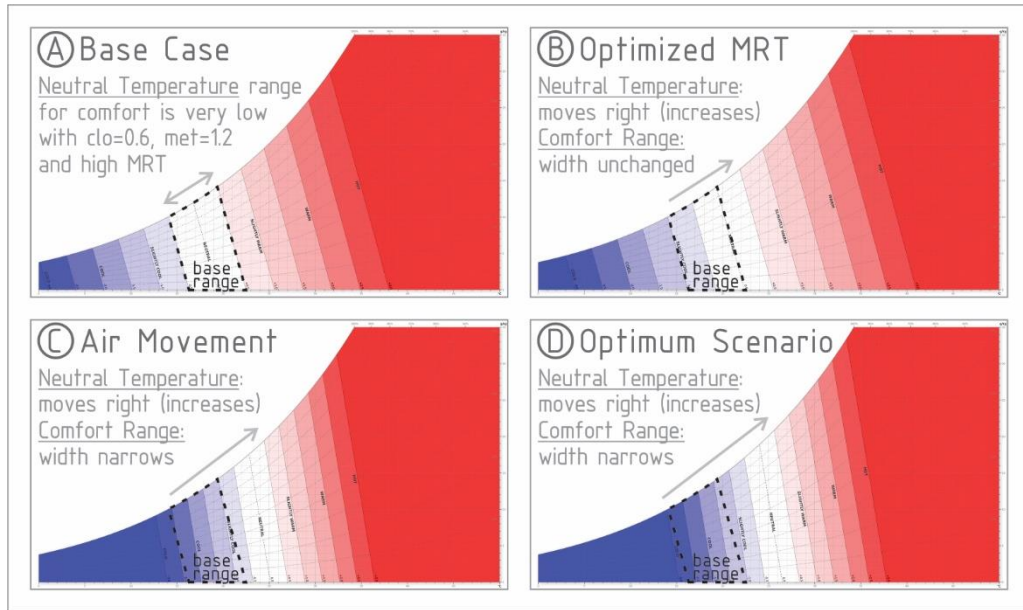


Figure 4.15: Psychrometric chart showing comfort temperature range.

For this example, the ambient temperature of the case study day is at 32.9 °C, which is still higher than the upper limit of 27 °C of the comfort range. Hence, in this particular scenario, the HVAC system needs to be operated to bring down the air temperature to below 27 °C. However, during other days when the temperature-humidity combination at the *Asr* prayer time is within the comfort zones, the HVAC need not be employed. Figure 4.16 shows the comfort temperature range for each prayer at the different humidity levels prevalent in Malaysia. For lower humidity levels, the range will be slightly higher while for higher humidity conditions it will be a bit lower. In the context of Malaysia, the yearly sunpath is fairly uniform, while the human metabolic rate and clothing levels remain the same at 1.2 met and 0.6 clo, respectively, during the prayers. Hence, comfort temperature ranges

established through this process are relevant throughout the year. While this range is suitable for the case study mosque, it can be applied to all mosques in Malaysia, in general. The shifting of neutral temperature by 4-7 °C can have tremendous energy-saving outcomes and consequential financial implications. Higher set-point temperatures require smaller equipment sizing or lesser units for the HVAC system. Furthermore, setting the thermostat higher than the usual practice of 18-22 °C will not overburden the machine which will extend its lifespan. This finding also opens up other research possibilities on the HVAC type, sizing, zoning, etc. in light of the large space yet low occupancy during daily prayers. Additionally, this also poses opportunities for further research on whether radiant cooling, accompanied by fans, would be enough to provide suitable comfort conditions during low occupancy periods.

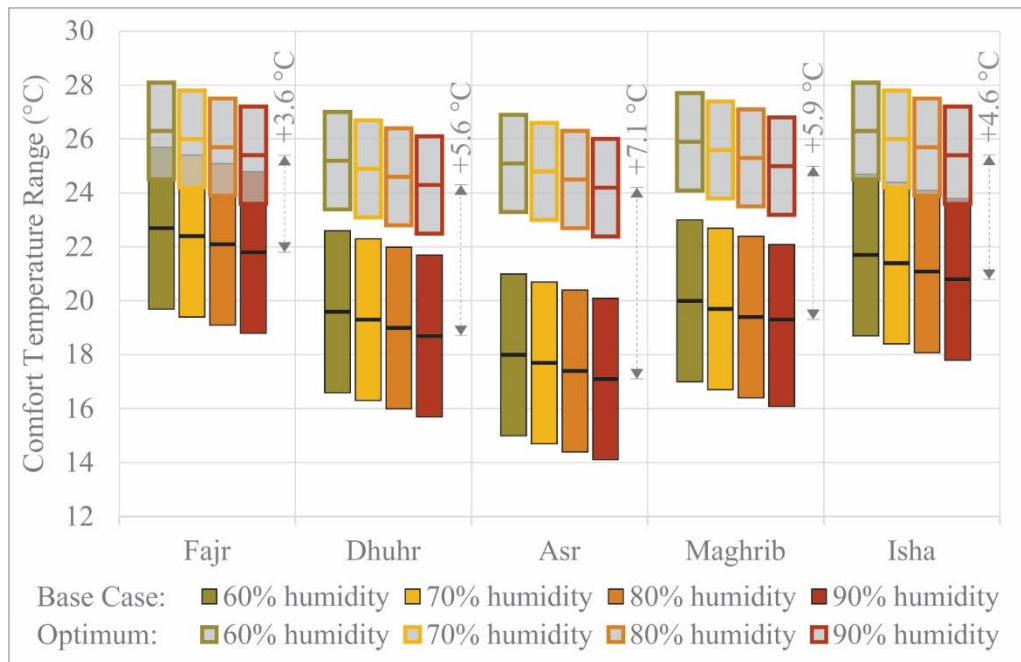


Figure 4.16: Comfort temperature range for optimized design solutions.

4.5.3 Energy Consumption and Implications

The previous section discusses how a higher set-point for the HVAC would reduce the energy needs of the mosque. Notwithstanding that consideration, it is evident from Section 4.5.1 that comfort conditions can be met during *Fajr* and *Isha* times without the need for HVAC utilization. Even with the current *Qiblah* wall setup, thermal comfort can be achieved with only the fans operating (Figures 4.11 and 4.12). Hence, it is highly recommended that users and management be educated about the importance of energy preservation and encouraged to follow such a schedule. If the HVAC system is turned off during those prayer times, the daily electricity usage for fans slightly increases yet energy needs for HVAC decrease by 61.2 kWh per day, saving 32.7% of daily energy usage (Figure 4.17). Compounded over the year, the proposed scenario brings about a 28.2% reduction from the current scenario. The optimized EUI is 109.6 kWh/m².year, which is well within the limits recommended (Malaysia, 2007). Since the ambient temperature remains the most decisive factor for thermal comfort, this schedule can be adapted for other instances when the air temperature is lower, especially during cooler days when there is rainfall. Hence, with due diligence of the users and management, further energy savings can also be achieved.

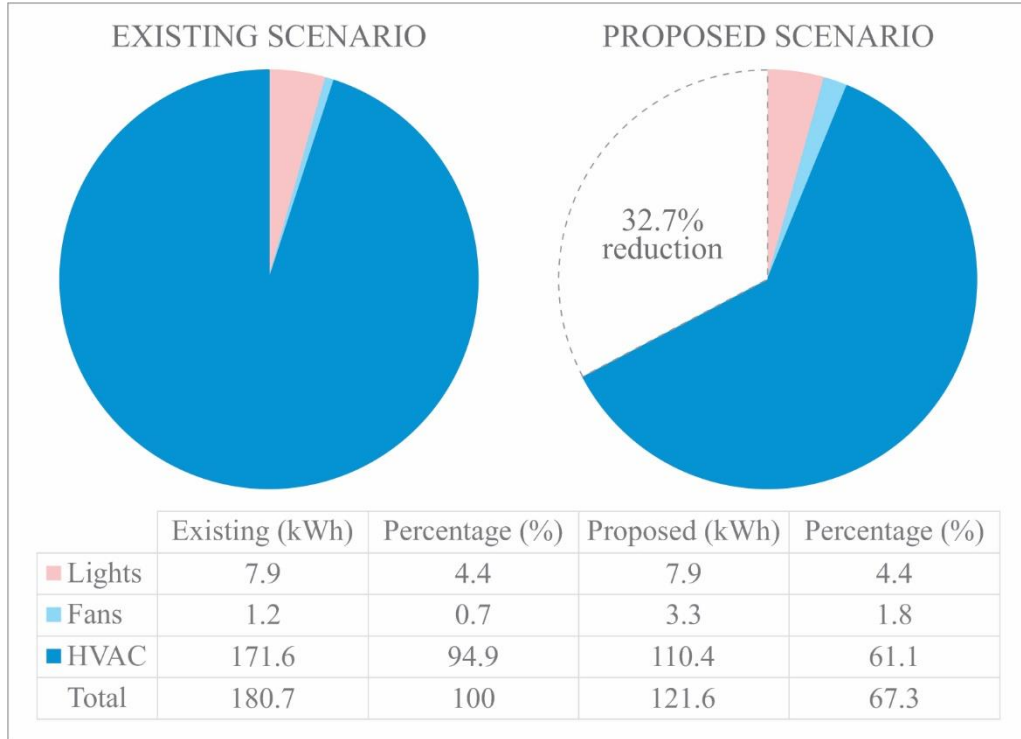


Figure 4.17: Predicted daily energy savings for the proposed scenario.

4.6 Summary of Results

This chapter has presented the results from both the field study and numerical analysis. The existing scenario has been analysed which illustrates that despite using a high amount of electricity, the comfort conditions are not met during most of the prayer times. Thereafter, findings from this research have been discussed in terms of *Qiblah* wall design and ventilation strategies. An analysis of thermal comfort has also been provided in light of both the PMV-PPD model as well as the adaptive model. Results have shown that the hypothesis initially posed at the beginning of this research stands true and that the optimization of the *Qiblah* wall, in conjunction with ventilation strategies, increases thermal comfort. Additionally, such measures positively impact the comfort temperature levels which has a significant impact on the predicted energy usage.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Summary of the Research

Mosques are operated intermittently five times a day for a short duration during the prayer times. The daily prayers typically have a very low occupancy level compared to the mandatory Friday prayers, yet the same prayer hall and the same HVAC system are operated to cater for the thermal comfort of the occupants. This results in high energy usage in mosques for thermal comfort purposes while oftentimes the comfort conditions are not met due to the short span of operation. An HVAC is an active system that operates by modifying the air temperature and humidity levels to bring the indoor conditions within comfort levels. A passive system, on the other hand, focuses on the building design principles to enhance thermal comfort conditions without the need for energy-extensive resources. The purpose of this research was to assess whether the thermal comfort conditions could be met during the low occupancy daily prayer times without the need for utilizing HVAC. In the context of Malaysia, the air speed component of thermal comfort is an important consideration due to extremely high humidity levels. Additionally, since the *Qiblah* is located towards the west, the high solar gain of the building structure influences the radiative heat exchange of the human body, thereby negatively impacting the MRT. It was hypothesized that by modulating only these two components, better comfort conditions could be achieved for short-term low-level occupancy periods. In order to meet the research objectives, the base case mosque was simulated on a CFD platform which holistically assesses the thermal comfort conditions.

The numerical model was verified and validated against field experiment data and parametric simulations were carried out for the worst-case scenario. Design alternatives of

the *Qiblah* wall and ventilation strategies by using mechanical fans were tested for the five prayer times. The major findings of this study, with respect to the research objectives, are summarized in Table 5.1. Since the congregants are located close to the *Qiblah* wall, a drop in the surface temperature through better wall design reduces the MRT, resulting in a positive effect on the thermal comfort of the occupants. Moreover, fans induce air movement which helps human thermoregulation and greatly enhances the comfort conditions. The findings indicate that the MRT reduction, coupled with air flow from the mechanical fans, can have a greater impact on the thermal comfort of the occupants at lower ambient temperatures. Hence, it is possible to achieve conditions within the comfort levels without the need of any HVAC during *Fajr* and *Isha*, when the air temperature is comparatively lower. This can be taken into consideration by encouraging the congregants to keep the HVAC turned off and operating only fans during these two prayer times to reduce energy consumption. Overall, the thermal comfort levels were greatly improved by employing alternative wall designs in all instances throughout the day. Since there is a considerable improvement for the worst-case day, it may be concluded that there would be better comfort conditions during other less extreme days as well. Furthermore, using the passive design strategies results in a shift in the comfort range which allows thermal comfort at higher temperature levels. This puts less pressure on the HVAC system and helps achieve energy efficiency.

Table 5.1: Major findings of the research.

Objective	Results and findings
i) To identify the relation between mosque thermal comfort requirements and energy usage pattern through energy audit of case study mosque.	<ul style="list-style-type: none">- Currently, 96% of energy is used for thermal comfort requirements.- Mosque operation timing is 50% of non-residential buildings but the EUI is 152.7 kWh/m².year, which is 12% higher than recommended for full-time usage.
ii) To evaluate the current thermal comfort conditions and the viability of natural ventilation during low occupancy periods in order to reduce energy usage by HVAC.	<ul style="list-style-type: none">- Thermal comfort is not achieved during the majority of prayer times, even with the HVAC operating from 30-45 mins prior to the prayer time.- It is not possible to provide comfort conditions only with natural ventilation even during low temperature periods due to high humidity conditions.
iii) To numerically analyse the influence of the design of the <i>Qiblah</i> wall in influencing the thermal comfort of the occupants in Malaysian mosques.	<ul style="list-style-type: none">- High MRT due to heated <i>Qiblah</i> wall hinders thermal comfort for the occupants.- Optimized wall design reduces the MRT by 2-4 °C, improving the PMV by as much as 24% and PPD by over 35%.

Table 5.1 continued

iv) To propose architectural design solutions for the <i>Qiblah</i> wall in conjunction with ventilation strategies that allow for optimum thermal comfort.	<ul style="list-style-type: none">- Thermal comfort can be achieved during <i>Fajr</i> and <i>Isha</i> with fans only, which reduces the need for HVAC usage.- This proposed scenario can save 32.7% daily energy usage and reduce the EUI by 28.2%.
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5.2 Practical Applications

The general principle behind the findings of this research is that an optimized *Qiblah* wall design lowers the heat gain of the wall and reduces the envelope thermal gain for the interior. On one hand, the insulative properties decrease the amount of heat being transmitted to the indoors. On the other hand, thermal lag ensures that the peak load is lessened, and also distributed, over time. The essence of this theory can be applied to both existing and new mosques whereby it is more desirable to prevent the solar rays from reaching the wall in the first place. If that cannot be avoided, then care must be taken to ensure that minimum solar radiation is absorbed by the wall or transmitted inside. The practical steps that can be taken to reduce the MRT due to the heat gain of the *Qiblah* wall are given below. The first two recommendations are for new constructions or retrofit designs of mosque buildings. However, the latter three suggestions may be applied to both new and existing mosque buildings without the need for any structural change.

- Using shading devices on the *Qiblah* wall. This can be extended by means of a balcony or corridor on that side as well.
- Placing a buffer space between the outer wall and the main prayer hall. The auxiliary spaces can be placed on the western side of the mosque which will prevent direct solar heat gain of the *Qiblah* wall.
- Increasing the solar reflectivity, and thus reducing the solar absorptivity, of the wall by using smooth finishes and white paint. Modern materials such as cooling paints can be used on that wall only, which can ensure 5-6 °C lower surface temperatures (Lei et al., 2017).
- Planting of trees or using an external trellis-based green wall at the *Qiblah* side of the building.

- Forming the congregation at a distance from the wall during low occupancy prayers in mosques where the *Qiblah* wall is directly exposed to the outside sun. Since MRT is dependent on proximity, congregants can be encouraged to pray at the middle portion of the hall to reduce the radiative heat transfer between the human body and the *Qiblah* wall.

5.3 Recommendations for Future Work

The findings from this research are promising both in terms of energy efficiency and human thermal comfort. The comfort temperature recommendations and the proposed HVAC operation schedule can be adapted for other medium-sized mosques of Malaysia. Additionally, the same research can be extended for larger mosques, where special considerations should be given to the scale difference concerning the occupancy level. Moreover, the methodology can also be replicated for mosques in other climatic contexts with suitable modifications. Furthermore, the results and findings of this study have opened up many research possibilities that may be addressed by future researchers:

- The premise of this research has been based on the insulative properties and thermal lag of the *Qiblah* wall. This may be furthered into research regarding energy storage within the wall or the use of phase change materials (Lizana et al., 2017) for rendering optimum comfort conditions.
- Since the radiative heat exchange of the human body is an important consideration, using radiative panels to reduce MRT may be a good prospect and an energy saving option as well (Baharun et al., 2018).
- One of the contributing factors for such a high PMV-PPD in the HH climates is the high humidity component. Since the temperature range often remains close to the

comfort levels, research should be done on whether dehumidifying the air would be a faster and more energy efficient alternative to cooling the air.

- Multitudes of research possibilities remain on the HVAC type, sizing, zoning, etc. in light of the large space yet low occupancy level during daily prayers. A cost-benefit analysis on the probability of a separate, smaller praying area for the daily prayers while dedicating the large prayer hall for full occupancy periods could also yield viable solutions.

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APPENDIX A

JOURNAL PUBLICATION 1: Review paper on mosque thermal performance.

Title: A comprehensive review on thermal performance and envelope thermal design of mosque buildings.

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<https://www.sciencedirect.com/science/article/abs/pii/S0360132320306764>

BUILDING AND ENVIRONMENT

<https://doi.org/10.1016/j.buildenv.2020.107305>

PII: S0360-1323(20)30676-4

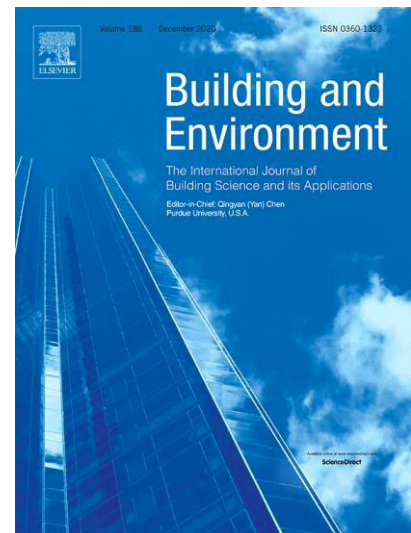
REFERENCE: BAE 107305

Received Date: 19 April 2020

Revised Date: 18 August 2020

Accepted Date: 15 September 2020

Available online: 19 September 2020



SCOPUS Citescore: 9.7

Impact Factor (Web of Science- ISI): 6.5

SCIMAGO Quartile: Q1



A comprehensive review on thermal performance and envelope thermal design of mosque buildings

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ARTICLE INFO

Keywords:

Thermal performance
Thermal comfort
Energy efficiency
Building envelope design
Intermittent occupancy
Mosque building

ABSTRACT

Mosque building is characterized by its unique spatial requirements and intermittent occupancy pattern. In order to create a suitable ambience for prayers, maintaining optimum thermal comfort of the interior is a must. As mosques are skin-load dominated buildings, the climatic conditions play a defining role in the thermal comfort of the users as well as the energy efficiency of the building. Therefore, appropriate building envelope designing that ensures optimal thermal performance is required to protect the interior from the external harsh climate and to ensure better thermal comfort for the users. Additionally, improving the overall thermal performance of the building allows reduced energy consumption and ensures improved energy efficiency. However, research in this niche is an emerging field and much work needs to be done to establish design standards. This review paper conducts a comprehensive literature review with the aim of identifying important aspects of mosque thermal performance. With this intent, the paper classifies findings from literature according to building design elements as well as different components of the mosque envelope such as walls, roofs and windows. Thereafter, it discusses the impact of the corresponding characteristics and parameters on the overall thermal performance of mosque buildings. As a result of this review, various research gaps and potential research prospects have been identified in different aspects of mosque designing. The paper concludes with suggesting prospective research scopes that may serve as a foundation for future research endeavors.

1. Introduction

Mosques are religious buildings which are characterized by a unique set of functional and operational requirements. Muslims gather in the mosques for congregational prayers five times a day for the prayers of *Fajr* (before sunrise), *Dhuhr* (after midday), *Asr* (afternoon), *Maghrib* (after sunset) and *Isha* (beginning part of the night) as well as the weekly *Jumuah* prayer (Friday midday prayer). Mosques are, thus, intermittently occupied throughout the day, with the occupancy timings lasting 30–45 min for each prayer. The highest occupancy is seen during the mandatory *Jumuah* prayers when the mosque is typically full, whereas the daily prayers have a fraction of the full occupancy capacity [1]. To cater for the large congregational prayers, mosques have a large, barrier-free and multiple volume space as the prayer hall. This prayer hall is typically designed to be rectangular in shape, with the long side

oriented towards the *Qiblah* (direction of the *Ka'bah* situated in *Makkah*). The congregational prayers are conducted in closely spaced rows facing towards the *Qiblah* wall. As this space is the main functional requirement of mosques, the design of the prayer hall remains somewhat similar in all mosques throughout the globe despite climatic and regional differences or cultural influences. The functional prerequisite of such a large prayer space coupled with the operational characteristics of intermittent and variable occupancy pattern play a defining role in the thermal comfort of the users as well as the thermal performance and energy efficiency of the mosque buildings.

In order to maintain the thermal comfort for users during prayer times, most mosques typically install a heating or cooling system for the prayer hall. These systems are the most energy-consuming aspect of the mosque [2], often using up to 80% of the overall energy consumption [3]. It has been found that mosques have a high energy expenditure per

Abbreviations: HD, Hot dry; HH, Hot humid; AC, Air-conditioned; NV, Naturally ventilated; DDH, Discomfort degree hours; EUI, Energy usage intensity; UHI, Urban heat island; CFD, Computational fluid dynamics; WWR, Window-to-wall ratio; SHGC, Solar heat gain coefficient; ACH, Air changes per hour; ASHRAE, American Society of Heating Refrigerating and Air-Conditioning Engineers.

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<https://doi.org/10.1016/j.buildenv.2020.107305>

Received 19 April 2020; Received in revised form 18 August 2020; Accepted 15 September 2020

Available online 19 September 2020

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capita and also per unit area compared to other buildings of the same region [4,5]. Despite using an unreasonably large amount of electricity, most mosques fail to achieve the required comfort temperature levels during the majority of the prayers [6]. According to studies [7], this high level of energy consumption is due to the poor performance of building envelope which requires the heating or cooling systems to be of more capacity than necessary and also requires longer operation times. This leads to electricity wastage, which can be attributed to the poor thermal performance of mosque buildings as well as inefficiency in management or unsuitable operational strategies [8]. Mosques have very low internal load or occupancy load [9] and are classified as external load dominated, or skin-load dominated buildings [10]. Hence, most of the interior thermal loads come from the external environment as the thermal load from the humans or equipment is negligible compared to the volume of the mosque. Components of the building envelope such as walls, roofs, windows and openings, thus, have the highest impact on the overall thermal performance of the building. This can largely influence the thermal comfort of the users and consequently, the overall energy usage as well. Therefore, poor thermal performance of the mosque building is a major contributor in increased energy consumption of mosques, resulting in energy wastage and lowered energy efficiency.

The energy efficiency of mosques largely depends on the occupant behavior of the end users as well as operational parameters and energy management protocol [11]. Nevertheless, optimizing the building envelope for better thermal performance can considerably lower the required energy for the heating or cooling systems [12]. Suitable envelope design for increased thermal performance of a building is determined by the geographic location and other subsequent factors such as climate type, sunpath, macro and microclimates of the site etc. Moreover, thermal performance of a building depends on the overall performance of the building envelope parts such as the walls, roofs, windows and openings working together as a system as a result of the synergy between the elements [13]. As such, changing or varying the parameters of one or more of these components will inevitably influence the efficiency of the other components and affect the performance of the building as a whole. Budaiwi [12] has found that the combined envelope parameters contributed 90% to the overall thermal load whereas the occupancy constituted only 7% of the thermal load for mosques. In this study, the most important attributes in the thermal performance of a mosque building were found to be wall (34%), roof (23%), infiltration (21%), window conduction (7%), and window solar gain (5%). Conversely, in a case study where these parameters were well designed for the case study mosque, the envelope contributed to less than half of the thermal load [14]. Thus, optimizing the efficiency of various parameters of these building components can significantly improve the thermal performance of the building.

With the aim of identifying the major factors influencing the thermal performance of mosque buildings, an extensive research was carried out. Papers concerning thermal comfort, thermal performance as well as energy efficiency of mosque buildings were obtained from Web of Science, Google Scholar and Scopus (Elsevier) databases. Moreover, unpublished thesis works of graduate students were also acquired from the ProQuest database since this is a relatively new research field with very few research papers. It is worth noting that papers in this field vary widely in their scopes, methodologies and objectives. Thus, it would be pertinent to provide an overview of the literature to set the context of this study as well as to outline the scopes. Thereafter, the findings have been categorized according to different design elements such as orientation, form and shape, surrounding context as well as different components of the mosque envelope such as walls, roofs and windows. Results and findings from literature are discussed under the corresponding characteristics and their respective contributions towards the overall thermal performance are also reviewed. Through this discussion, various research gaps have been identified which are crucial for the optimum thermal performance of mosque buildings. The paper concludes by highlighting future research prospects that are worthy of

investigating. It is hoped that the identified research gaps and research scopes will be addressed by future researchers towards developing design guidelines for better thermal performance of mosque buildings.

2. Overview of literature

In order to review the envelope thermal design of mosque buildings and discuss how the different components and parameters of the building impact its thermal performance, it is first necessary to discuss the climatic settings of the case study mosques as well as the type of research that has been conducted. Therefore, an overview of the existing literature will help outline the scope of this study and can set the context of this discussion.

2.1. Climatic context

Since suitable envelope design for optimum thermal performance is dependent on the climatic factors, it is important to set the main context of this study in relation to the climatic conditions and thermal comfort requirements. With this objective, the locations of the case study mosques of the 76 reviewed papers were plotted on a world map to identify the climatic contexts of the research and findings (Fig. 1). Additionally, Fig. 1 illustrates the hot dry (HD) climate in red and the hot humid (HH) climate in green, according to the widely-accepted Köppen-Geiger climate classifications [15]. Although statistics indicate that there are an estimated nearly 4 million mosques around the world [16], there is no clear data on its distribution around the globe. Therefore, the total Muslim population of different regions [17] has been depicted in the map as an indication of the percentage of mosques that might be situated in these areas. While the distribution of mosques will not be homogeneous, it can be deduced from the Muslim population density that most mosques are situated in the HD or HH climates since the majority of the world's Muslims reside in those areas [1].

From the location of the case study mosques, it can be clearly observed that most research in this field has also been conducted in the context of HD or HH climates. There are some studies [18–21] that have been conducted in the context of the temperate climates of Turkey. However, since these studies focus on the thermal comfort of users and do not comment on the thermal performance of the building components, it is beyond the scope of this review. It can also be noticed that all studies on mosques of HD and HH climates are concentrated in the Middle East and Southeast Asia, respectively. Although there is a sizeable Muslim population in the Indian Subcontinent and Africa, there seems to be a considerable lack of research on the thermal performance of mosques in those areas. The figure also illustrates the absence of research that is representative of other geo-climatic locations and different socio-cultural settings such as Europe and the Americas. Therefore, the discussion henceforth in this paper has been in the context of HD or HH climates, which has been indicated in the text where applicable.

The HD climate is characterized by very high daytime temperatures, often reaching up to 45 °C but with significantly lower night-time temperatures-resulting in a large diurnal range [1,15]. These areas have barely any rainfall and usually have humidity lower than 40%. On the other hand, the HH climate also has high temperatures but coupled with high humidity rates which stay constantly above 60% and often reaching up to 100%, causing frequent rainfalls. The temperature is only slightly lower at night and thus, the diurnal range is very small. For both the climates, the building thermal load of mosques is in the form of cooling loads as a result of heat gain through the building envelope since mosque buildings are skin-load dominated. Hence, improved thermal performance of the building implies ensuring less heat gain through the building envelope components. Although this paper discusses the findings in the context of HD climate of the Middle East and HH climate of Southeast Asia, the results can be adapted for other locations of Africa and South Asia where there are HD and HH climates with similar

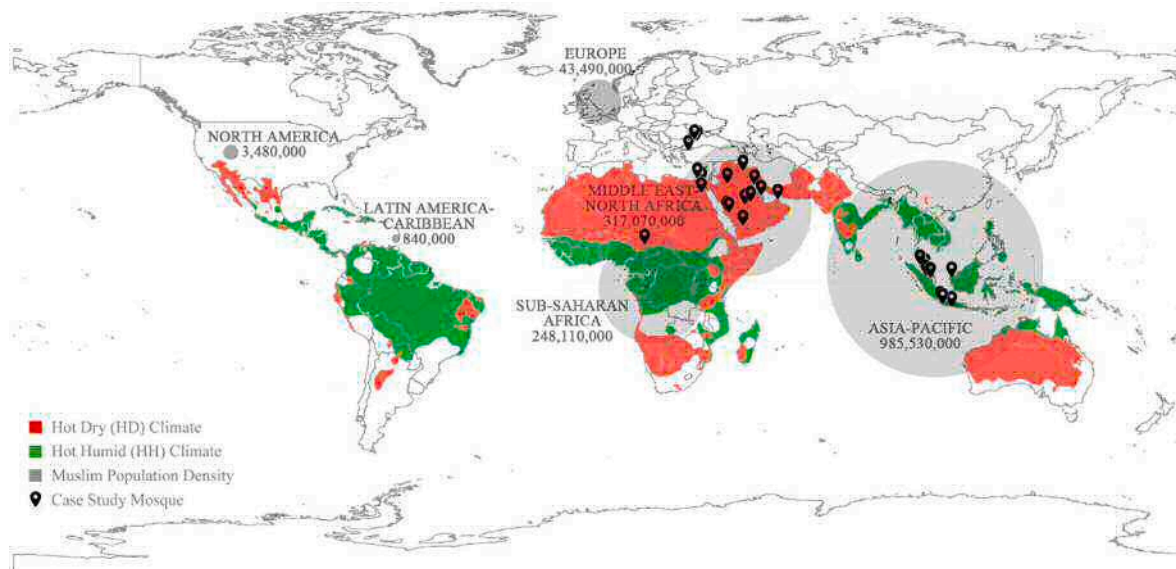


Fig. 1. Locations and climates of case study mosques found in the literature.

climatic requirements. One other factor that needs to be mentioned within this current discussion is that all these case studies are located in Muslim-majority countries, and in most countries, mosque buildings are not mandated to abide by the building codes and bylaws as it is a religious building. Thus, research into the mosque buildings of different socio-political settings of Europe and America needs to be done where building laws and regulations are followed strictly. Such research can provide valuable insights towards sustainable and energy efficient mosque designing.

Furthermore, for the purpose of this discussion, mosques can be classified as air-conditioned (AC) and naturally ventilated (NV) mosques. Since mosques discussed in this review are in the context of hot climates, the indoor environmental control system that is employed is usually in the form of air-cooling systems. AC mosques can be defined as mosque buildings where such mechanical system is employed for the thermal comfort of the users, either intermittently during the prayer times or throughout the day. On the other hand, NV mosques are buildings where the purpose of thermal cooling is achieved through natural ventilation, often with the help of ceiling fans and wall fans. These types of mosques can be fully NV where there are no cooling systems installed [14,22–27] or partially NV where mechanical intervention is only utilized during high occupancy periods such as the *Jumuah* prayers [28,29]. It is worth mentioning that all of these case studies of NV mosques are in the context of HH climates as no such case studies were found for HD climates. Additionally, within their respective countries, these mosques were found to be located in a comparative sub-urban or rural area and none are situated in an urban setting. It is hoped that this research gap on urban NV mosques or NV mosques in the context of HD climates will be addressed by future researchers.

2.2. Research type

The available literature can be broadly categorized into three types based on the methodology and research findings:

- (i) **Discussion papers:** Research papers such as [14,25–30] analyze the characteristics of one or several mosques and present a comparative discussion on different aspects of the mosque building. These studies do not offer any on-site quantitative data but present the findings as a form of qualitative discourse. The papers were generally found to be conference proceedings or published in non-indexed journals and were mostly students'

works. Despite not having any significant scientific outcome, these papers proved to be helpful in highlighting the design trends and vernacular styles of a particular region. Such discussions have, thus, provided valuable insights into common practice as well as best practice of mosque envelope designing within the respective climatic context.

- (ii) **Field studies:** Studies that included on-site data collection and surveys, with the results presented through graphical representations of data in the form of tables and charts are classified as field studies. These studies also offered comparative analysis on different mosque buildings and commented on probable solutions as the research outcome. Some of these studies are on the thermal comfort of users [31–35] while others are research on the impact of building components towards indoor environmental factors such as temperature and humidity [20,22–24,36]. There are also studies such as [2–4,6,37,38] that carry out energy audits to identify the major factors behind mosque energy consumption. It must be mentioned that there have yet been no scientific field experiments carried out in the context of mosques as experimentation at such a large scale is very expensive and time-consuming.
- (iii) **Numerical studies:** These studies [7–9,12–14,39–51] are parametric experiments and simulations on case study buildings that aimed at optimization of different building components to achieve improved thermal performance or better energy efficiency. These numerical experiments simulate multiple design options for one or more building components in the context of a case study mosque to obtain the optimum design parameters for those aspects. Through parametric analysis, researchers have also established correlations between the performance of building elements and the interior thermal comfort. It must be mentioned that some of the above-mentioned numerical studies [14,39–46] have not validated their findings with respect to on-site data. As such, although the results look practical, they might not be correct or conclusive, and more validated research needs to be done to establish the findings. On the other hand, studies such as [7–9, 12,13,47–49] have validated their results with energy usage data or climatic data from the site and the results are, therefore, more reliable.

While the findings from these studies, with their respective scopes and limitations, may not give specific details for the design of new

mosques, it can serve as a means to illustrate the key components of the envelope thermal design of mosque buildings. It is worth mentioning that all of these above-mentioned numerical studies are in the context of AC mosques of HD climates. There have only been two such studies [52, 53] carried out for NV mosques, which are also the only two numerical studies in the context of HH climate. However, both of these research aimed at improving thermal comfort conditions through enhanced natural ventilation and does not comment on the thermal performance of the mosque building components. With the wide availability of suitable software and machine advancements, many more numerical studies can be undertaken towards optimization of mosque thermal performance. The research gap of such studies in the HH climates must be addressed as the climatic conditions and considerations are vastly different from HD climates. Additionally, comparative research should also be carried out between the climates to evaluate the applicability of the research findings of HD climates in the context of HH climates.

2.3. Research scope

To derive a standard for objective comparison of the thermal performance of mosques, it is imperative to qualify the comparison criteria that have been discussed in this paper. As mentioned previously, research in this field varies vastly in objectives and methodology. Thus, researchers have used different standards to quantitatively evaluate the impact of building components on the thermal performance of mosque buildings. For the purpose of this study, these have been categorized and grouped as follows to outline the scope of the discussion:

- (i) Some studies qualify thermal performance as a means to attain desirable comfort conditions of the interior. Thus, the interior environmental condition compared to the exterior conditions is taken as an objective standard. For the context of hot climates, this practically translates as achieving lower air temperature in the prayer hall through optimized envelope design. Research such as [9,51] compares the results in the form of discomfort degree hour (DDH) over the span of a year. On the other hand, studies such as [6,23,24,34,35,39,41,54–57] comment on the thermal performance with respect to temperature changes.
- (ii) Studies such as [39,40,46,58,59] elaborate on the contribution of the building envelope components towards the overall thermal load of the building, in the form of kW or MW. Thus, improving the thermal performance of the building envelope implies that the cooling load is comparatively lower than the base case scenario. This gives a more objective and accurate measure of the building thermal performance and enables quantifying the relative contribution of each building component.
- (iii) There are also some studies which express the optimization as a percentage reduction in annual energy usage intensity (EUI) in the form of kWh/m².year, or reduction in the cooling energy expenditure (kWh or MWh). Although better thermal performance reduces the needs for mechanical intervention, energy usage of mosques is also largely dependent on operational parameters as well as the efficiency of the heating/cooling systems [11]. In order to justify this objective standard, findings need to be validated with real energy consumption data. Research such as [7,8,12,13,47,60] measures the thermal performance in the form of cooling loads as well as EUI which had been validated through data gathered from the energy audit of mosques. Thus, the results should be reflective of practical scenarios. On the other hand, there are some studies [14,42,43,61,62] that have expressed the findings in terms of energy usage but have not validated the data nor on detailed out the methodology. These papers also do not elaborate as to how the results, in the form of EUI, have been derived for the different building components.

As per the classification of research types mentioned in the previous

section, field studies usually reported the findings in the form of temperature reductions since such readings are easier to obtain. On the contrary, numerical modelling of the case study building was required to quantify the cooling load and energy usage. For NV mosque buildings, the energy requirements are low as there is no mechanical thermal control system in place. Therefore, better thermal performance cannot be quantified in terms of energy usage as there will be very little variation. The reduction in cooling load can give an objective measurement of the overall performance of the building envelope for such mosques. However, in practical terms, the reduction in ambient temperature will be a better indication of the building thermal performance as users will report better thermal comfort ratings. For AC mosques, optimizing the thermal performance of the building has been objectively quantified through the lowered thermal load and consequently, the reduced requirement of energy associated with thermal control systems [13]. In real settings, this translates to reduced operation times for cooling systems along with lower energy consumption for attaining thermal comfort conditions. Since research in this field varies widely in their scopes, all of these three objective criteria need to be discussed to gain a comprehensive understanding of the existing works. Hence, while discussing the respective findings for this review, the objective measurement criteria have been mentioned, wherever applicable.

3. Design of mosque

The architectural design and the surrounding context of mosques significantly impact the thermal performance of the building. This section will discuss how the orientation, form and shape as well as site surroundings affect the thermal performance of a mosque.

3.1. Surrounding context

Compared to new mosque buildings, old mosques situated in the context of relatively old city areas performed better thermally, both in the HD climate [41] and HH climate [54]. These mosques reported lower internal ambient temperature as well as less energy usage compared to the newer counterparts. New mosques were found to be not thermally resilient and fluctuated in temperature with the change of outdoor temperatures. On the other hand, old mosques showed less fluctuations during the day and the temperature increased gradually as the building envelope heated up towards the afternoon. Comparing the old city layout to the modern urban design, researchers [41] have found that site surrounding conditions is one of the major reasons for old mosques being more thermally comfortable. Cities in the past had narrow alleyways with high thermal mass constructions situated close to each other which provided shading from the sun. This implied that there was less heat gain from the solar rays and thus, allowed for better thermal performance of mosques. In modern times the streets are wide and there are a lot of openings around the large-sized mosques which allows unobstructed entering of the solar heat. Additionally, the mosques are built with modern construction materials which also contribute to the poor thermal performance of the building.

Moreover, mosques situated in the urban context also perform poorly compared to mosques in the rural or suburban areas due to the added heat from the surrounding built-up areas and paved roads. Especially in the context of cities that are prone to the urban heat island (UHI) phenomenon [63], residual heat from the surrounding infrastructures contributes to the thermal load long after the sunset due to the high thermal retention rate of the materials. This is why typically urban mosques tend to be AC mosques [64] while the majority of the case study NV mosques that have been reviewed for this study are situated in comparatively rural areas. For intermittent occupancy patterns, whereby a large area needs to be cooled within a short period of time, excess cooling load creates pressure on the cooling systems. Nevertheless, for urban mosques, designing a green surrounding landscape or locating it next to the waterbody allowed for creating a cool microclimate that helped reduce

the heat gain from the reradiation of nearby built-up areas [55]. However, it must be noted that these researches [24,25,55,63,64] are field studies comparing the indoor and outdoor ambient temperature differences and contrasting between different mosques. There have been no experiments or numerical studies carried out for such a comparison and thus, no objective conclusions can be derived. Research on the effects of UHI on mosque thermal performance is a yet unexplored field that requires much attention. Additionally, investigation on the rural context and vernacular design of mosques could provide valuable insights regarding passive and low energy mosque design.

3.2. Orientation

As with any other buildings, orientation plays a major role in the thermal performance of mosques. Suitable orientation with respect to the sunpath can ensure that the internal spaces are not prone to excessive heat gain from the heated afternoon sun. Since prayer needs to be done in the direction of the *Qiblah*, the prayer hall needs to be oriented facing towards the *Ka'bah*. Although mosque buildings can be positioned in any orientation despite the required orientation for the prayer hall, most mosques are usually designed to be symmetric [1]. In practice, more often than not, the whole mosque is designed symmetrically along the *Qiblah* axis without consideration of the solar geometry or site constraints. Similarly in literature, the two studies that were undertaken for the study of the form of mosques [39,51] also considered the orientation of the building as a fixed parameter and not a variable to be studied about. In these simulations, the orientation of the hypothetical case study mosques had been pre-determined according to the geo-location respective to the *Ka'bah* and only the forms were simulated as a variable. In an optimization experiment carried out by Al-Homoud [9], 14 design variables of the building were optimized by using direct search optimization technique to find the best case for increased thermal performance of the building. The paper also commented on how orientation can play an important role in the overall performance of a building and that it should be a core consideration while designing a mosque. Nevertheless, to avoid unnecessary complications in the simulation, the orientation was taken as a constant in this study as well.

One of the defining factors of mosque architecture is that the orientation of the prayer hall is always fixed for a particular geo-location. Mosques in the past typically had arcades or colonnades along the periphery as a part of structural requirements [30]. However, these spaces also ensured that the walls of the prayer hall are not directly exposed to the solar rays. With modern advancement in structural engineering, the large and barrier-free prayer hall can be built without the necessity of buttressing. However, omitting the external spaces has made the prayer halls prone to the heated afternoon sun. Especially in the context of the hot climates, where solar exposure is to be avoided, this can create excessive cooling loads since the western walls reradiate the heat even during the *Maghrib* and *Isha* prayers. Azmi [1] recommends that the symmetrical plan for mosques should be avoided and asymmetrical plans, with respect to the *Qiblah* axis and sunpath, be adapted. For colder climates, this can be taken advantage of by placing the prayer hall in a position where it can receive the ambient solar heat. For hotter climates, the prayer hall needs to be positioned farthest away from the western side by placing the auxiliary spaces towards the west to act as a buffer zone. However, there has neither been any research that investigates this aspect, nor any discourse that challenges the trend of symmetrical mosque designing. With the widespread availability of simulation software, numerical studies can be easily carried out that allows for testing multiple options to derive a suitable orientation and layout design for a specific geo-location.

3.3. Form and shape

Mosques are often built in a rectangular form to accommodate more people in the first row for prayers. No considerable difference was seen

in the energy consumption per unit area of mosques that had the length to width ratio of 1:1, 2:1 and 3:1 in plan [40]. However, there was a 6.5% increase in energy requirement for every meter height increase, when the base case 4 m height of the prayer hall interior was increased to 5 m and 6 m, respectively. Mushtaha & Helmy [39] carried out a study in Ecotect to compare the impact of mosque forms on its thermal performance. Amongst mosques with square, rectangular and octagonal plans, octagonal mosques performed the best as it has the smallest surface area compared to the internal volume. Another study [51] simulates the suitability of two traditional mosque forms: the Arab style flat-roofed rectangular mosque with a courtyard, and the Ottoman style dome-roofed square mosque. It was found that the square mosque is more suitable in the context of hot climates as it does not introduce unwanted heat through the courtyard. This study has found that the excess heat gained through the courtyard may increase the DDH by nearly 40% for Arab style mosques. However, it must be noted that both the above-mentioned studies have been carried out in Ecotect which does not consider temperature variation over a span of time or other variable aspects such as ventilation, air flow etc. Thus, the results from these research regarding the applicability of different forms and shapes may not be conclusive. Further studies need to be done comparing the different mosque styles and forms in the context of different climatic conditions. One important aspect that needs to be researched further is how the increased height of mosques impacts its thermal performance and energy usage. Whilst mosques of the past used this feature as a means to facilitate natural ventilation, the overhead space can cause much energy wastage in AC mosques, which is an aspect worth looking into.

3.4. Functional design elements

Functional design elements such as courtyards or wind towers have been integrated in mosques since the earliest of times [30]. These elements had been adapted from the vernacular architecture of the region and would help increase the thermal performance and thermal resilience of the building. Although in modern times mosques have adapted similar iconic designs, in most cases the adaptations are replications of other mosques which are implemented without regard to the climatic factors. Much research needs to be done on how the aesthetic components can be integrated with the functional requirements for enhanced thermal performance. Imam [65] recommends using the minaret as a solar chimney or wind tower depending on the climatic context. Some research has been done on a case study of Al-Rahmania Mosque in Saudi Arabia, where the minaret doubles as a cooling wind tower [66]. In this research, the wind tower was able to lower the indoor temperature by a maximum of 4–8 °C during the hottest months of the year, which considerably reduced energy consumption. However, other research suggests that using cooling towers as a passive means to reduce temperature is only applicable in places having relative humidity lower than 40% [36]. This study found that a wind tower with a cooling capacity of 200 W/m² is predicted to be able to drop the indoor temperature by more than 8 °C. However, research in both these papers [36,65] shows the calculations mathematically and depicts ideas through sketches without any practical or numerical testing. More studies in the form of experiments and simulations need to be done regarding the viability of such claims. This aspect could have immense potential towards the reduction of energy usage as a large number of mosques are situated in the HD climates where the humidity level is very low.

Courtyards (*sahn*) are another common traditional feature in mosques that have functional benefits and can enhance the building thermal performance. Arcades (*riwaq*) along the courtyard can serve as a shading device for the walls and openings as well as functioning as a shaded walkway and a spillover area during high occupancy prayer times (Fig. 2a). Shaded outdoor spaces adjacent to the courtyard showed much better thermal performance and exhibited better thermal comfort conditions compared to the open areas of the courtyards [67]. Such arcades



Fig. 2. (a) Courtyard in a traditional mosque in HD climate (Great Mosque of Kairouan, Tunisia) [68], (b) Courtyard in a modern mosque in HH climate (Cyberjaya Mosque, Malaysia) [28].

along the perimeter of the mosque can reduce the cooling load by 15% as it prevents heat gain through the wall [59]. If the provision is made for prayers to be held in the arcades, then the Friday prayer can be extended to the courtyard while the daily prayers are held inside the main prayer hall. In this way, the mosque can be designed to be much smaller with less carbon footprint [37]. However, it must be noted that mosque courtyards will perform differently than courtyards in the house due to its aspect ratio. It has been found that courtyards in mosques retain about 10% of the heat due to reradiation at night which can add to the cooling load early next morning [30]. Therefore, in HH climates, where there is less diurnal temperature variation, smaller courtyards should be used to shade walls and create a walkway without adding to the heat gain (Fig. 2b).

One of the major benefits of deriving design inspirations from traditional design elements is that it allows the options of adapting passive and low energy architecture. Whilst nowadays there is a trend towards clean and renewable sources of energy, not enough attention is given to passive approaches of reducing energy consumption through climate-specific designing. Such design strategies can allow for better thermal performance and lower the cooling load significantly. This can reduce the need for mechanical intervention and even allow optimum comfort conditions with the help of only ceiling or wall fans. Cyberjaya Mosque in Malaysia and Al Irsyad Mosque in Indonesia are two such examples of mosques built on traditional principles yet in modern settings and built with modern materials and technologies (Fig. 3). Both these mosques are NV and only require the cooling systems to be operated during large gatherings such as during the *Jumuah* prayers [28, 29]. With a combination of using functional design elements adapted from traditional design such as courtyards, arcades and corridors, architects of these mosques have ensured that the building performs well thermally. Thus, during daily prayers with lower occupancy, the ceiling fans suffice for ensuring the thermal comfort of the users which saves much energy. It is, thus, necessary for the architects to be aware of the functional design elements of mosques and their impact on the overall thermal performance of the building.

Adaptations from traditional elements is a field that needs to be explored more in the context of mosques. Majority of the traditional design elements found in mosques developed either as a structural or functional necessity. For example, domes allowed for large, barrier-free prayer halls while minarets ensured that the *adhaan* (call for prayer) could be heard from far away. With modern advances in structural engineering and electrical sound systems, neither of these elements is a necessity. However, such design elements have become iconic of mosque architecture and are replicated throughout the globe. With the trend of upholding the symbolism of mosques, often design elements are placed without geo-climatic considerations, which greatly impact the thermal performance and energy usage of the building. While such iconic design elements may be necessary for the case of religious buildings, research must also be done on minimizing the negative impact it poses on the energy efficiency of the building. On one hand, there should be policy-level research, discussions and debate involving architects, historians, religious scholars, and government officials regarding the necessity and implementation of iconic designs. On the other hand, scientific research should also be carried out towards the applicability and adaptation of such elements for different climate types. Coupling these elements with active and passive energy-saving technologies and inventions from modern scientific advancements should also be researched by the experts in their respective fields.

4. Walls

In the building envelope system, walls are one of the key aspects in envelope designing which can contribute positively or negatively towards the thermal performance of a building. Typically, a well-designed wall can protect the interior from the harsh climate and prevent temperature fluctuations in both hot and cold climates. For skin-load dominated buildings such as mosques, walls can be a major contributor towards the building thermal load. Hence, suitable wall design is of utmost importance for the optimum thermal performance in both AC and NV mosques. The aspects and parameters which have been found to



Fig. 3. (a) Cyberjaya mosque in Malaysia [28] and (b) Al Irsyad mosque in Indonesia [29].

play a role in the overall thermal contribution of the wall will be discussed in this section. It may be noted that there have been no field studies or numerical experiments regarding the impact of walls on mosque thermal performance in the context of HH climates. Although the discussion papers give examples and case studies of different types of mosques with different wall characteristics, the results cannot be compared and contrasted as there is no objective standard to quantify the findings. Thus, the following section only discusses findings from studies carried out on AC mosque in HD climates. However, the main purpose of the wall for both HD and HH climate types is to prevent heat gain from the solar rays, which applies to both AC and NV mosques. Therefore, the design principle as well as the suitable parameters would be similar in both climatic contexts.

4.1. Wall design

Usually, the *Qiblah* wall of a mosque is designed to be without any openings while the design of the other three walls is up to the discretion of the architect. Openings and window placements vary depending on whether the mosque is AC or NV. However, these will be discussed at a later dedicated section for windows, while this section focuses on the design of the wall itself. One of the common design elements found in traditional mosque architecture is *mashrabiya* (lattice-work). The *mashrabiya* is an excellent example of utilizing passive means towards enhancing thermal performance. It is essentially a non-load bearing partition wall with perforations in different motifs and designs (Fig. 4a). This screen shades the interior from the direct sun while allowing the air to flow inside. As mentioned in Section 3.1, old cities have narrow alleyways which keep the area shaded and the adjacent air cool. On the other hand, the air in the courtyard is heated from direct solar exposure and creates a low pressure as the hot air rises due to convection current. Thus, the high-pressure cooler air flows through the latticework towards the low-pressure area. This ensures that the interior has cooler space due to the constant airflow and air change. In modern times, the *mashrabiya* has also been adapted as a component for shell and core constructions (Fig. 4b). The shell of the mosque building is made of lightweight latticework which permits the core to have glass walls facing the exterior. This allows for maintaining the privacy of the interior and admits daylight into the interior whilst ensuring shading from the direct sun.

Whilst there are research regarding *mashrabiya* for other building types [70], there are none for mosque buildings or prayer halls. Since prayer halls have a much larger space and volume, the airflow dynamics would considerably differ in the case of mosques. Computational fluid dynamics (CFD) can be used to carry out the simulations to test the viability of it in the context of various climates. Another prospective research scope in this context is that of using an adaptive intelligent façade in the form of *mashrabiya*. This type of smart building façade can dynamically adapt its configuration depending on the airflow and shading requirements. Research on such technology is a very new concept and can also be done in the context of mosques. This idea can be

explored especially in the case of intermittent occupancy patterns of mosques. Such façades can be closed off in between the prayers, ensuring no additional heat gain is occurring when the mosque is empty. During prayer times, it can be programmed to create openings, allowing for suitable ventilation depending on the occupancy level.

4.2. Wall materials and thermal mass

Mosques designed with vernacular and climate-suitable materials typically allow for better thermal comfort conditions of the interior. As such, in an energy audit of several mosques in Egypt, it has been found that older mosques with thick brick walls consumed less energy [37]. The vernacular materials can even be incorporated with modern amenities as can be seen in the case of Almadi mosque, which is a pilot project undertaken by the local authorities in Riyadh, Saudi Arabia. This mosque is built with adobe bricks and, as predicted, it shows better thermal performance compared to other mosques of the same area [71]. Optimum comfort temperatures could be maintained in the prayer hall of this mosque for the majority part of the day without the need of mechanical intervention. This is due to the high thermal mass of the materials which causes thermal lag whereby the wall retains heat from the solar radiation and later reradiates the heat with a time delay. Such a phenomenon allows for the shifting of the peak cooling loads and also allows for night cooling of the wall during unoccupied periods by dissipating the stored heat [51]. However, using vernacular materials, such as adobe bricks, might not always be suitable and practical in all circumstances. Nevertheless, mosques built with similar principles but with modern materials such as concrete or brick proved to be successful in creating a comfortable interior with comparatively lower internal temperature [30]. It must be mentioned that walls need to be considerably thick in order to utilize the full benefit of the thermal lag effect. Hence, old mosques generally had thick walls for the thermal mass as well as for structural integrity. In modern times, although mosque walls are built with high thermal mass materials such as brick or concrete, the walls are not designed to be thick as it does not need to support the structural load. Therefore, the thermal delay is very small and does not significantly impact the thermal performance.

In a numerical study conducted in Baghdad [41], the thickness of the wall for optimum thermal performance was found to be 36 cm when built with high thermal mass materials. Increasing it to 48 cm yielded no major change for the same wall concerning the cost associated with the added material. Moreover, in the same experiment, a 36 cm solid wall and a 36 cm double wall with cavity performed similarly as well. However, the suggestion put forth in this study that the optimum time lag should be 8–14 hours is not technically possible to achieve in practice. Al-Homoud [13] suggests that a minimum time lag of 1.5 hours can offset the cooling load sufficiently. This can also offset the energy demand which peaks during prayer times as all mosques of the same region operate during the same time. Taking the same principle into consideration, precooling of the building mass before prayers has been



Fig. 4. (a) Traditional use of *mashrabiya* in Masjid Altinbugha al-Maridani, Egypt [68], (b) Modern adaptation of *mashrabiya* as a building shell in Masjid Daing Abdul Rahman, Malaysia [69].

suggested by researchers [18] to reduce the pressure on the air-conditioning system. Combined with other active means such as wall integrated radiant cooling system or advanced passive technologies such as phase change material (PCM) [72] and thermal energy storage systems [73], it can significantly reduce the cooling load. This is a field that demands much attention as suitable wall design has a high potential of reducing energy consumption, especially in the context of the occupancy pattern of mosques. With intermittent occupancy patterns, the cooling system needs to be run for short spans of times, spaced throughout the day. Taking full benefit of advanced active and passive load shifting strategies can help reduce the peak cooling load that occurs during prayer times by distributing and shifting the load. This also implies that with less cooling load, smaller machines with lower capacity can be used during the daily prayers to maintain comfortable temperature.

Whilst the discussion in this section has been regarding high thermal mass walls, the usage of low thermal mass walls in mosques must also be mentioned. Traditional mosques in HH climates have typically been built with low thermal mass materials such as timber [74]. This implies that the interior is susceptible to temperature changes with temperature fluctuations of the outdoors. Therefore, when the outdoor temperature is high during the daytime, the indoor spaces remain hot as well and cool down towards the evening time. However, such mosques were always built in the setting of surrounding green vegetations which created cool microclimates and lowered the temperature of the adjacent air. Additionally, shaded balconies on all sides ensured that the air would further cool down before entering the prayer hall. This continuous airflow is of utmost importance in the HH climate to ensure that the high humidity of the air is dissipated. However, in the modern setting, the surrounding area of mosques always remain hot due to the surrounding infrastructure, and natural ventilation in such context creates even higher indoor temperature due to the buildup residual heat. Moreover, low thermal mass structure is improbable and impractical in the context of UHI where the temperature remains high even throughout the night. Thus, research needs to be done on adapting high thermal mass structure and its impact on the thermal performance of mosques for the HH climates. Additionally, active and passive technologies mentioned in this section should also be researched for this climatic context. With a combination of high and low thermal mass materials and integrating such technologies, it may be possible to maintain naturally ventilated mosques in HH climates, especially during the times of low occupancy.

4.3. Wall insulation

Both in hot and cold climates alike, insulating the interior from the exterior conditions is the single most important criterion in the design of thermally efficient walls and, in extension, the thermal performance of the building. Although walls with a high thermal mass also provide insulative properties, wall insulation will be discussed under a separate section as there are other means to maintain wall insulation without using high thermal mass materials or very thick walls. As with all other buildings, walls with high R-value components or overall lower U-values are preferable for envelope thermal design as it prevents direct conductive heat gain. For hot climates, this reduces heat gain from the exterior while for cold climates it ensures that internal heat is not lost through the building fabric. In the case of AC mosques in hot climates, insulation also decreases conduction losses through the envelope [9,60]. Compared to other building parameters, improving the wall insulation showed the biggest improvement in mosque thermal performance in terms of lowering the ambient temperature [39]. Suitable insulation ensured that the temperature of the interior was an average of 2.1 °C lower than the outside temperature, a reduction of 2–4 °C compared to the base case uninsulated mosque. In a simulation carried out to optimize the wall U-value for mosques in Riyadh and Jeddah from a base case U-value of 1.87 W/m²K, it was found that the optimization trends were favorable towards the lowest value within a range of 0.34–6.25 W/m²K, implying that highly insulated walls were more suitable [13].

When the U-value of walls was reduced from 1.8 W/m²K to 0.9 W/m²K, it was possible to reduce the total heat gain through building fabric by 20% [51], which considerably lowered the cooling load. Additionally, reducing the overall cooling load by adding insulation to the wall allowed for a reduction in the annual energy usage by up to 10% [40]. In another validated numerical study, it was found that improving the wall insulation alone can achieve about 12% reduction in the overall cooling load [12]. In this experiment, wall insulation of 25 mm of expanded polystyrene with an R-value of 0.73 m²K/W was added to the inside of a typical wall of hollow concrete blocks plastered with cement, having a baseline U-value 2.41 W/m²K. This resulted in an overall U-value of 0.87 W/m²K and helped achieve about 9% reduction in cooling energy. In a similar experiment [7], decreasing the wall U-value from 2.4 W/m²K to 0.75 W/m²K through an added layer of 32 mm of expanded polystyrene insulation with an R-value of 0.92 m²K/W reduced the annual required cooling energy by 5.7%. In a simulation carried out by Al-Shamrani et al. [42], the base case wall construction of 200 mm concrete blocks with plaster, which is typical of mosques in Saudi Arabia, had a U-value of 2.579 W/m²K. However, if the wall was changed to a double concrete wall of 100 mm and 150 mm with 50 mm insulation of polystyrene or polyurethane, the U-value is reduced to under 0.5 W/m²K which results in more than 20% reduction in the annual energy usage. In the same experiment, when the insulation thickness is increased to 70 mm, the savings can be as much as 25% compared to the initial usage.

Despite the importance of wall insulation, it was found that the impact of thermal insulation on cooling energy is not directly proportional to the added thermal resistance value. When the insulation was doubled, the decrease in cooling energy was 2% compared to the initial reduction of 9% which is only 16% of the initial reduction value [12]. After a considerable reduction in cooling load, a further increase in insulation yielded such negligible results which, considering the installation and operational costs, may not be feasible. However, it needs to be kept in consideration that additional insulation may affect the peak cooling load as well. In an experiment [12] of adding extra insulation to the mosque building, the overall cooling load decreased but the peak cooling load increased due to the thermal lag effect. This is because the latent load associated with the extra insulation occurred with a time-shift which coincided with the peak sensible load, resulting in an increase of the peak cooling load. With intermittent occupancy patterns, wall insulation can be one of the major considerations in improving the thermal performance of mosques. Most mosques see a sudden increase in temperature after the cooling system is switched off after prayers, which is indicative of the poor insulation of the prayer hall walls. Thereafter, heat builds up in the uninsulated prayer hall which creates pressure on the cooling system when it is switched on again for the next prayer time. If a thermal energy storage system, as mentioned in the previous section, can be utilized when the cooling system is running, proper insulation can ensure that further heat will not build up in between prayers. Detailed research must be done on how the combination of wall thermal lag effect and insulation can be used to lower the cooling demand during the prayer times.

4.4. Wall shading and solar absorptance

Shading of the wall prevents the wall from being directly exposed to solar radiation, limiting the heat gain through walls. Although the walls remain exposed to the indirect solar radiation from the surrounding, the percentage of such heat gain compared to heat gain due to direct radiation is insignificant. With less heat gain through radiation, less heat is conducted to the interior and thus, the wall contributes less to the cooling load. This is one of the reasons why traditional mosques in the hot climates have arcades, porticos or shaded balconies around the prayer hall [35,41]. As courtyard *riwaq* or shaded arcades have no direct heat gain from the solar radiation, the interior spaces adjacent to the wall remains cool and the thermal comfort is not hampered because of the radiant temperature [30]. Additionally, air adjacent to the *riwaq*

remains cool and, therefore, does not add to the cooling load through convective heat transfer when air enters through the openings. Although the design element of *riwaq* has been discussed alongside courtyards in Section 3.4, it does not necessarily imply that courtyards are a prerequisite for such arcades. Using *riwaq* alongside the perimeter of the mosque resulted in 25% less heat gain through the exterior walls of a mosque [59]. This resulted in a 15% reduction of the cooling load and a 12% reduction in the cooling energy. Despite having such a significant impact on the cooling load and the consequent thermal performance of a building, this aspect of shading of walls has been mostly ignored in mosque literature. This is a feature that demands more attention as utilization of suitable design and parameters for shading of walls may allow the option for natural ventilation in mosques. With improved thermal performance, the cooling system might not be necessary to operate during low occupancy daily prayers, saving a substantial amount of energy.

Another aspect that is not discussed much in literature is the solar absorptance of wall materials and finishes. Results from thermal images [23] show that the unshaded and exposed concrete structure of the case study mosque had the capacity to store and dissipate heat long after the sunset. This could have been avoided by using shading devices as well as low solar absorptance of external finishes to protect the structure from the direct solar gains. In circumstances where adding arcades or balconies for shading might not be an option, designing the wall with light-colored reflective surfaces ensure that less solar radiation is absorbed. Optimization of building parameters [13] showed that usually lower solar absorptance was favored for walls in the case of hot climates. Budaiwi [12] found that when wall solar absorptance is increased from 0.5 to 0.7, a 3.7% increase in cooling energy was observed. On the other hand, if the solar absorptance is reduced to 0.3 then the cooling load is reduced by 2.5% with an associated reduction of 3.8% in the required cooling energy. Although the standalone contribution of solar

absorptance is not very significant compared to other characteristics of the wall, research needs to be done on its impact on the thermal performance of mosques when coupled with shading strategies and nearby vegetations.

5. Roof

The roof is the biggest contributor of heat gain through the exterior envelope as it is constantly exposed to the overhead sun throughout the day. However, its contribution towards building thermal performance varies for hot and cold climates. In hot countries, the heat from the sun should be prevented from entering the building, while such heat may be desirable for colder climates. Nevertheless, the discussion in this section will be focusing on hot climates only as the case study mosques of the available literature are situated in such climates. Since mosques are external load dominated buildings, the design of roofs demands much attention because a significant portion of the thermal gain occurs through the roof. Contrary to the discussion on walls, there has been some research on mosque roof design in the context of HH climates as well as studies on NV mosques which will be discussed in due course.

5.1. Roof design

Mosque roof design varies according to geo-location, climate as well as socio-cultural factors. If broadly categorized, the roof of mosques can be classified into three types: flat roof, domed roof and pitched roof. Many researchers and historians further classify the roofs into many subcategories depending on the type of structure used, origin, design etc. However, the thermal properties and characteristics remain somewhat similar for pitched and pyramid roofs [34] or for domed and vaulted roofs [75]. Thus, these three categories will suffice for the purpose of the discussion on mosque thermal performance.



Fig. 5. (a) Traditional flat-roofed mosque in HD climate (Great Mosque of Kairouan, Tunisia) [68], (b) Traditional pyramid-roofed mosque in HH climate (Masjid Kampung Laut, Malaysia) [74], (c) Contemporary dome-roofed mosque in HD climate (Sheikh Zayed Mosque, UAE) [68], (d) Contemporary dome-roofed mosque in HH climate (Selangor State Mosque, Malaysia) [68].

Traditionally, flat roofs were more common in mosques in the HD climates of the Middle East (Fig. 5a), while mosques of HH climates of Southeast Asia usually had pyramid or pitched roofs (Fig. 5b). However, in modern times most mosques, irrespective of climatic context, have been built with domed roofs as an iconic expression of mosque design (Fig. 5c & 5d). In a comparative study [51] between flat roofs and domed roofs for HD climates, it has been found that dome-roofed mosques proved to be a better option as it had 30% less DDH compared to flat-roofed mosques. However, this study was referenced in Section 3.3 where the additional heat gain was occurring through the courtyard. Thus, this result may not be indicative of the contribution of the roof type towards the thermal performance. In another experiment, traditional reinforced concrete flat roof performed best compared to a pitched roof or pitched concrete slab at 30° for HD climates [41].

In the context of the HH climate of Malaysia, it has been found that there was no big variation in indoor temperature for different designs of roofs [24,54]. However, the readings in this field study were taken at the height of 1.5 m; yet the air temperature of this height cannot decisively indicate the thermal performance of the roof when the height of the prayer hall was over 10 m. On the contrary, in a field study carried out in Indonesia [57], researchers have found that mosques with a pyramid roof show more fluctuations in temperature with the variation of outdoor temperature, while mosques with domed roof show stable performance irrespective of solar radiation. This is similar to a study [34] where these two types of mosques were studied with respect to the airflow pattern and the stratification of air underneath the roof. It was found that while the domed roof can stratify the air, a pitched roof can circulate the air within the interior and help achieve equilibrium in temperature. This makes the domed roof desirable for big mosques as there would be options for stack effect ventilation but may create stagnation in medium and small-scale mosques. For smaller mosques, a pitched roof might prove to be more helpful as it will allow for better ventilation by circulating the air within the interior. However, the applicability of different types of roofs for such a climatic context cannot be conclusively derived from one study alone, even more so because this study does not validate the results with on-site readings. Extensive research, thus, needs to be done to test the viability and suitability of different roof designs concerning the climatic conditions. While there have been other studies [76] commenting and comparing on the applicability of various roof forms in the context of different climates, none have been done that is pertinent to the spatial requirements of mosques.

Keeping the discussion of roof forms aside, one common aspect of all mosque roofs is that it covers a large space and is at a considerable height due to the spatial characteristics of prayer halls. Such height coupled with the large, barrier-free space should be taken advantage of in both AC and NV mosques whilst designing for the optimum thermal performance of the mosque buildings. The high roof allows the hot air to rise due to buoyancy, ensuring that the lower portion of the prayer hall remains relatively cooler. It was found that the pyramid roof or tiered pyramid roof provides opportunities for stack effect for ventilation purposes [22,27]. Strategically placing vent fans [77] or ventilation louvres [28] along the roof allow for cooling of the interior through removing the heated air that rises upwards. This method is especially useful in the context of HH climates where continuous air change is necessary to prevent humidity buildup in the interior. However, researchers [78] have suggested that for NV mosques, such ventilation must be minimized during the daytime to reduce the heat gain through convective currents. On the contrary, these high windows coupled with other openings can help in heat flushing through night-time ventilation strategies. In this method, the dense cool air from the outdoor settles at the bottom of the prayer hall, pushing the warm air through the high openings and dissipating the indoor heat through increased air movement. Nevertheless, care must be taken in the context of UHI where the diurnal range of the outdoor temperature does not vary significantly to allow for this strategy to work.

Since most modern mosques have domes, it is imperative to discuss

the thermal performance of such roof configurations. However, research on mosque thermal performance with respect to domes are very minimal. Nonetheless, studies on different roof configurations that have been conducted on other building types can provide helpful insights for the researchers. In a study on a domed roof, it was found that domes do not directly transmit the solar radiation to the interior but heat the space at the top of the prayer hall as the radiations meet at the focal point which is at the center of the dome [79]. The heat is then dissipated throughout the interior through the mixing of air and convection current. If this heated air can be removed through openings, it can be ensured that the interior cooling load is lowered [80,81]. However, care must be taken when designing openings to initiate airflow as glazing at the roof causes heat gain from the direct solar radiation especially when the sun is overhead during *Dhuhr* and *Asr* prayers. Researchers have concluded that by combining solar chimneys or wind catchers with domes, a pressure difference can be created which can enhance air movement and ventilation [75,82]. It was also found that domed roofs dissipate more heat than flat roofs due to the enlarged curved surface [76]. Thus, in places with large diurnal differences, such as the HD climates, domes may be suitable if night-time ventilation is used as a cooling strategy. While these research findings are valuable on their own merits, similar studies also need to be conducted for mosque buildings to verify if these results are applicable in the context of mosque design as well.

5.2. Roof materials and insulation

Similar to the optimization results of the wall insulation for hot climates, roof U-value was favorable for lower levels, implying that more insulated roof configuration was preferable in the envelope thermal design of mosque buildings in the hot climates [9]. Roof insulation is even more significant than the wall insulation as the roof remains exposed to the sun throughout the day. This can be seen in the experiment when adding roof insulation of R-value 0.49 m²K/W showed the same results in the decrease in cooling energy as that of adding a 0.73 m²K/W wall insulation [12]. Researchers [13] have suggested maintaining the roof U-value at under 0.6 W/m²K to achieve the optimal thermal performance, though such a low level might be hard to achieve in reality due to cost and maintenance issues. In the context of HD climates, the best results in terms of cooling load were found when a traditional reinforced concrete flat roof was used with a 15 cm insulation, providing the optimum U-value of 0.8 W/m²K [41]. In another optimization experiment [58], the typical roof construction of concrete with damp proof membrane and plaster had a U-value of 2.48 W/m²K. With an insulation of 50 mm polystyrene, a U-value as low as 0.49 W/m²K could be achieved which allowed for an 8% reduction in cooling load. However, this particular study does not validate its findings and such a low U-value does not seem to be practically achievable for roofs.

In a case study mosque for Dammam, Saudi Arabia, polystyrene insulation was found to reduce the EUI of mosques by up to 19% [61]. In a numerical experiment for envelope retrofit [7], it was found that around 11.8% of cooling energy is reduced by insulating the roof with 64 mm of preformed roof insulation with an R-value of 1.22 m²K/W. In a similar study [12], the roof U-value was reduced from 1.93 W/m²K to 0.99 W/m²K by adding 25 mm preformed roof insulation, which allowed the required cooling energy to be reduced by 10%. However, adding extra insulation did not give significant results as only a further of 4% and 2% in reduction was obtained when the insulation was doubled and tripled, respectively. The findings are similar to another experiment [47] where insulation with an R-value of 1.75 m²K/W added to an uninsulated roof helped achieve a 38% reduction in the annual energy usage yet using double the insulation gave a further 4% reduction. With such a wide variation in the results, findings from these studies need to be verified by undertaking similar experiments on other case study mosques as well. Another factor that must be mentioned within the context of this discussion is the thermal lag due to the thermal mass of the roof. The thermal lag of the roof works similarly to that of the

wall but may have a lesser impact on the ambient indoor temperature due to the increased height of the prayer hall. However, there have been no objective research on the thermal mass of the roof and its impact on the thermal performance of mosques. Taking advantage of the thermal mass and the flat roof, researchers have recommended using green roofs to provide the necessary insulation levels while at the same time serving an aesthetic purpose [46]. While green roofs may be a suitable option for HD climates, special consideration must be given to the drainage system if it is to be adapted in HH climates where there is regular heavy rainfall.

5.3. Roof shading and solar absorptance

Since the roof is exposed to the direct solar radiation throughout the day, the amount of heat absorbed by the roof becomes a concern in hot climates as this heat would be transmitted to the interior either immediately or after a time lag. As such, researchers have recommended using a double roof so that the shading of the topmost roof can reduce the direct heat gain of the roof adjacent to the prayer hall [41]. The shading device for the roof does not necessarily have to be an added feature and can be incorporated within the functional design. Multiple minarets and cupolas may serve as a shading device for the roof [58], though these elements might not impact the cooling load considerably. Building integrated photovoltaic (BIPV) design has been used in the Cyberjaya mosque in Malaysia [28], which doubles as shading for the roof and has significantly reduced the cooling load. It has been found that [59], adding a shading plane 3 m above the roof can reduce the overall cooling load by 16% as it can halve the contribution of the roof towards the internal heat gain. In another experiment, using a roof shading through a double roof reduces electrical energy consumption by 8% [40]. Shading of the roof is an aspect that seems to be barely discussed in the literature. However, with modern technological and material advancements, tensile membranes and canopies can be used as a lightweight option to provide shading for the roof to prevent direct heat gain.

The purpose of roof shading is to decrease direct solar heat gain which can also be done by using light-colored high-reflectance roof with a low level of absorptance and emissivity [23]. In a simulation experiment [12], when the roof solar absorptance coefficient was changed from the base case of 0.7 to 0.9, a 6.4% increase in cooling energy was observed. Reducing the roof solar absorptance to 0.5 decreased the cooling load by 2.8% and an associated reduction in cooling energy by 6.8%. In a similar experiment, about a 6.9% reduction in cooling energy is observed when the solar absorptance coefficient was reduced from 0.7 to 0.5 [7]. Despite its significant impact on the cooling load and associated cooling energy, it would be difficult to maintain such a low ratio of solar absorptance, especially with flat roofs. Thus, researchers [13] recommend keeping the solar absorptance at below 0.7 and to keep the roof surface as reflective as possible in order to reflect the solar radiation. Using cool roof strategies is a comparatively new concept in modern times [83] which may be adapted in mosques. Such roofs have been engineered to reflect more sunlight and absorb less radiation compared to other roofing types. Further studies need to be done on adapting such roofing materials in the context of mosques, especially since mosques are typically dome-roofed.

6. Windows and openings

Windows and openings are the weakest components in the envelope thermal design of the building in hot climates as it allows direct and indirect solar rays to enter the interior. However, windows have very different functions for AC and NV mosques. For AC mosques, windows can be designed to be of a minimal amount, as long as the daylighting and visual comfort factors are kept in consideration. On the other hand, windows and openings in NV mosques are a means to ensure natural ventilation of the interior. Thus, NV mosques generally have a higher percentage of window area compared to AC mosques, and consequently, more contribution of the windows towards the cooling load of the

building. This section will discuss the different thermal aspects of windows in the context of both AC and NV mosques.

6.1. Window design

Without considering the benefits of daylighting or other characteristics of the window such as shading coefficient, U-value and emittance, the best results were yielded for minimum glazing area for hot climates [9]. However, this is the case for AC mosques which does not require openings to maintain ventilation, and thus, minimizing the window-to-wall ratio (WWR) would limit the contribution of the windows towards the thermal performance of the interior. Considering daylight requirements, researchers suggested that not more than 15–20% of a wall area be windows, with minimum possible glazing at the west wall [13]. When the glazing area was even lower, with a 10% WWR, it was found that windows have a negligible impact on both the cooling load and the cooling energy requirements [12]. However, if the WWR is increased, it adds significantly to the cooling load. In this numerical experiment, when the window area is doubled, it contributes to the envelope thermal gain and adds an extra 6% to the cooling load which results in an increase of 7% in cooling energy. Since the windows are kept closed in an AC mosque, the window contributes to the cooling load through radiative heat transfer as well as conduction through the glazing surface. Through designing appropriate shading means and using efficient glazing, both these types of heat gain can be reduced. On the contrary, an additional heat gain factor for windows in NV mosques is through convective heat transfer of the heated air. In such cases, although shading strategies can reduce radiative heat gain, proper placement of windows is a must for avoiding heat gain through convection.

Orientation and placement of the windows are important considerations whilst designing the openings. Typically, windows in the north and south are preferred while windows on the east and west are to be avoided. In one research [41], when the typical mosque was simulated by removing the glazing portions in the east and west, the interior temperature was lowered by 3–5 °C. However, given that ample shading is provided, the interior air temperature was not significantly impacted by the placement of the same window configuration at different orientations [57]. Since mosques are deep-plan spaces, most mosque designs have a high WWR, even much higher than is required by building guidelines. Additionally, due to the symmetric design of mosques, windows are often oriented towards the direct solar rays of east or west. Using suitable shading devices and designing arcades towards those sides can prevent heat gain through radiation and conduction. However, in the case of NV mosques, such windows can still add to the cooling load due to heat gain from convection. For such cases, research needs to be done on the suitable orientation of the building and the appropriate placement of windows. Another considering factor in the design of NV mosques is ensuring the facilitation of cross ventilation through windows and openings. Since this is an important topic in the discussion of the thermal performance of mosques, it will be reviewed under a separate dedicated section.

6.2. Window materials

Optimization of window properties such as solar heat gain coefficient (SHGC), thermal emittance and U-value for hot climates show that the optimum values simulated were towards the lower ends of the specified constraint boundaries [9]. This implies that window configurations with high insulation and glazing that allows for lower solar energy transmittance work best for hot countries. However, the effect of these properties on the heat gain or cooling load is proportional to the amount of glass area of the mosque. This can be seen in the numerical study [7] for AC mosques with very minimal windows (WWR = 10%), where optimizing the window characteristics yielded negligible results. Reducing the SHGC from 0.7 to 0.5 showed a change of only 0.7% in the

cooling energy requirements. In order to reduce the window U-value, double glazing windows can be a good option as it reduces heat gain through windows and has been found to reduce energy usage by 6% compared to windows with single glazing [40]. In another simulation carried out for a mosque in Kuwait, when the window of 10% WWR had specifications changed from single clear glass (U-value = $6.71 \text{ W/m}^2\text{K}$, SHGC = 0.82) to double electrochromic absorbing glass (U-value = $1.48 \text{ W/m}^2\text{K}$, SHGC = 0.30), a reduction of 9% was achieved in the energy usage [47]. It must be noted that all of these studies had set the WWR at a very low percentage for the purpose of numerical studies while in practical the window percentage is much higher in mosques. Thus, in real mosques, the contribution of window parameters towards the cooling load will be much higher. As windows can greatly impact the energy usage of mosques, care must be taken while choosing windows with suitable material properties. Energy efficient and high-rating windows from different manufacturers are widely available nowadays. Whilst the initial costs of such windows may be high, the long-term benefit concerning the thermal performance of mosques can justify such investments.

6.3. Window shading

Although usage of *riwaq* for the shading of walls and windows has been discussed in an earlier section, window shading will be discussed separately. This is because many mosques might not have arcades, yet shading of windows is a must for mosques, especially in the hot climates. Window shading reduces the introduction of direct solar radiation to the interior which lowers the cooling load. The importance of shading varies according to the orientation of openings as heat gain through windows depends on the amount of solar irradiation. Thus, similar to the discussion in the previous section, shading is of more importance for the windows situated on the east and the west. The solar angles vary depending on the geo-location, and thus, the parameters for horizontal and vertical shading components for windows would vary too. Although the glazing still allows for indirect solar gain in a shaded window, without heat gain from the direct solar rays, the indoor will have a lower ambient temperature. As with the other characteristics of windows, the effect of shading in reducing the heat gain and the subsequent impact on the cooling load is proportional to the amount and area of windows [9]. A lot of NV mosques in Malaysia [25,54] and Indonesia [57] have a very high percentage of WWR which would require a large amount of shading to be employed. In such cases, mosques usually have roof extended over the balcony which doubles as shading for the windows. It was found that 35–45% of heat gain through openings could be reduced by employing different depths of such shaded balconies to provide for the shading of windows [59].

In the numerical studies on window shading, the parameters were once again set for a very low WWR since the case study buildings were AC mosques in these experiments. Under such circumstances, for places in the Middle East where the sun stays directly overhead during most of the day, shading is a less effective strategy in improving thermal performance [39]. In this simulation study, shading from the vertical solar angles yielded a very insignificant reduction in the interior temperature compared to the unshaded base case for a mosque in UAE. In another study [84], adding louvres as shading for the windows resulted in a reduction of 6% in the overall cooling load for the case study building. Similar findings can be observed in a separate numerical experiment where shading with a projection factor of 1 gave only a 5% reduction in energy usage with window configuration of 10% WWR for a mosque in Kuwait [47]. Other researchers [7], however, found the impact to be even more insignificant as the shading provided a reduction of only 0.5% in cooling energy requirements for the otherwise unshaded windows having a 10% WWR. This may be because the latter experiment has a case study mosque that is one-third the area of the other mosques and thus, has a very minimal area of windows. However, there needs to be more research conducted on the impact of shading on the thermal

performance of mosques in hot climates. These research need to include case studies which have a higher WWR that is typical of the mosques. Additionally, the impact of the design and dimensions of shading devices on the thermal performance of NV mosques needs to be studied as well.

6.4. Ventilation and infiltration

Ventilation is one of the most important factors in the design of an NV mosque. Windows and openings in NV mosques allow for the humidity to be dissipated with the help of airflow [52], which helps in sensible cooling of the users through the evaporation of sweat. Moreover, such airflow helps in reducing the latent cooling load of the building. Therefore, NV mosques usually have multiple openings on all sides to facilitate cross ventilation. Coupled with courtyards or atria, the window configuration can also allow for ventilation through the stack effect [26]. To facilitate ventilation, there can be vent fans installed at high levels, which creates a pressure difference and allows for the removal of the hot air so that relatively cooler air can come inside through lower-level openings and windows [85]. However, it is to be noted that a large number of windows and openings cause the indoor temperature to be similar to the outdoors. This implies that the interior will be heated during the noon and afternoon times but would eventually cool off during the evening hours. This would not be a problem for comparatively rural areas with the surrounding context of vegetations and low density of infrastructure because the surrounding air temperature will be low [25,64]. Where the local microclimate is very heated, such as the case for UHI, allowing natural ventilation through openings will increase the cooling load of the prayer hall due to heat gain through convection. CFD modelling can help further research in this area by enabling parametric analysis of suitable window configurations that allow for cross ventilation. Research should also be done combining the window configurations with other building elements such as *riwaq*, *mashrabiya* and different types of roofs to find suitable means of ventilation.

Whilst windows and openings help ensure ventilation in NV mosques, AC mosques must be kept air-tight so that energy is not wasted due to leakage or infiltration. Although often neglected in studies due to complicity in quantifying or measuring techniques, infiltration has been found to contribute to over one-fifth of the overall cooling load [12]. This is thrice the amount of occupancy load and can hugely impact energy consumption. In general, optimum energy usage was found when the infiltration amount was at a minimum [9]. As door opening is inevitable during prayer times, windows and other leaks should be properly sealed to minimize infiltration loads. To prevent heat gain from conduction or convection, most AC mosques always keep the windows closed. However, care has to be taken so that the required amount of fresh air is introduced and a proper rate of air changes per hour (ACH) is maintained for the number of occupants [38,86]. This is more important during high occupancy *Jumuah* prayers when it was found that there was a 96% increase in volatile organic compounds (VOC) and CO_2 [87]. The level observed in this study was towards the higher limit of acceptable pollutants in indoor air as set by ANSI/ASHRAE Standard 62.1–2007 by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [88]. This can be a matter of concern if the mosque windows remain shut at all times since the buildup of such pollutants can impact indoor air quality. In AC mosques, windows might need to be kept open occasionally, especially during the time in between prayers, to allow for fresh air. However, a proper balance needs to be struck between ventilation requirements and the impact of infiltration on the cooling load.

Usually, an ACH of 0.5 has been taken to be reasonable for mosques during unoccupied times and 1.0 ACH during the prayer times, considering the small ratio of exterior wall area compared to the large volume of the mosque [12]. If the infiltration can be reduced from 1.0 ACH to 0.5 ACH it reduces the cooling load by 11.5% resulting in a 6% reduction in cooling energy. The impact of infiltration on the energy

requirements can be understood from the findings of this numerical study where the total cooling load increases by 43% when the infiltration is tripled to 3.0 ACH. In another study [7], a reduction of 9.1% and 6.6% in cooling energy consumption is achieved when the air infiltration rate is reduced from 1.0 ACH to 0.5 ACH for an uninsulated and an insulated mosque, respectively. This finding can illustrate how the convective heat gain impacts the cooling load as well. For an uninsulated mosque, the heat gain through convection also contributed to the heat gain of the uninsulated wall. Thus, when the infiltration rate was reduced, a higher reduction in cooling energy was observed compared to insulated mosques. However, this paper also states that such a low level of ACH might be technically impossible to achieve, given the mosque occupancy pattern. The same study mentioned that a 1.5 ACH is a more practical scenario due to the uncontrolled door operation during prayer times, which can lead to an 8.5% increase in energy usage. Notwithstanding its significance, maintaining a low ACH can be quite impossible to achieve, and thus, researchers [13] recommend using double doors to minimize infiltration.

7. Optimizing mosque thermal performance

Amongst the research mentioned in the previous sections, there are some numerical studies aimed at optimization of mosque thermal performance. These experiments simulate multiple design options for one or more building components in the context of a case study mosque in order to achieve optimum envelope thermal design for the mosque building. Such parametric analysis addresses the building components as a system and simulations have been carried out with the objective criteria of obtaining the design configuration that would allow reduced energy usage. A comparative discussion and commentary on the energy efficiency achieved through parametric studies can emphasize the significant influence building components have on the thermal performance of the building. Since the prayer halls of the case study mosques are of different dimensions, neither the cooling load nor the cooling energy consumption would be an accurate criterion for comparison. On

the other hand, EUI ($\text{kWh}/\text{m}^2\text{year}$) can serve as an objective comparison standard as it is measured over the span of a year and calculated per unit area of the mosque building. Fig. 6 has been drawn up to compare the experiments' findings to highlight the relative impact of building components on the thermal performance and consequently, the energy usage of a building. Energy usage reduction has been expressed in the form of a percentage of the base case model to highlight attained energy efficiency. Before proceeding with the discussion on the comparison, it is essential to mention the background and scope of these research according to the classifications made in Section 2:

- (i) All of these research are numerical studies carried out in the context of HD climates as there were no similar studies in the context of mosques in the HH climates. Subsequently, all the case study mosques are AC mosques as there are no numerical experiments on NV case study mosques found in the literature.
- (ii) Studies such as [7–9,12,13,47,48] had validated their results with actual energy consumption data of the case study mosques. On the other hand, research such as [14,39,42,43] have not validated their data and thus, the results may not be realistic.
- (iii) It should be also be noted that some papers such as [14,39,42,43] had presented their findings as raw data in the form of monthly energy usage or energy usage per equipment and utility. To draw an objective comparison, further calculations needed to be done to derive the EUI values.

Since the cooling system is the most energy consuming aspect of a mosque building, the findings for optimizing the efficiency and operational strategies of such systems are also included in the comparison table. It can be seen that the optimization of air-conditioning efficiency and operation timings can easily reduce energy usage by 30% [48] to as much as 50% [14]. However, discussion regarding the cooling system is beyond the scope of this study as this review focuses on the thermal performance of the building components. Amongst the building components and parameters, the combined insulation of roof and walls

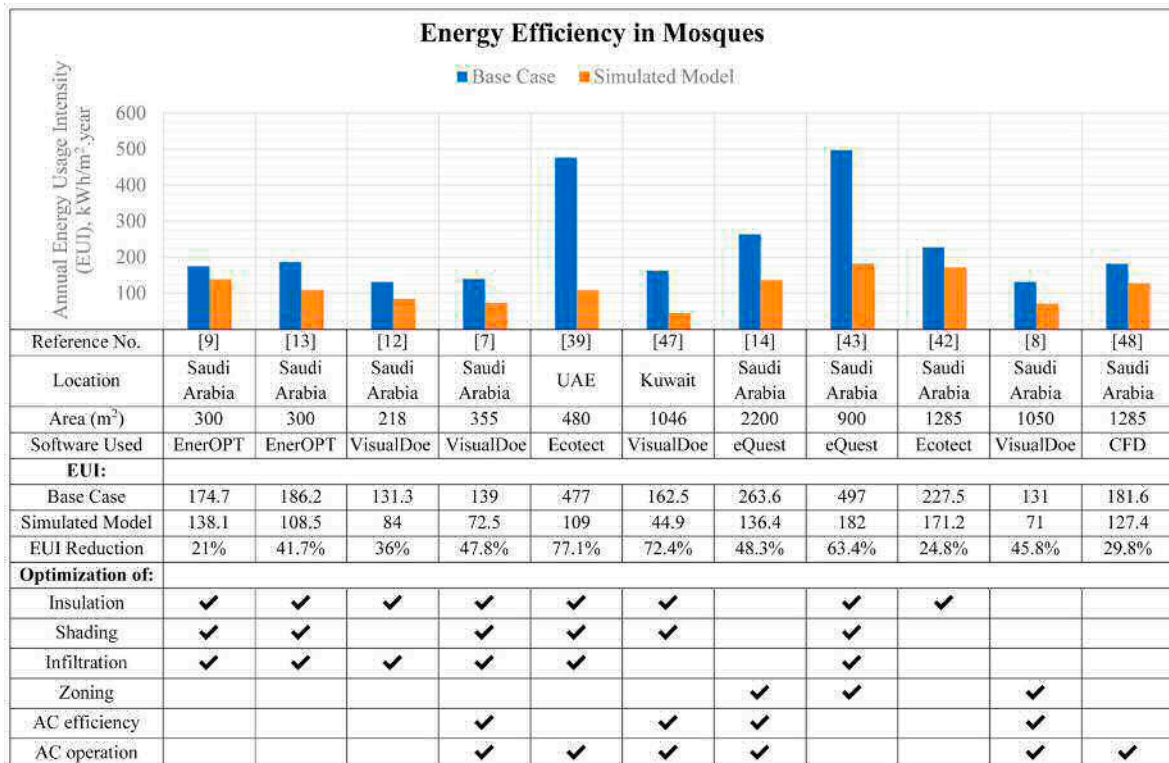


Fig. 6. Comparison of thermal performance optimization experiments.

proved to be the best approach in improving building thermal performance as it can be seen in most of these studies. Shading of walls and windows also provided for a significant change in overall energy consumption due to less heat gain through building surface resulting in lower cooling load. Since all these case studies are AC mosques, reducing infiltration through sealing of leaks was also an important criterion to be considered. Similar studies must also be carried out for NV mosques to gauge the comparative influence of different building components on mosque cooling load. However, in the case of NV mosques, the software utilized here, except for CFD, might not be applicable as these assume steady state conditions. In hot climates, natural ventilation is a crucial factor in the thermal performance of NV mosques as well as the thermal comfort of the users. Therefore, CFD based dynamic simulations can give more accurate and objective results in such contexts.

Although this comparison table has been presented to compare the findings of optimization experiments, the context and building characteristics varied widely among the case study buildings. Since the initial assumptions as well as the parameters and limits set for the variables vary from case to case, these findings should not be taken as an absolute value neither should these be considered as an evaluation standard. Additionally, the simulation software have their respective drawbacks and without validated data, the results may be skewed. Moreover, a lot of these studies portray an ideal scenario and such a level of optimization would not be attainable in real-life scenarios due to technical and financial constraints. Thus, the results may not provide comprehensive conclusions as the percentage savings portrayed here might not be achieved in real buildings. Nevertheless, the findings from these studies and the comparison between the findings may serve as a means to portray the relative significance of the building components within each case study mosque building. Further similar research needs to be carried out for different building components within the same climatic setting as well as for different types of climates. Results from many such validated studies on the building components can help future researchers establish design guidelines for energy efficient designing of mosques.

8. Suggestions for future research

Thermal performance of mosque buildings is an important research field considering the impact it can have on the energy usage of mosques. Since the prayer hall is a large space that is intermittently occupied throughout the day, mosque designing poses a unique challenge when designing for the thermal comfort of the users as well as the energy efficiency of the building. Research on mosque thermal performance and envelope thermal design is in its early years and much work is yet to be done that addresses these unique functional requirements and operational characteristics of mosques. Many crucial research gaps have been identified throughout this literature review and are discussed in the relevant sections. Some suggestions and prospective research scopes will be put forth in this section based on these research gaps. The recommendations have been grouped into three categories according to their relevance. Further research on these, in light of mosque design and occupancy patterns, can help advance the optimization of mosque thermal performance. It is hoped that these suggestions will serve as the foundation for many future research endeavors.

(i) Climatic context:

- Although building performance largely depends on climatic factors, mosques across the globe have similar design features regardless of the climatic conditions. How has the universal adaptation of such an iconic design of mosques impacted its thermal performance? Research should be carried out on various types of mosques within a climate and across different climate types. Quantifying and comparing the energy usage for prototype mosque design in different climatic contexts can help establish the comparative performance of the design. Additionally, there should be multi-level collaborative research on analyzing and

debating the necessity of iconic design of mosques considering its impact on energy usage.

- Most research shows that mosques in the hot climates waste a lot of energy due to poor envelope design. How do mosques in the colder and temperate climates perform where there are heating needs? Investigations should be carried out on the thermal performance and envelope thermal design of mosque buildings in those climates with respect to the climatic context and thermal comfort requirements.
 - Can passive and low energy means for building envelope design be adapted from vernacular architectural practices to be applied in the designing of modern mosques? Conducting numerical studies for different building components of mosques could help identify if these strategies are helpful in the context of mosque design. Through parametric studies, suitable design components from the traditional architecture of each climate can be identified. Based on those, climate-specific guidelines should also be developed for mosque design with respect to the spatial requirements.
 - How do urban mosques differ from rural mosques in terms of energy efficiency? Researching the effect of UHI on the thermal performance of mosques should be a major priority since urban mosques are more energy intensive. Consideration should be given on how the reradiated heat affects the mosque cooling load that peaks during the prayer times. Surveys should also be carried out on whether the thermal comfort requirements and preferences vary for people living in such urban contexts.
 - How do mosques with sustainable and green building ratings perform in terms of energy efficiency? How have the building bylaws and energy codes helped in reducing energy usage for the intermittent occupancy pattern of mosques? Ideas and strategies should be adapted from the sustainable design guidelines of other countries that could be applicable for mosques in Muslim-majority countries.
- (ii) Building components:
- Most modern mosques throughout the world are built with the same types of materials. How does the usage of such materials impact the thermal performance of mosques? Can the adaptation of traditional design elements and materials be suitable for modern contexts? Other building types of modern vernacular architecture should be explored to gauge the viability of such design adaptations.
 - How do mosques with arcades and courtyards perform differently than mosques without these building elements? How is the thermal load of the prayer hall affected by the usage of these design components? Parametric studies should be undertaken to determine the suitable orientation and dimensions of balconies and *riwaq* that can ensure optimum building performance.
 - Can the utilization of the thermal lag effect be taken advantage of for the intermittent occupancy pattern of mosques? Investigations should be conducted on whether the time delay for heat transfer helps or hinders during the specific prayer times. Additionally, although usually employed in the context of HD climates, research should also be conducted on whether this strategy can be adapted in the context of HH climates.
 - How do the different traditional and modern roof types perform with respect to the climatic conditions? How is the performance of such roof configurations different for small or big mosques? Detailed studies should be carried out comparing the thermal performance of different roof types to test their suitability for the different climate types.
 - Can mosques facilitate natural ventilation during low occupancy periods? Various configurations of shading and window parameters should be explored that allow for better ventilation while maintaining lower cooling loads.
- (iii) Active and passive strategies:

- Can phase change materials or other thermal energy storing systems be employed to take advantage of the thermal lag effect in order to distribute the peak load during prayer times? Can such load shifting help reduce the machine sizing and capacity of the heating/cooling systems in the context of intermittent occupancy? Moreover, the viability of such strategies should also be examined with respect to the large size of the prayer halls.
- Is wall integrated radiative heating/cooling systems coupled with natural ventilation enough to ensure thermal comfort conditions, especially during lower occupancy daily prayers? How do such strategies affect thermal comfort conditions when the prayer hall is at full occupancy? Can this technique be successfully adapted for smaller zoning dedicated to the regular prayers?
- Does the integration of wind catchers and cooling towers within minarets suffice as a means of natural ventilation? How can the large space with high ceilings be taken advantage of in order to create pressure differences that allow for airflow through the wind catchers? Furthermore, research should also be conducted on whether such strategies can be applied for the HH climates as well.
- How can the emerging technology of adaptive intelligent building façade be combined with the traditional *mashrabiya* to facilitate natural ventilation? Can an intelligent façade, operating in accordance with the occupancy level, help maintain the thermal comfort conditions for the users? Research should be undertaken if such technologies can help reduce the accumulation of thermal load, especially during the unoccupied periods in between the prayers.
- Can an automated system for the operational profile help reduce energy usage in mosques? Detailed investigations should be done for determining and establishing energy management protocols suitable for the intermittent operational pattern of mosques.

9. Conclusion

In this paper, a comprehensive literature review of envelope thermal design of mosque buildings has been carried out focusing on the thermal performance of the building. The unique spatial, functional and operational characteristics of mosques impact the thermal performance and energy efficiency of the buildings as well as the thermal comfort of the users. Since mosques are external load dominated buildings, improving the thermal performance of the building envelope can enhance the user thermal comfort and reduce the energy consumption for heating or cooling purposes. This review paper highlights the factors influencing mosque thermal performance by identifying the important aspects of mosque design and discussing how the different components and parameters of the building impact its thermal performance. The findings were categorized according to various design elements and components of the building envelope such as walls, roofs and openings. A comparison was also drawn between thermal performance optimization studies to emphasize the significance it can play on building energy consumption. From this extensive review, the following conclusions can be drawn:

- Nearly all relevant research has been conducted in the context of the hot dry climates of the Middle East and the hot humid climates of Southeast Asia. Although there are many mosques around the world, there is a considerable research gap for other regions and climates.
- Mosques in rural, suburban or the old cities exhibit better comfort conditions and thermal performance. Conversely, urban and modern mosques proved to be more energy intensive.
- Mosques are skin-load dominated buildings and thus, the majority of heating or cooling load is due to external climatic factors. Therefore, optimization of the building envelope can significantly improve the thermal performance of the building and reduce energy usage.
- Heat gain through the walls, roof and windows are the biggest contributors towards cooling loads of mosques in the hot climates.

Consequently, the biggest percentage of energy can be saved by applying suitable insulation to the walls and roof along with providing shading for the windows.

- Energy usage of mosques is largely dependent on the occupant behavior of the end users as well as the operational profiles and energy management protocol. Thus, without suitable heating/cooling system and appropriate operational strategies, energy efficiency cannot be achieved.

Research on mosque architecture is still in its early years and the available literature varies widely in terms of scope, methodology, objectives and findings. Nevertheless, a literature review may serve as a foundation for researchers in identifying research scopes and conducting further research for advancing this field. Through this literature review, it has become evident that there are numerous research gaps worthy of addressing to help ensure better thermal performance of mosque buildings. This paper ends with posing some research questions that demand investigation considering the spatial, functional and operational characteristics of mosques. It is hoped that the suggested research prospects will be undertaken by future researchers towards optimization of mosque thermal performance. It is also envisioned that this extensive study may serve as a baseline for further research in developing practical design guidelines for sustainable and energy efficient mosques.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX B

JOURNAL PUBLICATION 2: Review paper on mosque energy efficiency.

Title: A review on the factors influencing energy efficiency of mosque buildings.

by Nabeeha Amatullah Azmi, Müslüm Arıcı, Azhaili Baharun

<https://www.sciencedirect.com/science/article/pii/S0959652621002304>

JOURNAL OF CLEANER PRODUCTION

<https://doi.org/10.1016/j.jclepro.2021.126010>

PII: S0959-6526(21)00230-4

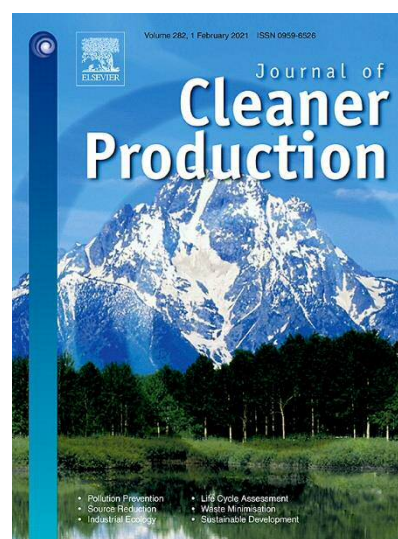
REFERENCE: JCLP 126010

Received Date: 4 November 2020

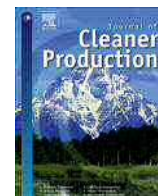
Revised Date: 24 December 2020

Accepted Date: 13 January 2021

Available online: 18 January 2021



SCOPUS Citescore: 13.1
Impact Factor (Web of Science- ISI): 9.3
SCIMAGO Quartile: Q1



A review on the factors influencing energy efficiency of mosque buildings

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ARTICLE INFO

Article history:

Received 4 November 2020

Received in revised form

24 December 2020

Accepted 13 January 2021

Available online 18 January 2021

Handling editor: Prof. Jiri Jaromir Klemes

Keywords:

Energy efficiency

Thermal comfort

Thermal performance

Building design

Intermittent occupancy

Operational strategy

ABSTRACT

Mosques are external load dominated buildings that are characterized by their intermittent and varying occupancy schedules. Most mosques employ some form of mechanical heating/cooling system in order to maintain suitable thermal comfort conditions for the users during prayer times. Due to the unique spatial characteristics and occupancy patterns of mosques, these systems are often found to be energy-intensive which impacts the overall energy efficiency of the building. The inefficiency in mosque energy usage has been typically attributed to the poor thermal performance of the buildings along with unsuitable operational strategies for the occupancy schedule of mosques. This paper reviews contemporary literature on mosque energy usage with an aim of identifying the factors that influence the energy efficiency of mosque buildings. Findings from the literature have been categorized according to different parameters of the building design as well as design and operational strategies of the heating/cooling systems. Discussion on the common practice and best practice has also been done with respect to thermal comfort standards and requirements. In addition to that, this paper compares and critically evaluates the studies that have aimed at reducing energy consumption and improving energy efficiency in mosques. Findings from multiple research suggest that as much as half of the energy usage can be reduced with the optimization of building design and operational strategies of mosques. The review of contemporary literature provides valuable insights into mosque energy usage patterns and identifies the important aspects to be considered in reducing energy consumption in mosque buildings. Through this literature review, numerous research gaps have been identified that may be pivotal in designing energy efficient mosques. Based on those, future potential research prospects have also been suggested.

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1. Introduction

The built environment sector is the largest consumer of energy in the world by taking up about 40–50% of global resources (International Energy Agency, 2010). Most of this energy is used for consumption and maintenance in existing buildings and more than half of it is used for heating and cooling purposes only (US Department of Energy, 2012). A similar pattern of high energy

usage can also be noticed in mosque buildings, where Muslims gather for daily and weekly prayers (AL-Homoud et al., 2005a). Mosques are significantly different from all other building types due to the distinctive functional and operational requirements. Mosque buildings incorporate a large prayer hall which has intermittent occupancy during the five daily congregational prayers—*Fajr* (dawn), *Dhuhr* (after midday), *Asr* (afternoon), *Maghrib* (after sunset) and *Isha* (nighttime). With intermittent and varying occupancy schedules, the occupancy pattern can vary from being full during *Jumuah* (Friday midday) prayers to about 10–30% occupancy at the daily prayers (Azmi and Kandar, 2019). Each of the five daily prayers generally lasts for 30–45 minutes while the weekly Friday prayer takes about 2 hours, including the pre and post rituals. As user thermal comfort is of utmost importance in a religious building, mosques usually employ mechanical heating, ventilation and air-conditioning (HVAC) systems to ensure a suitable ambience

Abbreviations: HVAC, Heating ventilation and air-conditioning; EUI, Energy usage intensity; AC, Air-conditioning; BIM, Building information modeling; COP, Coefficient of performance; EER, Energy efficiency ratio; EIR, Energy input ratio; BEM, Building energy modeling; ASHRAE, American Society of Heating Refrigerating and Air-Conditioning Engineers; CFD, Computational fluid dynamics.

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for prayers. These systems are typically run intermittently throughout the day following the prayer and occupancy schedules while remaining switched off during the time in between prayers. Since the prayer hall is a large space with high ceilings, a substantial amount of energy is required for the operation of the HVAC systems (Al-Homoud, 2009). Additionally, running these systems with such operation profiles significantly reduces their efficiency over time (Budaiwi et al., 2013).

Due to the variable and intermittent nature of the operation of mosques, it poses a critical situation in design whilst considering both the thermal comfort of the congregants, and the energy consumption of the heating and cooling systems (Azmi and Ibrahim, 2020). If designed for the maximum occupancy, it can create unnecessary energy wastage during the whole week as the regular occupancy is a fraction of the full capacity and the mosque remains empty for a majority part of the day. On the other hand, designing for the occupancy during daily prayers does not fully cater for the times when the mosque is full during the mandatory weekly prayer on Fridays. Most mosques are, therefore, designed for the highest occupancy load to ensure acceptable thermal comfort conditions at all occupancy levels. Studies have highlighted that mosque energy usage intensity (EUI) is similar to that of other office buildings of the same area (Abdou et al., 2005) and oftentimes can be as much as triple the amount of office energy usage (Hussin et al., 2018b). While offices use about one-fourth of the consumed energy for powering equipment (US Environment Protection Agency, 2013), without such equipment load in mosques, such energy consumption can be considered a high energy usage rate per unit area (Azmi, 2021). Additionally, since most mosques have an overall operation time of less than half of office usage duration (Saidur, 2009) and a lower occupancy load during those times, such EUI translates to a significantly larger energy consumption rate per capita. Consequently, comparing with other buildings in the same region, mosques also have higher energy costs per unit area of the building (Al-Homoud et al., 2005a).

Despite the high energy expenditure, most mosques were found to have indoor temperature and humidity levels that were not within the comfort limits (Al-Homoud et al., 2009). In this specific study, only one mosque out of the five case study mosques had optimum comfort levels yet that particular mosque had the lowest EUI amongst all the mosques. This implies that typically most heating/cooling systems in mosques are not energy efficient and waste a lot of energy. This inefficiency in energy usage, on one hand, has been attributed to unsuitable envelope thermal designing leading to the poor thermal performance of mosque buildings (Budaiwi, 2011). On the other hand, design and operational strategies of heating and cooling systems that are ill-suited with the intermittent occupancy patterns are also a big contributor to the energy wastage (Budaiwi and Abdou, 2013). It is worth noting that in any building, the design and operational strategies of the heating/cooling system, as well as human thermal behaviour, are directly influenced by the thermal performance of the building. Moreover, mosques are skin-load or external load dominated buildings which means that climate-dependent design features impact its thermal performance more than the internal and occupant loads (Al-Homoud, 2005). Thus, the energy efficiency of the building is largely dependent on the overall thermal performance of the building components, such as the walls, roof and windows, working together as a system (Al-Homoud et al., 2009). This is especially true for the energy efficiency of the heating/cooling system as more energy is consumed to achieve thermal comfort within a mosque that has a poor thermal performance (Abdou et al., 2002).

It has been found that optimizing the mosque thermal performance through improved envelope thermal design can allow for

more than one-third reduction in energy usage (Budaiwi, 2011). With an efficient air-conditioning (AC) system and optimized operational strategy in addition to suitable building design, up to 50% energy savings could be attained in mosques (Budaiwi et al., 2013). In another study, a 40% reduction in the energy requirements could be achieved with improved building design, which increased to a 60% savings when an efficient cooling system was also employed (Al Anzi and Al-Shammeri, 2010). Proper design and operational strategies not only increase the energy efficiency of the building but also contribute to lower emissions and lesser carbon footprint associated with the mosque due to reduced energy usage (Abideen, 1997). It can also save as much as 40% in life cycle cost (LCC) with a payback period of 4 years (Al Anzi and Al-Shammeri, 2010). Unfortunately, specific design requirements for the energy efficiency of religious buildings like mosques are not covered in the building bylaws and regulations in many Muslim-majority countries such as Malaysia (Department of Standards Malaysia, 2007) and Turkey (Turkish Standards, 2013). There are an estimated worldwide 4 million completed mosques as of 2019 (Deloitte, 2019), while many more are under construction or at a proposal level. As it can be seen from the above-mentioned studies, the energy saving potential of mosques can be significant if the design and operational strategies can be optimized.

With such significant findings, there has been an increasing research interest in the scientific study of mosque buildings in recent times. Recent publications have also reviewed various aspects of the mosque buildings from different perspectives. Azmi and Kandar (2019) have highlighted the importance of environmental sustainability in the design and construction phases of the mosque. From there, they have derived four distinctive characteristics of the mosque design that are to be considered in the pre-design and design phases. Yüksel et al. (2020a) have reviewed contemporary literature that discusses thermal comfort, indoor air quality and energy consumption of mosques. Although this study has tabulated and listed the papers that had focused on the energy consumption of mosques, it does not provide a detailed comparative discussion on the factors influencing the energy consumption in mosques. A comprehensive and critical analysis of results and findings from literature is necessary to assess mosque energy usage considering the unique functional and operational characteristics of mosques. In order to evaluate the options, practicality and steps towards achieving energy efficient mosques, the various factors affecting the energy usage of mosques must be identified. Thus, a thorough literature review was carried out with a view to investigate the aspects impacting the thermal performance and influencing the energy efficiency of mosque buildings. This current study is a continuation of the research (Azmi and Ibrahim, 2020) that had presented the findings on thermal performance and envelope thermal design of mosque buildings. The previous paper provided an in-depth discussion on the design aspects and structural characteristics of the different components of mosque envelope design, such as walls, roof and windows. The discourse was in the context of internal ambient temperature for naturally ventilated mosques and thermal load for air-conditioned mosques. This current study, however, will address the energy usage pattern and energy efficiency of the mosque buildings which are influenced by both the design and operational parameters of the mosques.

This paper first outlines the methodology of the conducted review, discussing the background, context and content of the available literature. In order to identify the aspects that contribute to the high energy usage of mosques, the influencing factors have been broadly classified into two categories- (i) design parameters of the mosque buildings and (ii) design and operational strategies for the heating/cooling systems. Results and findings from the literature have been further classified into sub-categories within these

two aspects and a comparative discussion has been done in each category in the following sections. It must be mentioned that most of the available studies are in the context of hot-humid or hot-dry climates since the majority of global Muslims reside in these regions (Azmi and Kandar, 2019). As such, this discussion is mainly focused on thermal load in the form of cooling loads and thermal control systems employing a cooling mechanism. The probable solutions derived from the studies have also been outlined and the research gaps have been identified in light of the functional, spatial and operational characteristics of mosques. Through this review, the critical design elements of the building and various parameters of the heating/cooling system that influence mosque energy efficiency have been highlighted. Thereafter, this review compares and rigorously evaluates the literature aimed at optimizing the energy efficiency of mosques. The paper concludes by mentioning the research findings and presenting several compelling suggestions for future research towards energy efficient mosque design. It is envisioned that the research gaps that have been highlighted and the research suggestions that have been provided in this paper will be addressed by future researchers. It is also hoped that based on the identified design and operational factors, suitable standards and guidelines can be developed in the future that will address the factors influencing mosque energy efficiency.

2. Review methodology

An extensive literature search was carried out using Web of Science, Scopus, Google Scholar and ProQuest databases in order to obtain literature pertaining to mosque building performance and energy usage. No specific time limit was set as this is an emerging field that is just beginning to gain pace in academia. Search from these databases returned a total of 116 research papers spanning over the last twenty-five-year period. It may be noted that whilst there are studies regarding the concept of Islamic architecture or mosque design principles predating this time period, the earliest available literature on the scientific aspects of mosque building design dates back to 1996. These 116 research papers, from the years 1996–2020, underwent a preliminary screening of contents (Fig. 1). Amongst those, 24 papers were omitted because- (i) 6 papers were exactly similar to their counterparts in the form of

duplicate publications, (ii) 8 papers had no research findings or the contents were copied verbatim from different websites, and (iii) 10 papers discussed sustainability in general terms without considering thermal comfort of users or energy efficiency of buildings. The remaining 92 papers, classified according to the yearly frequency in Fig. 2, were reviewed for this paper.

The relevant literature was classified into three major categories according to the research focus, as depicted in Fig. 1, and a further seven subcategories based on the methodology of the studies. It must be noted that although 92 papers were reviewed in this study, the papers classified into the major and subcategories total to 100. This is because 8 papers had more than one research focus and were classified into both the relevant categories, accordingly. A short description of the three major categories and the subsequent seven subcategories are given below:

- (a) Thermal comfort:
 - (i) Thermal comfort (User): Assessment and surveys on user thermal comfort as well as comparing it with existing standards.
 - (ii) Thermal comfort (Building): Impact of building design on thermal comfort conditions such as air temperature, relative humidity etc. and the optimization of building parameters for achieving better comfort conditions.
 - (iii) Thermal comfort (HVAC): Improving thermal comfort conditions by optimizing the HVAC parameters.
- (b) Building design:
 - (i) Building design (Discussion): Discussion and commentary regarding building thermal design often focusing on vernacular design elements.
 - (ii) Building design (Energy) Improving and optimizing building design parameters such as walls, roof, windows etc. for reduced thermal load and better energy efficiency.
- (c) Energy usage:
 - (i) Energy usage (Audit): Energy consumption pattern and recommendations for energy efficiency in the context of one or more case study mosques.
 - (ii) Energy usage (HVAC) Improving HVAC parameters such as efficiency and operational strategies for energy usage reduction.

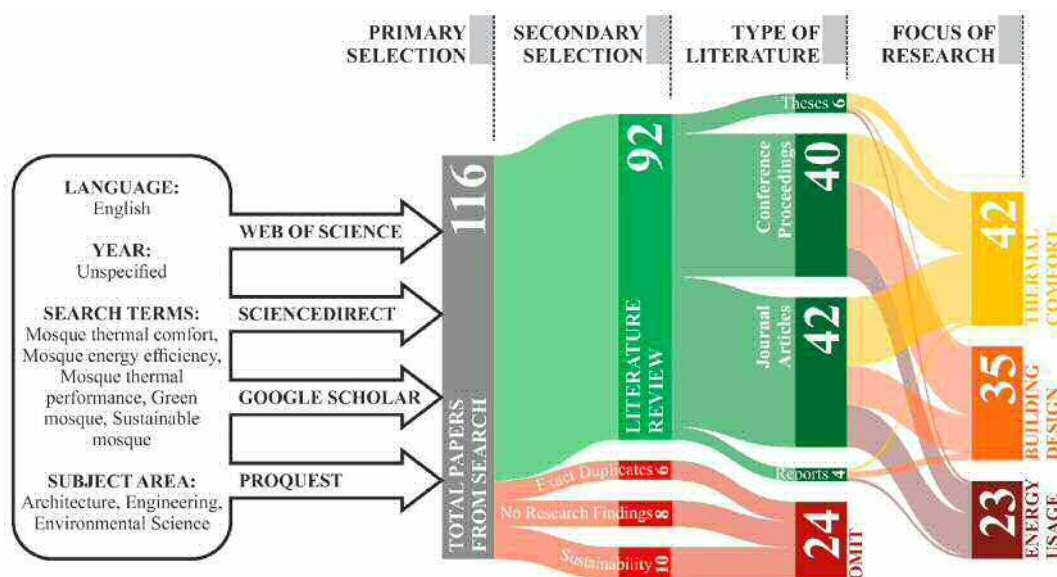


Fig. 1. Selection of literature.

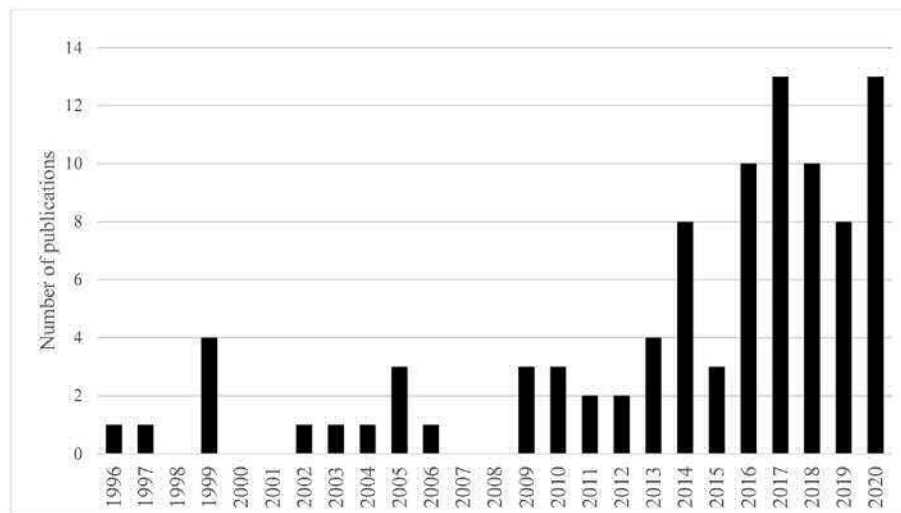


Fig. 2. Frequency of literature in the last twenty-five years.

The discussion papers, thermal comfort surveys, and energy audits provided the background and context for the study which helped define the scope for this research. To identify the various factors influencing the energy usage of mosques, the remaining papers were clustered according to building parameters or HVAC parameters. Subsequently, these were categorized into two: (i) Design parameters of the mosque buildings and (ii) Design and operational strategies for the heating/cooling systems (Fig. 3).

A further classification of the literature was done according to the Köppen climate classification (Kottek et al., 2006) since the climatic factors play a large role in the building design as well as the HVAC design (Fig. 4). As mentioned in previous literature (Azmi and Ibrahim, 2020), the majority of studies have been carried out in hot-

dry and hot-humid climates (Fig. 4a). Consequently, most research on mosque energy efficiency have also been on case study mosques located in hot climates (Fig. 4b). Additionally, this figure also depicts that there has been more research interest in the energy efficiency of mosques concerning the building design compared to the impact of HVAC. Furthermore, when classified according to the seven aforementioned categories (Fig. 4c), it can be seen that the discussions of energy efficiency with respect to building and HVAC design have been largely dominated by studies conducted in the hot-dry climates. The scope of this study as well as the discussions and commentary for the subsequent sections will be mainly focused in the context of hot climates as most available literature pertaining to mosque energy efficiency are in such settings.

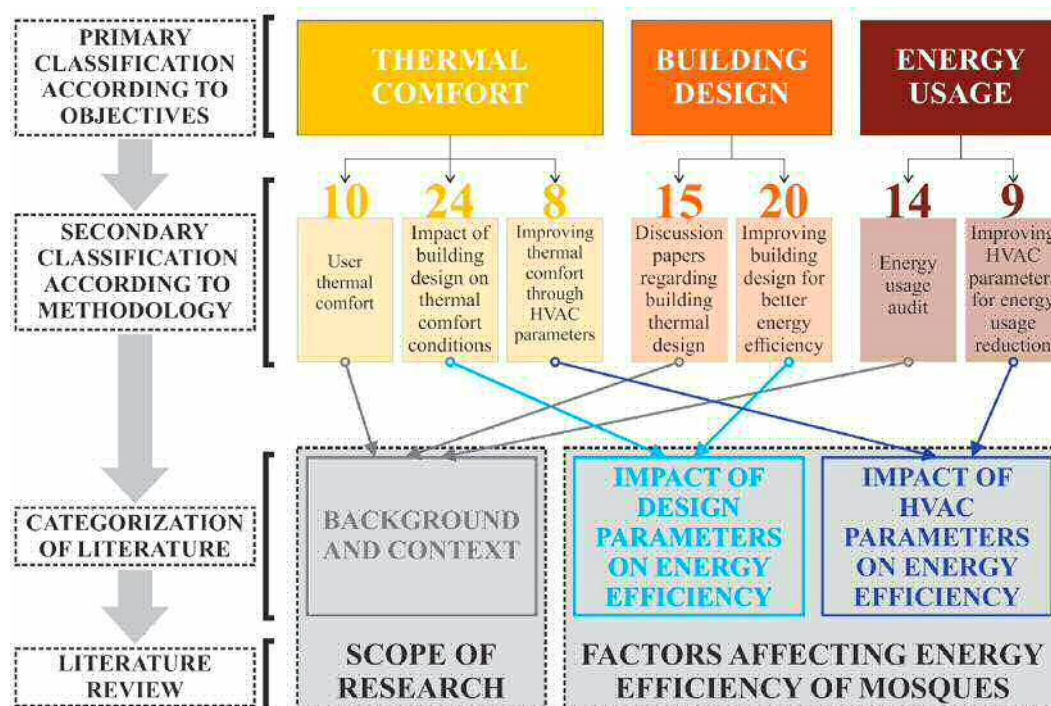


Fig. 3. Review methodology.

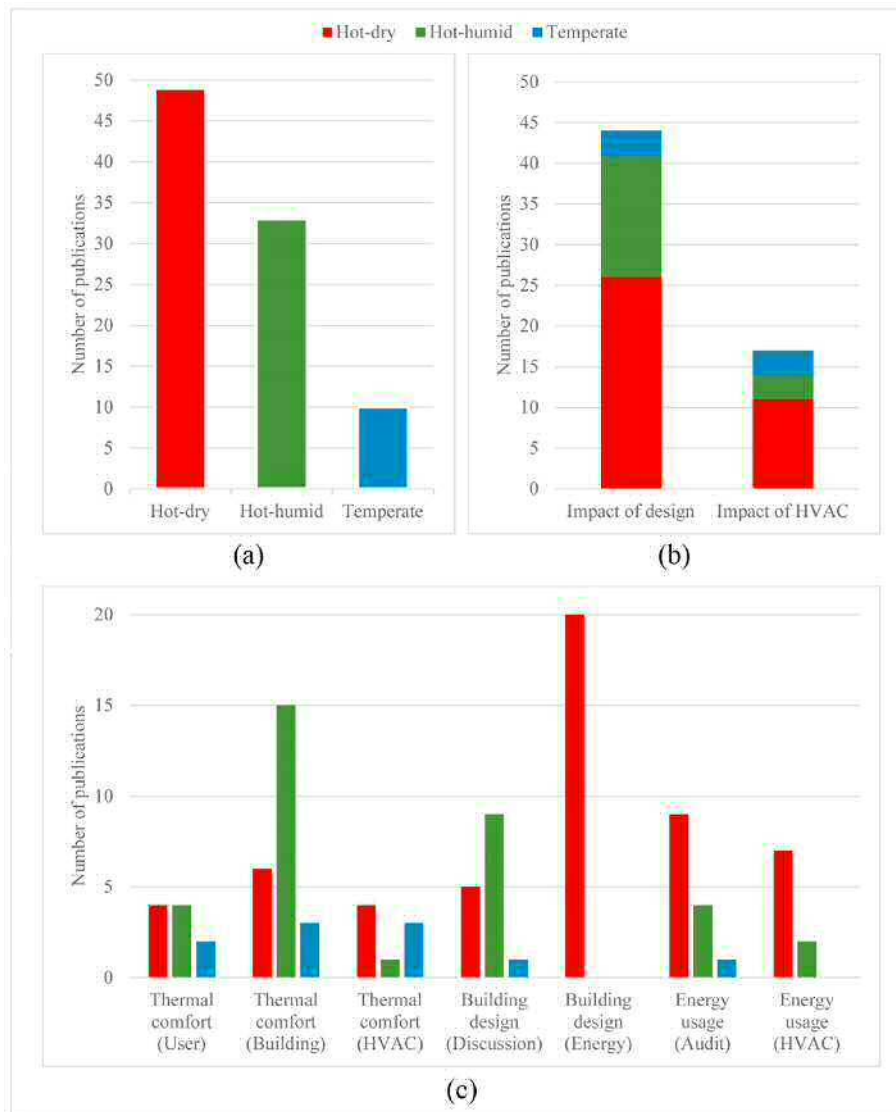


Fig. 4. Classification of literature (a) according to climate type, (b) discussion on mosque energy efficiency, and (c) research focus.

3. Impact of design parameters of buildings

Mosques are skin-load or external load dominated buildings with less internal heat generation as there are no equipment loads. Moreover, the human factor contributing to the overall thermal load is quite insignificant considering the overall volume of the prayer hall. As such, the majority of the internal thermal load of the mosque is contributed by the external environment. Therefore, mosque thermal design is mostly dependent on climate-specific design variables and parameters of the building (Al-Homoud, 1999). Consequentially, mosque energy usage is also highly affected by the overall thermal performance of the building components working together as a system (Azmi and Ibrahim, 2020). In most cases, the efficiency of mosque thermal performance can be gauged by how the interior reacts once the mechanical system is turned off. This can be seen in instances where the temperature spikes up immediately after the HVAC system is turned off, often resulting in higher temperatures than the outdoor due to residual heat (Al-Homoud, 2009). Designing of the mosque building without considering the geo-climatic context adds to the internal cooling load in hot climates and heating load in cold climates. On

one hand, the added thermal load requires bigger machine sizing with higher nominal powers. On the other hand, these machines need to be run for longer durations in order to achieve thermal comfort conditions. Field experiments have shown that mosques with higher EUI are also typically the ones that have a higher thermal load contributed by the building envelope components (Al-Homoud et al., 2005b). Thus, for external load dominated buildings like mosques, energy efficiency is a direct consequence of the design of the building impacted by the climatic conditions.

The heating and cooling loads in such buildings can be taken as a standard to objectively measure the contribution of the building design towards the energy efficiency of the building. Therefore, when the thermal load of the building is high the energy usage would be higher and vice versa. Climate-suitable design practices are not specific to the mosque and there are many established design principles (Sadineni et al., 2011) that can be adapted by architects or engineers during the designing of new mosques. However, specific design characteristics of mosques, such as the orientation requirements and spatial layout (Azmi and Kandar, 2019), are to be considered during the design phases. To achieve energy efficiency in mosques, passive and vernacular strategies can

be employed that help in lowering the thermal load (Toe and Kubota, 2015) in conjunction with best practices of the building design for energy efficiency (Pacheco et al., 2012). Modern technology involving building information modeling (BIM) can be utilized for parametric studies towards optimization of the building envelope. For mosques that are already in operation, changes to the building design might not be structurally possible or economically feasible. In such instances, design retrofits and renovations may help reduce the energy requirements of the mosque. Assessing the relative influence of different design components on the building thermal loads and energy requirements can help in identifying and applying the most effective remedies and retrofits that allow for optimal energy performance. As aforementioned, a detailed review of the thermal performance of various building parameters of the mosque has been done in another paper (Azmi and Ibrahim, 2020). Thus, in order to avoid repetition, this section will only discuss aspects that are pertinent to the energy efficiency of mosques. Table 1 lists the relevant literature whilst the following sections will elaborate on the findings.

3.1. Location and surroundings

The setting, location and surrounding of a mosque building can impact its thermal performance and influence the energy efficiency of the building. From a survey of over fifty mosques in Baghdad, Iraq, it has been found that in general, old mosques performed better and consumed less energy compared to new mosques (Hameed, 2011). Various studies show that older buildings typically have lower thermal loads because of the compact urban layout (Nordin and Misni, 2017) and due to using materials with a thermal mass that is appropriate for the climatic conditions (Al-Tassan and Bahobail, 2006; Varzaneh et al., 2014). On the other hand, newer mosques require higher energy usage as the modern building materials and surrounding large open areas increase the envelope thermal load (Baharudin and Ismail, 2014). Furthermore, mosques in densely built urban areas are subject to additional heat gain from the urban heat island (Abdullah et al., 2016) whereby the reradiated heat from the surrounding areas keeps the interior warm even after the sunset. Therefore, these mosques required longer AC times, resulting in much higher energy usage (Nordin and Misni, 2018). In

Table 1
Relevant literature discussing the impact of building parameters on energy efficiency.

Author(s) and Year	Case study mosque	Location	Climate	Type of Research	Research Focus	Investigated Parameter(s)
Azmi and Ibrahim (2020)	-	-	-	Review Paper	Building design (Energy)	Building design and envelope thermal design parameters
Mohammed et al. (2020)	Sultan Al-Ashraf Qaytbay Mosque	Cairo, Egypt	Hot-dry	Numerical Study (Ansys CFD)	Thermal comfort (Building)	Natural ventilation
Azmi and Kandar (2019)	3 case study mosques	Johor Bahru, Malaysia	Hot-humid	Field Study	Building design (Discussion)	Zoning, orientation
Kamar et al. (2019)	Masjid Al-Jawahir	Johor Bahru, Malaysia	Hot-humid	Numerical Study (Ansys CFD)	Thermal comfort (Building)	Natural ventilation
Abdallah (2019)	AUTS Western House Mosque	Assiut, Egypt	Hot-dry	Numerical Study (Design Builder)	Building design (Energy)	Roof and wall insulation, window shading
Alabdullatif et al. (2019)	Hypothetical mosque	Riyadh, Saudi Arabia	Hot-dry	Numerical Study (Design Builder)	Building design (Energy)	Vertical garden
Bughrara et al. (2018)	Salepçioğlu Mosque	Izmir, Turkey	Temperate	Numerical Study (Design Builder)	Thermal comfort (Building)	Roof insulation, glazing properties, night ventilation
Mushtaha and Helmy (2017)	Prototype mosque	Sharjah, UAE	Hot-dry	Numerical Study (Ecotect)	Building design (Energy)	Building form, roof and wall insulation, window shading, ventilation
Alabdullatif and Omer (2017)	Hypothetical mosque	Riyadh, Saudi Arabia	Hot-dry	Numerical Study (Design Builder)	Building design (Energy)	Roof insulation, window shading
Alabdullatif (2017)	Hypothetical mosque	Riyadh, Saudi Arabia	Hot-dry	Numerical Study (Design Builder)	Building design (Energy)	Roof insulation
Al-Shaalan et al. (2017)	Al Obeikan mosque	Riyadh, Saudi Arabia	Hot-dry	Numerical Study (eQuest)	Building design (Energy)	Zoning
Alabdullatif et al. (2016)	Prince Sultan Mosque	Riyadh, Saudi Arabia	Hot-dry	Numerical Study (EnergyPlus)	Building design (Energy)	Green roof, window shading
Noman et al. (2016)	Masjid Al-Jawahir	Johor Bahru, Malaysia	Hot-humid	Numerical Study (Ansys CFD)	Thermal comfort (Building)	Natural ventilation
Numan and Almaziad (2016)	Prototype mosque	Dammam, Saudi Arabia	Hot-dry	Numerical Study (VisualDoe)	Building design (Energy)	Wall and window shading, wall insulation
Al-Shamrani et al., 2016	Al-Arifi mosque	Al-Khobar, Saudi Arabia	Hot-dry	Numerical Study (Ecotect)	Building design (Energy)	Wall insulation
Al-Shaalan et al., 2014	Al-Hajri mosque	Riyadh, Saudi Arabia	Hot-dry	Numerical Study (eQuest)	Building design (Energy)	Zoning
Mohammad and Khalid (2014)	Hypothetical mosque	Dammam, Saudi Arabia	Hot-dry	Numerical Study (PC-Doe)	Building design (Energy)	Building dimension, wall and roof insulation, glazing properties
Budaiwi (2011)	Prototype mosque	Dammam, Saudi Arabia	Hot-dry	Numerical Study (VisualDoe)	Building design (Energy)	Roof and wall insulation, infiltration
Al Anzi and Al-Shammeri (2010)	Prototype mosque	Kuwait City, Kuwait	Hot-dry	Numerical Study (VisualDOE)	Building design (Energy)	Roof insulation, glazing properties
Budaiwi (2011)	Prototype mosque	Riyadh and Jeddah, Saudi Arabia	Hot-dry	Numerical Study (EnerOPT, EnerWIN)	Building design (Energy)	Optimizing 14 building parameters using direct search optimization
Asfour (2009)	Hypothetical mosque	Riyadh, Saudi Arabia	Hot-dry	Numerical Study (Ecotect)	Building design (Energy)	Roof design, courtyard
Al-Homoud (1999)	Prototype mosque	Riyadh and Jeddah, Saudi Arabia	Hot-dry	Numerical Study (EnerOPT, EnerWIN)	Building design (Energy)	Optimizing 14 building parameters using direct search optimization
Numan et al. (1999)	Hypothetical mosque	Dammam, Saudi Arabia	Hot-dry	Numerical Study (PC-Doe)	Building design (Energy)	Building dimension, wall and roof insulation, glazing properties
Abideen (1997)	6 case study mosques	Jeddah, Saudi Arabia	Hot-dry	Field Study	Building design (Energy)	Roof and wall insulation, window shading, night ventilation

contrast, mosques situated in comparatively rural areas (Eusof et al., 2015) with either low density of infrastructure (Omar et al., 2018) or when surrounded by more vegetation (Munir et al., 2020) were found to be much less energy-intensive compared to urban mosques. This is because many rural mosques are often fully or partially naturally ventilated as the surrounding context provides better comfort conditions without the necessity of mechanical interventions. Whilst such a setting cannot be replicated in the urban context, research needs to be done on identifying the underlying design principles that may be adapted to the urban mosques. There are modern urban mosques which have shown considerably low energy usage during low occupancy periods as it does not require mechanical thermal control systems due to the efficient building design (Aziz, 2016; Murtani and Sardi, 2019). In order to identify the comparative impact of location and design, further objective research needs to be done on the energy usage and energy efficiency of such mosques.

3.2. Design components and elements

Mosque design elements such as materials, roof type, layout etc. that are adapted from traditional design practices can allow the building to perform better leading to reduced energy consumption. Thus, mosque buildings in the hot-humid climates of Malaysia (Bakhlah and Hassan, 2012) and Indonesia (Sugini et al., 2017) had less cooling load when pitched roof (Hassan, 2010), shaded balconies and atria (Baharudin and Ismail, 2016) were used. Similarly, mosques in the Middle East with hot-dry climates that have domed roofs (Hwaish, 2018), arcades (Al-Rabghi et al., 2017) and courtyards (Cook, 1999) also required less AC timings and used less energy to achieve thermal comfort conditions (Alabdullatif, 2017). Other design elements such as green roofs (Alabdullatif and Omer, 2017), vertical gardens (Alabdullatif et al., 2019), wind catchers (Najmul Imam, 2003), and cooling wind towers (Alfraidi et al., 2016; Al-Saud and Al-Hemiddi, 1999) have been found to be beneficial in reducing the cooling loads of mosque buildings in hot-dry climates. It must be noted that most of these studies have merely reported results and facts from field studies without further investigations into the design components. Therefore, no quantitative data or validated conclusions could be derived with respect to the energy efficiency of various design elements. There has been some experimental research with regards to the impact of wall and roof designs on mosque energy usage. However, since those studies focus more on the structural and construction details of the building envelope, they are discussed separately in Section 3.4 titled 'Envelope thermal design'. It is also worth mentioning that mosques are typically designed with symmetrical plans according to the orientation requirements yet without regard to climatic factors and solar angles. Such design may add to the thermal load of the building, warranting higher energy usage. Researchers (Azmi and Kandar, 2019) have, thus, proposed an asymmetric layout of mosques so that the prayer hall is not exposed to the afternoon sun in the west (Fig. 5).

Another factor that must be noted is that modern mosques usually have domes and minarets as a symbol of iconic design, although it is not required by the religion. How such design, irrespective of climate, location or surrounding context may influence the energy usage of a mosque has not been explored in literature. Incorporating modern design elements and energy reducing active or passive technologies into traditional design elements can also be scope for further research. Most of the above-mentioned studies do stress the importance of climate-specific design yet addresses the concepts from a very theoretical discussion perspective. Detailed systematic research on the efficiency of these vernacular design elements must be done in order to evaluate their contribution

towards thermal loads. Further experimental studies also need to be conducted to assess the applicability of these design components in their respective climatic contexts. Research into traditional design styles may give valuable insights into passive and low energy techniques that help lower the need for mechanical intervention (AKYILDIZ and Olgun, 2020). This is a niche that is yet to be explored but possibly has the most energy saving potential towards designing energy efficient and sustainable mosques. The concept of smart mosques is a relatively new discourse in the discussion of modern mosque design (Deloitte, 2019). The aim of such mosques, on one hand, is to use renewable and clean energy sources to attain energy efficiency. On the other hand, with the energy efficient design practices, these mosques also aim to educate end-users towards awareness of energy consumption. However, much research needs to be done with respect to this concept in order to evaluate its feasibility. With experimental simulation studies and energy audits, the viability and practicality of the design elements and their respective impact on mosque energy efficiency may be assessed.

3.3. Dimensions of prayer hall

There is no conclusive data with regards to the impact of mosque sizing on its energy usage. One study has found that smaller mosques consume less energy per unit area compared to bigger mosques as the fixtures are typically manually controlled (AL-Tamimi and Qahtan, 2018). On the other hand, in a survey carried out on twenty-five mosques in Egypt (Abdallah, 2016), it was found that smaller mosques consume higher energy per unit area because of the high number of AC units and lighting compared to the floor area. Increasing the mosque size while keeping the height as a constant causes a relative reduction of wall surface area with respect to the unit floor area. This subsequently causes a reduction of the contribution of the façade towards the cooling load (Numan et al., 1999). As such, doubling the floor area can cause a 6% reduction in energy usage per square meter (Mohammad and Khalid, 2014). In a comparison between the energy usage of four mosques in Saudi Arabia (Abdou et al., 2005), it has been found that typically mosque size does not play much of a role in the overall energy usage per unit area. Different mosques with capacities ranging from less than 200 people to over 1000 people showed a similar range of EUI of 175–193 kWh/m².year, averaging at 187.3 kWh/m².year with a 9% range of deviation. In a similar study, it was also found that the smallest mosque had the highest EUI while the largest mosque had the lowest EUI among five mosques (AL-Homoud et al., 2005a). However, it should be noted that the large mosque had overall thrice the total energy usage (kWh) measured over 5 years compared to the small mosque during the same time period. Large mosques frequently have unoccupied spaces during the daily prayers. As there is less occupant load compared to floor area, the interior can be sufficiently air-conditioned using less energy in comparison to full occupancy periods. Since the energy usage is measured per unit area, this gives a much lower EUI compared to other smaller mosques that regularly have high occupancy. However, a low EUI does not necessarily indicate energy efficiency as the overall energy usage may be considerably higher, much of which are wasted to cool the unoccupied spaces.

Instead of wasting energy to cool unoccupied spaces, Azmi and Kandar (2019) suggest that mosques can opt for separate zoning with a separate or smaller cooling mechanism for daily prayers while the central system may be operated during high occupancy prayers. With zoning employed, the peak cooling load will be considerably smaller for the daily prayers and energy can be conserved through using smaller AC machines (Al-Homoud, 2009).

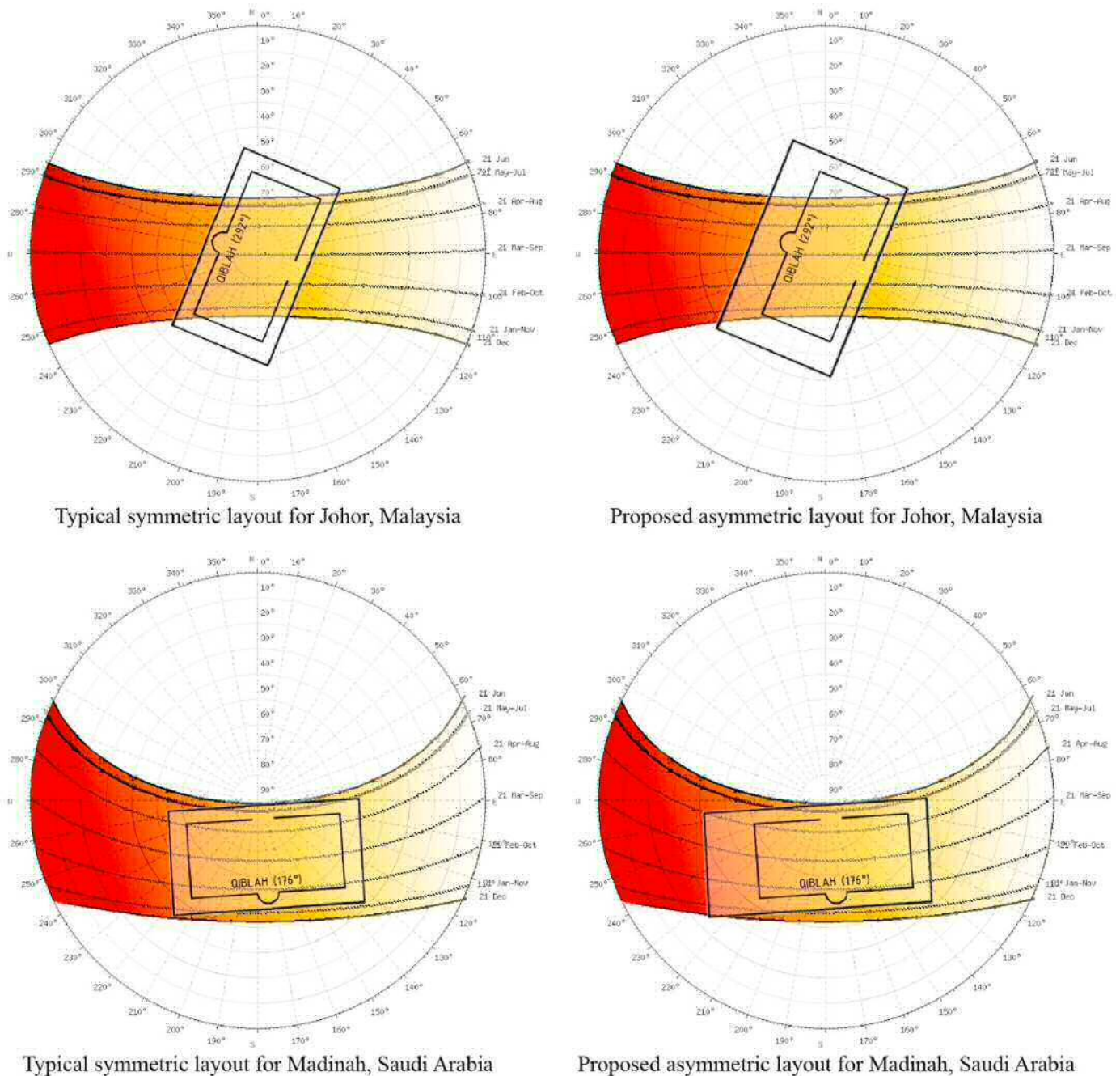


Fig. 5. Asymmetric mosque plans with a buffer space in the west (Azmi and Kandar, 2019).

Zoning one-fourth of the mosque area with thick transparent plastic sheets as a thermal barrier was shown to reduce the required cooling energy by more than 30% (Al-Shaalan et al., 2014). In a simulation for a big mosque in Riyadh, Saudi Arabia, a 40% reduction was achieved in the cooling energy usage when one-third of the area was zoned dedicatedly for the daily prayers (Al-Shaalan et al., 2017). In another study, employing a rear zone for the daily prayers reduced the energy consumption by more than half (Al-Tamimi et al., 2020). When different mosques were compared in terms of yearly EUI (Abdou et al., 2005), mosques with separate thermal zoning for daily and Friday prayers performed considerably better than other mosques that did not have zoning.

This is due to the fact that separate cooling systems were utilized for the daily and Friday prayers which ensured that energy was not wasted cooling the entire space while only a fraction of the prayer hall was occupied during most prayers. This aspect is yet to be fully explored both in research as well as in practice. As all mosques have variable occupancy levels, developing a design strategy for zoning and testing its viability through experiments can help in reducing energy wastage in mosques. This can be in the form of a physical or thermal barrier that may be adjusted according to the occupancy needs or a prototype mosque design where separate areas are used for the daily and weekly prayers. Fig. 6 shows some zoning strategies that have been suggested in the literature.

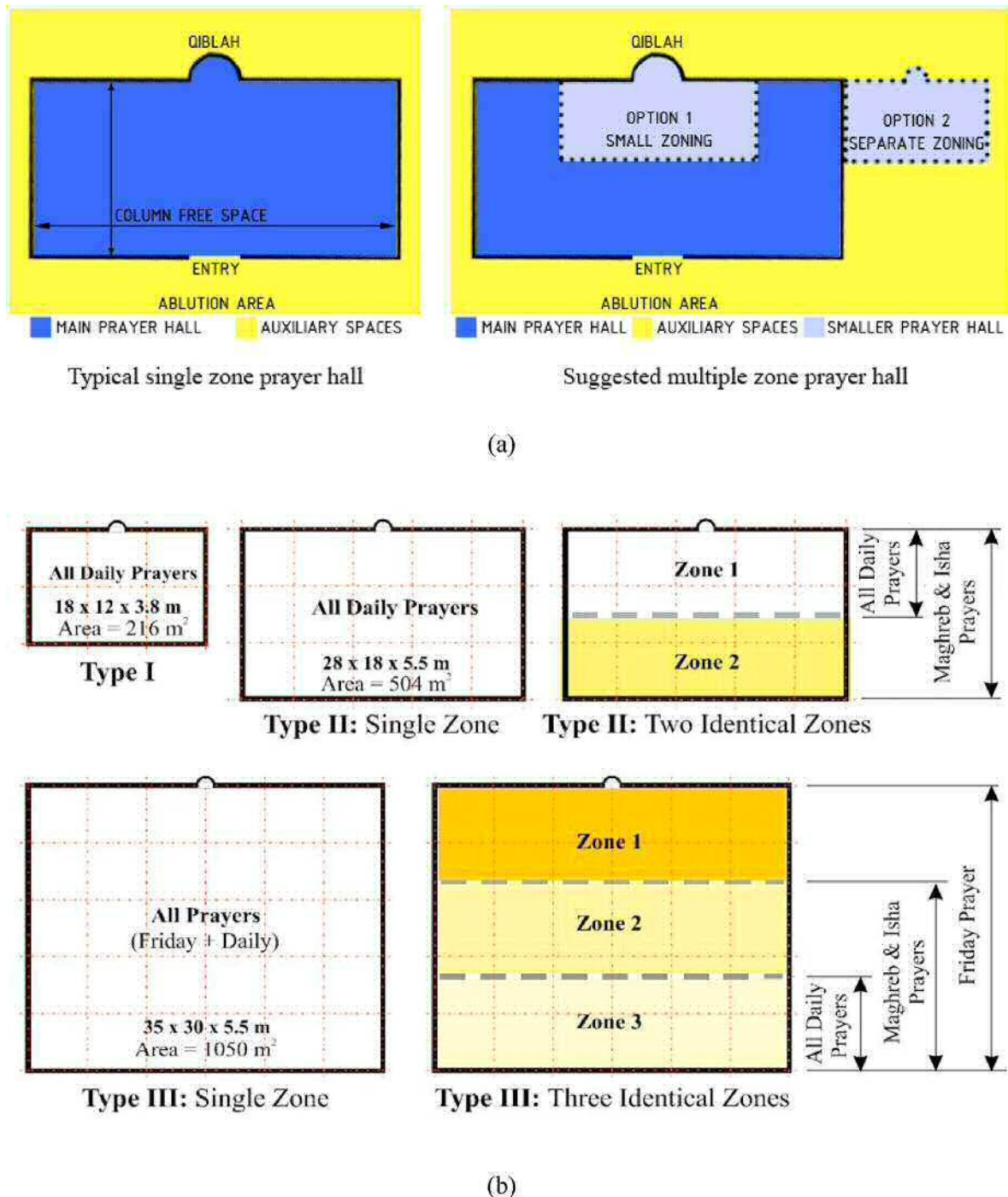


Fig. 6. Zoning strategies for variable occupancies proposed by (a) Azmi and Kandar (2019), and (b) Budaiwi and Abdou (2013).

3.4. Envelope thermal design

Mosque thermal load is mainly due to the external environmental factors since the contribution of the equipment loads and occupancy loads are minimal. In such skin-load dominated buildings, envelope thermal design plays the most important role in the thermal performance and thermal load of the building. As with any other building, the various parameters of the walls, roof, windows and openings should be optimized for the optimum performance of the building envelope (Fig. 7). The discussion of a detailed analysis of each component of the building envelope is beyond the scope of

this research and has already been elaborated in-depth in a previous paper (Azmi and Ibrahim, 2020). As such, only mosque energy efficiency with regards to the overall building envelope thermal design is addressed in this study. Research (Budaiwi, 2011) shows that the overall building envelope parameters, such as the walls, roof and windows, can contribute as much as nine times compared to the combined contribution of the equipment and occupancy towards the cooling load of mosques. Buildings with an optimized thermal envelope showed 20% less thermal load due to reduced heat gain through the building fabric (Asfour, 2009). On the contrary, buildings with poor thermal performance resulting

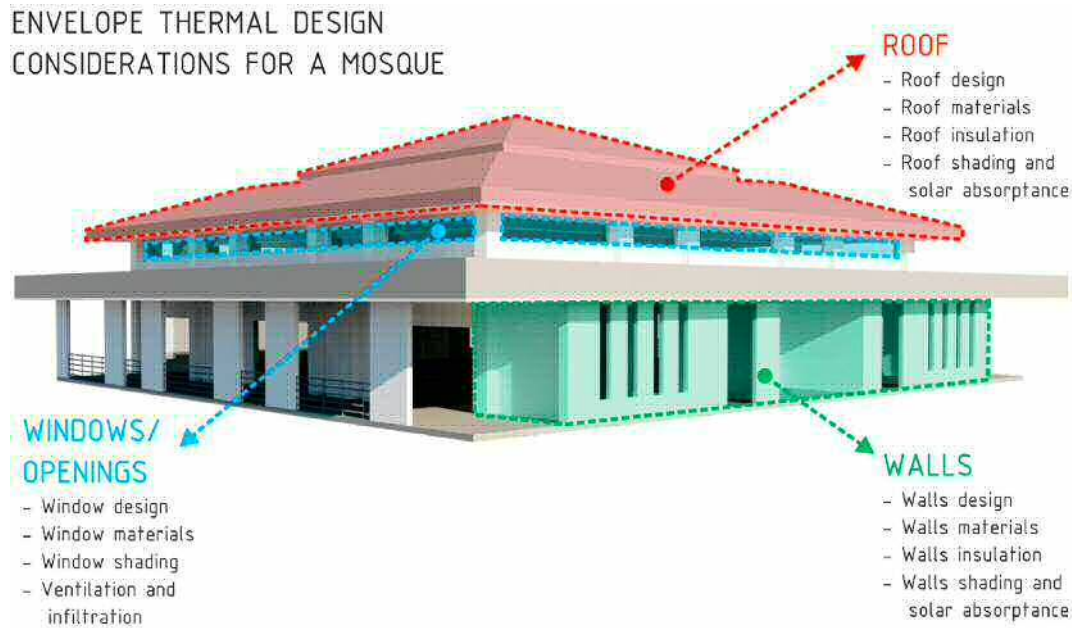


Fig. 7. Considerations in the envelope thermal design of mosques (Azmi, 2021).

from unsuitable thermal design required longer AC timings which significantly increased the energy consumption (Ibrahim et al., 2014). Through simulation experiments, it can be seen that mosques with suitable envelope thermal design had an annual EUI less than half (Abdou et al., 2005) or as low as one third (Abdallah, 2016) of the EUI of other mosques of the same area. In an optimization study by , the energy consumption was reduced by one-fifth when 14 different building envelope parameters were optimized by random search optimization technique. In a follow-up experiment (Al-Homoud, 2009), the optimized simulation showed an energy usage which was 41.7% less than the actual collected data of the case study mosque.

Optimizing all the building parameters might not be practical especially for existing buildings, but carefully designing the most important parameters might help to substantially reduce the energy demand as those contribute most to the cooling load. Budaiwi et al. (2013) shows that insulating the walls, and sealing leaks to reduce infiltration can allow for a reduction of 26% in annual energy consumption. It was found that 88% of the predicted energy demand, a total of 131 kWh/m².year out of 149 kWh/m².year, was used in cooling the space of a particular case study mosque (Budaiwi, 2011). Simulation results showed that with added envelope insulation and through reducing infiltration and leakage, up to 36% energy savings could be made in that mosque. These results are an indication of the importance of suitable building envelope design for energy efficiency in mosque buildings. Buildings with optimum envelope thermal properties have significantly lower energy consumption due to lowered heating or cooling load which consequently enables energy efficient heating/cooling system designing. It may be noted that although windows can play a significant role in the thermal performance of a building, these research focused only on optimizing the walls and roofs. In all of these above-mentioned studies, windows had an insignificant contribution towards the cooling load and cooling energy as a minimal window area compared to the overall wall surface area was considered. In reality, this ratio is much higher in order to cater to the visual comfort of the users as well as daylighting requirements. Although some studies carry out basic research on the shading of windows (Abdallah, 2019; Alabdullatif et al.,

2016; Atmaca and Gedik, 2017), the assumptions and variables have not been clearly laid out and the simulation results have not been validated in these studies.

Some other studies have carried out simulation experiments on both the design of the building along with the operational strategies. A comparative analysis of the studies has been done in Section 5 along with some commentary on the findings. In order to avoid repetition, those results are not discussed in this section. It is worth mentioning that most research on envelope thermal design has been conducted for mosques in hot-dry climates. While similar strategies can be adapted in hot-humid places with high cooling loads, not all the techniques will be appropriate. Further experimental studies must be conducted for different climate types to assess the relative contribution of various envelope components on the thermal load and overall energy efficiency of mosque buildings. Validated numerical studies can help determine design parameters that can lower the heating/cooling loads, and thus, the energy usage. Hence, a wide array of research needs to be done which studies various materials for the insulation of roof and wall, as well as the glazing properties and placement of windows in order to find suitable building envelope parameters for specific climates and locations. Whilst studies need to be done for lowering the thermal load for the existing design typology, attention must also be given to researching climate-specific design aspects that can reduce the requirement of mechanical intervention. For example, the hot-humid climates can utilize operable windows at suitable placements to allow for natural ventilation as a means to lower the cooling requirements. Similarly, utilization of high thermal mass materials and *mashrabiya* vents can offset the thermal gain in hot-dry climates which leads to lower AC timings (Azmi and Ibrahim, 2020). Unfortunately, there remains a serious lack of research in the adaptation of low energy principles within mosque designs, which has also been highlighted in Section 3.2.

4. Impact of design and operational strategies of AC system

Most mosques in modern days employ some form of mechanical heating/cooling system as the required comfort conditions cannot be achieved by passive building design strategies alone (Mushtaha

and Helmy, 2017). Even mosques that had been previously naturally ventilated are being converted to air-conditioned mosques through retrofitting to ensure better thermal comfort conditions for the worshippers (Hussin et al., 2018a). In hot climates, cooling systems are the most energy-consuming aspect in mosques, using up to 70–80% (AL-Homoud et al., 2005a) of the overall energy consumption of the building. Despite the high energy demand, the desired thermal comfort is not necessarily achieved most of the time due to unsuitable HVAC systems, lack of maintenance, and improper operation strategies (AL-Homoud et al., 2009). Thus, the HVAC systems and operation profiles must be optimized for the intermittent usage of mosques in order to achieve suitable thermal comfort conditions whilst maintaining energy efficiency. It must be mentioned that the relevant available research has been carried out for mosques in hot climates that only have year-long cooling loads. Some countries in the hot-dry climates have a short winter, but the heating load is so negligible that it does not require heating systems to be installed. There have been some studies conducted for the temperate climates of Turkey where there is a significant heating load (Kibar, 2018; Bughrara et al., 2017; Bughrara et al., 2018). However, the focus of these studies is not on the energy usage of such systems but the different aspects and variables of thermal comfort within the prayer hall. Nevertheless, field study on the comparative energy usage of mosques in such climates has found that AC based heating system uses 16% less energy than traditional radiant cooling systems (Atmaca and Gedik, 2020). Thus, the various aspects of energy efficiency of the AC system discussed in the context of hot climates may also be applicable for mosques in temperate climates using similar mechanical heating systems.

Although much energy is wasted because of the poor thermal performance of the building, the AC system characteristics such as coefficient of performance (COP) or energy efficiency ratio (EER), as well as its operational schedule have the highest impact on the energy consumption pattern and the amount of energy expended in a mosque (Budaiwi et al., 2013). Since these systems run intermittently and only for a short time during each prayer, it results in higher energy expenditure for heating or cooling as well. Research shows that improving system efficiency coupled with reduced yet optimized operating hours in an existing mosque allowed for more than one-third of energy savings (Budaiwi et al., 2013). Other research (Al Anzi and Al-Shammeri, 2010) suggests that improving AC operational strategies can save more than 20% of consumed energy. Much research remains to be done to determine the suitable HVAC type and system sizing for the variable and intermittent occupancy pattern of mosques. Moreover, suitable operational strategies need to be deduced to ensure that thermal comfort conditions are attained during the occupancy period without wasting energy for the unoccupied timings. Optimization of the HVAC parameters has high energy saving potential as it can be adapted to both existing and new buildings alike. Analyzing building energy usage patterns through building energy modeling (BEM) can help optimize the operational strategies for the intermittent occupancy of mosques (Harish and Kumar, 2016). In existing buildings, such simulation studies may also help evaluate the performance of the current systems and the feasibility of replacing those with high-efficiency machines (Li and Wen, 2014). Occupancy-based intelligent control strategies (Salimi and Hammad, 2019) can also be developed which can be used in conjunction with the smart mosque concept mentioned in Section 3.2. A holistic and multidimensional approach towards the optimization of design and operational strategies (Kljajić et al., 2016) must also be considered so that such strategies can be standardized into energy policies for the respective countries.

It must be mentioned that due to intermittent occupancy timings, energy usage is heavily influenced by the operational

parameters during post-occupancy in buildings. Thus, user thermal behaviour and human tendency can largely impact the energy efficiency of the building (Abideen, 1997). One of the major factors that have been found to be responsible for high energy usage in mosques is that the end-users remain unaware of the amount of consumed energy as mosques are often maintained by a centralized fund or a regulating body. Moreover, many mosques are built and maintained by the government, warranting highly subsidized electricity bills as it is a religious building. With general unawareness of the electricity bills and due to subsidized rates, a lot of times the AC and lighting fixtures are not turned off in between prayer times. Although the energy usage by fixtures such as lights may seem to be insignificant compared to energy consumption by cooling systems, lighting for the whole mosque may use nearly half as much electricity compared to the energy usage that is required by the AC system (AL-Homoud et al., 2005a). Without responsible consumption due to lack of awareness, the energy efficiency of the mosque is greatly hindered. However, keeping the management policy, users' tendencies, and public awareness aside, this section will focus only on the technical aspects of the AC system and operational strategies that influence the energy consumption pattern. Table 2 lists the relevant literature with respect to the impact of design and parameters of the AC system on mosque energy efficiency. The subsequent sections will discuss the different aspects of the systems in light of mosque energy usage.

4.1. Type of AC system

Considering the intermittent occupancy pattern of mosques, the use of central AC such as variable air volume (VAV) systems and other advanced AC system types have not been deemed to be viable options as the operation is commencing at large time intervals for a short period of occupancy (Budaiwi et al., 2013). As such, usually mosques employ fan coil or split AC systems- with constant volume and no controlled ventilation. Researchers (AL-Homoud et al., 2005a) have also found that mosques with window units used a lower percentage of electricity for AC compared to other options. However, due to old AC units and 100% occupancy during prayer times, this particular mosque also had fans working full time which added to the energy requirements. Thus, calculated over a year, the overall required energy for thermal control in this mosque was higher than that of other mosques. In contrast, mosques running two types of systems might use excessive energy as was seen in the case of a mosque that utilizes both window type and floor mounted systems (AL-Homoud et al., 2009). Since the mosque is a single zone area with intermittent occupancy compared to other multiple zone buildings with regular occupancy, most researchers carrying out simulations modeled the AC system as a simple residential direct expansion unit (Budaiwi et al., 2013; Al Anzi and Al-Shammeri, 2010). There have been no experimental studies comparing the energy efficiency for different types of cooling systems considering the occupancy pattern of mosques. Since the intermittent and varying occupancy level would greatly affect the efficiency of AC systems, it requires further research devoted to this aspect.

4.2. Capacity of AC system

Optimization of the building thermal performance lowers the cooling load as well as the peak cooling load of a mosque. This will, in turn, reduce the required equipment load and allow downsizing of the system so that a comfortable interior can be maintained with a lower capacity machine (AL-Homoud, 2009). In one experiment (AL-Homoud, 1999), a reduction of 12% and 15.4% in peak cooling load was achieved for Riyadh and Jeddah, respectively, which resulted in a significant reduction in the capacity of the AC system.

Table 2
Relevant literature discussing the impact of HVAC parameters on energy efficiency.

Author(s) and Year	Case study mosque	Location	Climate	Type of Research	Research Focus	Investigated Parameter(s)
Hussin et al. (2020a)	Penang State Mosque	Penang, Malaysia	Hot-humid	Field Study	Energy Usage (HVAC)	Operation timing
Hussin et al. (2020b)	Penang State Mosque	Penang, Malaysia	Hot-humid	Numerical Study (Ansys CFD)	Energy Usage (HVAC)	Temperature set point, variable airflow
Samiuddin and Budaiwi (2018)	Prototype mosque	Dhahran, Saudi Arabia	Hot-dry	Numerical Study (Design Builder CFD)	Thermal Comfort (HVAC)	AC air distribution scheme
Alashaab and Alamery (2018)	Omar Ibn Abdul Aziz Mosque	Baghdad, Iraq	Hot-dry	Numerical Study (Ansys CFD)	Thermal Comfort (HVAC)	AC air distribution scheme
Jaafar et al. (2017)	Masjid Al- Haram	Makkah, Saudi Arabia	Hot-dry	Numerical Study (Ansys CFD)	Thermal Comfort (HVAC)	Rate of air change per hour
Al-Shaalan et al., 2017	Al Obeikan mosque	Riyadh, Saudi Arabia	Hot-dry	Numerical Study (eQuest)	Energy Usage (HVAC)	Zoning, AC efficiency
Samiuddin (2014)	Prototype mosque	Dhahran, Saudi Arabia	Hot-dry	Numerical Study (Design Builder CFD)	Energy Usage (HVAC)	AC air distribution scheme
Al-Shaalan et al., 2014	Al-Hajri mosque	Riyadh, Saudi Arabia	Hot-dry	Numerical Study (eQuest)	Energy Usage (HVAC)	Zoning, AC efficiency, operation timing, number of AC units
Budaiwi and Abdou (2013)	Prototype mosque	Dammam, Saudi Arabia	Hot-dry	Numerical Study (VisualDOE)	Energy Usage (HVAC)	Operation timing, AC efficiency
Khalil et al. (2013)	Nabiha Yaken Mosque	Cairo, Egypt	Hot-dry	Numerical Study (Ansys CFD)	Thermal Comfort (HVAC)	Number of AC units
Budaiwi et al. (2013)	Owais Al-Qarni Mosque	Dammam, Saudi Arabia	Hot-dry	Numerical Study (VisualDOE)	Energy Usage (HVAC)	AC efficiency, operation timing
Al Anzi and Al-Shammeri (2010)	Prototype mosque	Kuwait City, Kuwait	Hot-dry	Numerical Study (VisualDOE)	Energy Usage (HVAC)	AC efficiency, operation timing

With this reduction in peak cooling load, the required capacity of the system was reduced from 40.3 to 35.5 tons for Riyadh and from 35.1 to 29.7 tons for Jeddah. In another experiment (Mushtaha and Helmy, 2017), the peak cooling load was reduced by 67.5% with the optimization of design which allowed for designing a much smaller cooling system. Similar results were also found where the overall cooling load was reduced by 60% due to the suitable thermal design of a mosque building which resulted in a reduction of AC load by 69% (Numan and Almaziad, 2016).

However, the intermittent occupancy nature of the mosque must be taken into consideration whilst determining the AC capacity (Atmaca and Gedik, 2019). Instead of a lower capacity machine running for longer times, researchers (Budaiwi and Abdou, 2013) recommend that system oversizing with lesser run-times may allow for up to one-fourth reduction in energy usage. On the contrary, another study (Khalil et al., 2013) suggests that instead of higher capacity machines, employing more AC units of lower capacity allows for maintaining homogenous temperature distribution within the prayer hall, allowing for better comfort levels. Other researchers suggested that zoning be employed for different occupancy levels and separate AC systems should be installed according to the requirements of that particular zone (Al-Homoud, 2009). As the occupancy is much lower during the daily prayers, the peak cooling load will be considerably smaller, and energy can be conserved by utilizing smaller machines. On the other hand, during Friday prayers with larger gatherings, the whole mosque can be cooled using centralized systems. Although the startup cost would be higher for the installation of two different systems, researchers predicted that it would be more energy efficient and would save money in the long run. This is an area that requires much research as mosques have intermittent and variable occupancy patterns. The research may be done in conjunction with the zoning strategies mentioned in Section 3.3 in order to attain maximum energy efficiency.

4.3. Efficiency of AC system

Usually installed AC systems in mosques have a much higher nominal cooling capacity than the requirements predicted from

simulations, which can even be multiples of the required capacity (Hussin et al., 2019). In practical, however, the actual cooling capacities of these systems are much lower than their nominal values as a result of reduced efficiency due to poor maintenance. As such, while the results from simulations may show that thermal comfort is achieved, it might not be the case in reality. Researchers (Budaiwi et al., 2013) have found that in a case study mosque, the prayer hall attained thermal comfort conditions only during *Fajr* times whereas simulation results from the calibrated model showed that it can be achieved during all prayer times. This may be due to the fact that the AC system was not functioning properly because of improper maintenance or the system was not operated appropriately in accordance with the occupancy schedule. This is one of the drawbacks of research findings because the simulations do not take into consideration practical scenarios such as inefficiency of the system caused over time and by lack of necessary maintenance. Nevertheless, systems with higher efficiency ratings will lower energy consumption and subsequently, lessen energy wastage. It has been found that about 23.5% of energy can be saved when a more efficient AC is used that has an energy input ratio (EIR) of 0.37 compared to the base case of 0.52 (Budaiwi et al., 2013). Similarly, improving the EER to 10, 11 and 12 gave a saving of 5%, 12% and 17%, respectively, for a mosque in Kuwait (Al Anzi and Al-Shammeri, 2010). In another simulation study in Saudi Arabia (Al-Shaalan et al., 2014), using an efficient AC system with a higher COP helped reduce the monthly cooling energy consumption by 25% compared to the original system with a COP of 2.5. Most of these studies have been carried out in the form of simulations for the total run-time of AC systems for a certain period or only for a specific time during prayers. Research should, however, be conducted on a monthly or yearly basis to quantify whether the intermittent usage pattern impacts the efficiency of such AC systems.

4.4. Operation timings of AC system

Typically, the energy usage by the AC system is dictated more by its operational strategies rather than the capacity or the efficiency of the machines. Thus, it is still possible that a highly efficient

system with suitable capacity might yield an unreasonably high energy consumption yet not provide for suitable comfort temperatures. Operational profiles and loads of various systems such as lighting and AC system of the mosque are reflective of their intermittent nature (Budaiwi et al., 2013). With such occupancy schedules, the AC is turned on every few hours for a short while and then switched off once prayers are over (Fig. 8). However, in many cases, it was found that the AC is kept running throughout the whole day (Ariff et al., 2012; Hussin et al., 2015) even when there is no occupancy outside of the prayer times. Since the operation strategy depends mostly on the end users, maintaining a suitable operation strategy for the AC system is of utmost importance (El Shennawy and Abdallah, 2017). Limiting the AC operation

duration to 1 hour for *Fajr*, *Dhuhr* and *Asr* and 3 continuous hours for combined *Maghrib* and *Isha* prayers resulted in 15.7% less energy usage from the base case of 2 hours operating time per prayer (Budaiwi et al., 2013). Another experiment showed that 30% of energy can be saved by intermittent operation timings totaling 9.5 hours as compared to 16 hours of continuous operation timing from *Fajr* to *Isha* which is practiced in a lot of mosques (Samiuddin, 2014). Similarly, changing the AC operation schedule to only during prayer times and switching off machines in the unoccupied back spaces saves a 22% in annual energy usage (Al Anzi and Al-Shammeri, 2010).

Other studies (Khalil et al., 2013) suggest that while all the AC units might need to be in operation during the hot day time, early

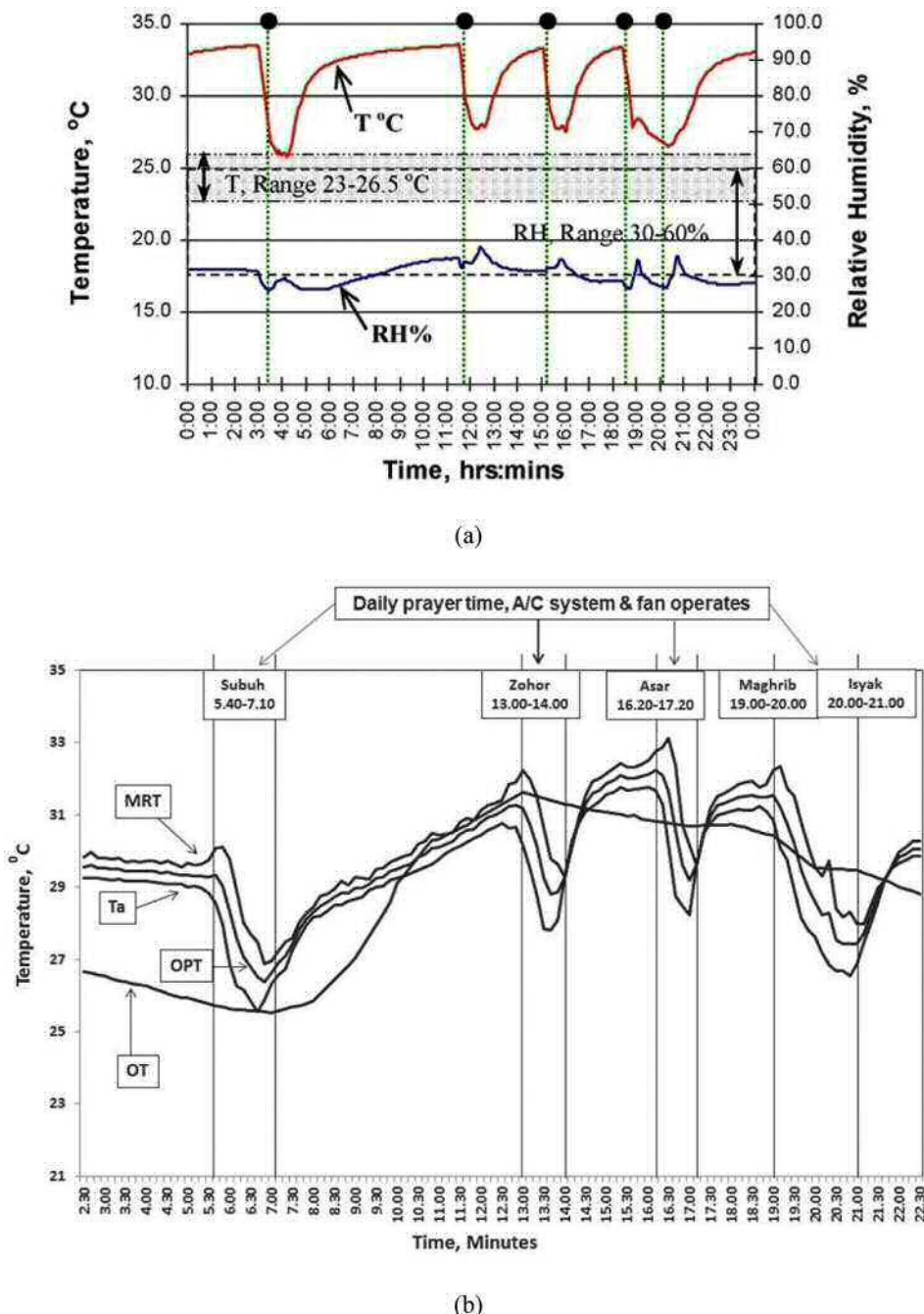


Fig. 8. Intermittent nature of AC operation timing in the studies by (a) Al-Homoud et al., 2009, and (b) Hussin et al. (2015).

morning *Fajr* prayers and nighttime *Isha* prayers do not require all the machines to run. In this study, 9 units were switched on during the day while only 4 units were operational during *Fajr* and *Isha* as the temperature was much lower during these two times. Simulation results showed that despite fewer machines in operation, thermal comfort was still achieved while reducing energy usage by 44% during those times. To maintain the operation schedules of the systems, researchers (Hussin et al., 2020a; Atmaca and Gedik, 2020) have suggested intelligent and automated on/off mechanism in order to reduce energy wastage. Researchers (AL-Tamimi and Qahtan, 2018) have also concluded that due to the short time of the prayers, the AC systems cannot attain the desired comfort temperature range unless it is switched on at least 30 minutes before the arrival of the congregants. Thus, the precooling of building mass several degrees below the comfort level before prayers will help to absorb a portion of the peak heat load (Yüksel et al., 2020b). In such a scenario, although the AC will run for longer hours, it would result in less demand and smaller equipment size which would be more energy efficient. Further validated research on operational strategies needs to be done aiming at providing suitable thermal comfort conditions during the short-spanned prayer times while maintaining energy efficiency.

4.5. Temperature set-point and comfort conditions

An important aspect of energy efficiency in mosques that often seems to be ignored in literature is the AC set-point temperature with regards to the comfort temperature range of the users. The comfort temperature range for people in hot climates is usually found to be higher than the recommended standards as they are adapted to such climatic conditions (Al-Ajmi et al., 2017). Surveys carried out in Kuwait (Al-Dabbous et al., 2013), Iraq (Alashaab and Alamery, 2018), Malaysia (Azmi and Kandar, 2020; Hussin et al., 2014), Saudi Arabia (Shohan and Gadi, 2020), Turkey (Diler, 2019), Indonesia (Soegijanto and Yohana, 2004), Nigeria (Shodiya et al., 2016), and Egypt (Abdallah, 2019) have all shown that mosque users feel comfortable at 3–6 °C higher than the commonly used standards set by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2013). Fig. 9 illustrates how the comfort temperature range in various hot climates can be much higher and also broader than the existing standards. However, most mosques still employ the ASHRAE recommended 23–26.5 °C as the set-point temperature for the thermostat (Al-Homoud, 2009). Studies have shown that with such temperature set-points, users in mosques of hot countries have reported discomfort because of feeling too cold (Saeed, 1996; Al-Ajmi, 2010). This implies that the AC set-point temperature is much lower than it is necessary to maintain thermal comfort of users. On one hand, this can create unnecessary energy wastage as more energy is required to maintain a temperature which has a bigger temperature difference from the outside. On the other hand, such extensive usage for maintaining lower temperatures can significantly reduce the efficiency of the machine over time.

Al-Ajmi (2010) predicts that changing the set-point temperature from 24 °C to 26 °C may allow saving up to 20% of cooling energy. Similarly, other researchers (Mushtaha and Helmy, 2017) recommend increasing the set-point temperature from 23 °C to 26 °C in order to reduce cooling energy consumption. It was found (Samiuddin, 2014) that one set-point, a temperature of 24 °C in this particular research, cannot achieve thermal comfort and might be the reason behind energy wastage. Thus, it was recommended that a temperature range be used which enables the AC to conserve energy while maintaining the indoor temperature according to the upper and lower limits of the setpoint. Energy usage reduction with respect to AC set-point temperature has not yet been objectively

researched in literature. With such discrepancies between the survey findings and the comfort temperature range recommended in standards, more studies need to be conducted to establish suitable thermal comfort conditions and indices for mosque buildings. Since mosques only turn on the cooling system with the onset of prayers, the AC temperature is lowered further and the distribution fan is set on high to quickly achieve the desired temperature (Samiuddin and Budaiwi, 2018). This essentially wastes more energy and also creates pocket-spaces with temperature variations increasing the thermal discomfort of the users. To test the viability of a certain set-point and distribution scheme, researchers (Ghaleb, 2017) have recommended the use of computational fluid dynamics (CFD) which has proven to be more accurate in determining thermal comfort for places with high human density such as mosques. Additionally, other high-tech options such as real-time thermal comfort sensors (Kumar et al., 2010) and smart wearable sensors (Nizetić et al., 2020) should also be explored in the context of the high-density occupancy pattern of mosques.

5. Critical evaluation of energy optimization experiments

In the previous sections, various design and operational factors affecting the energy usage of mosques have been highlighted. There have been some experimental studies in the literature that propose improved design or optimized operation strategies for mosques to achieve energy efficiency. These studies took one or more parameters as a variable, and multiple options of the base case model were simulated in order to achieve the optimized scenario for energy efficiency. This section will discuss the findings from such experimental simulation studies and present a comparative analysis. The results have been presented in the form of tables and graphs (Fig. 10) for a better comparison between the impact of various design components and operational parameters on the energy efficiency of mosque buildings. Since these mosques are of different sizes, the energy usage has been expressed in the form of EUI as an objective comparison standard for the optimization experiments. For some research papers such as (Mushtaha and Helmy, 2017; Al-Shaalan et al., 2014; Al-Shaalan et al., 2017; Al-Shamrani et al., 2016), additional calculations were done to obtain the EUI values as the results were presented as raw data for monthly energy usage. It should be noted that all these studies have been undertaken for air-conditioned mosques in hot-dry climates and thus, the results would be more suitable for mosques in similar climatic conditions. Nevertheless, the comparison depicts how the energy efficiency of mosque buildings might be impacted by different design and operational factors.

Although results have been portrayed in such a way to allow for comparing and contrasting, the findings are not to be taken as an absolute value but as a means to assess the relative importance of each factor. Thus, the results must not be interpreted as a standard for all mosques but should be considered within the same experiment so as to identify the contributing aspects for energy consumption. Since there are a lot of factors that influence the findings of simulation studies, some comments are presented for these papers so that it may help future researchers:

Firstly, a huge difference in findings can be observed in the results ranging from 20% to nearly 80%. This is because not all studies had the same reference as the base case scenario. Experiments such as (Mushtaha and Helmy, 2017; Al-Shaalan et al., 2017) have a high level of reduction through optimization because those also have high EUI as a beginning point. These studies assume the absolute worst case and a very high level of energy usage as the hypothetical base case scenario. In reality, mosques do not have such extreme design or operational parameters resulting in such high EUI values. Results in (Al-Homoud, 2009; Budaiwi, 2011) show about a 40%

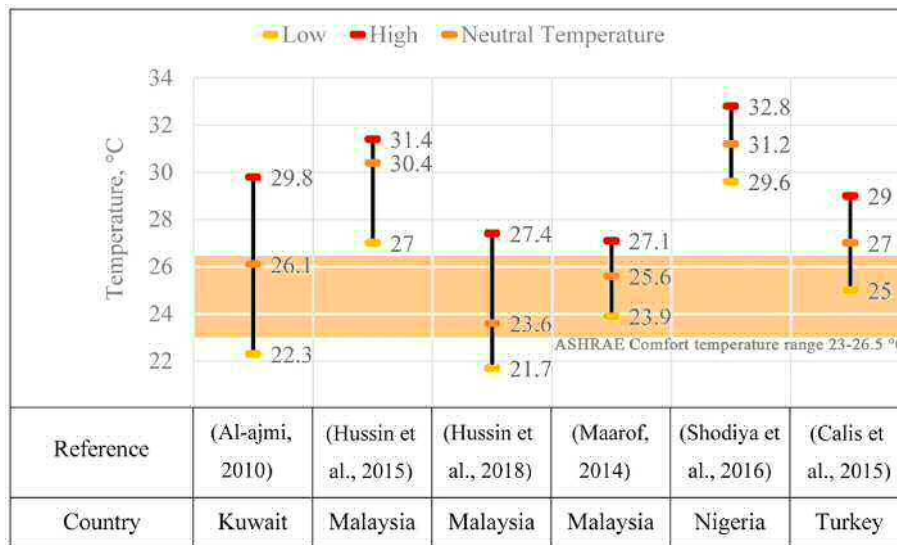


Fig. 9. Neutral temperature and comfort temperature range established from studies (Maarof, 2014; Calis et al., 2015).

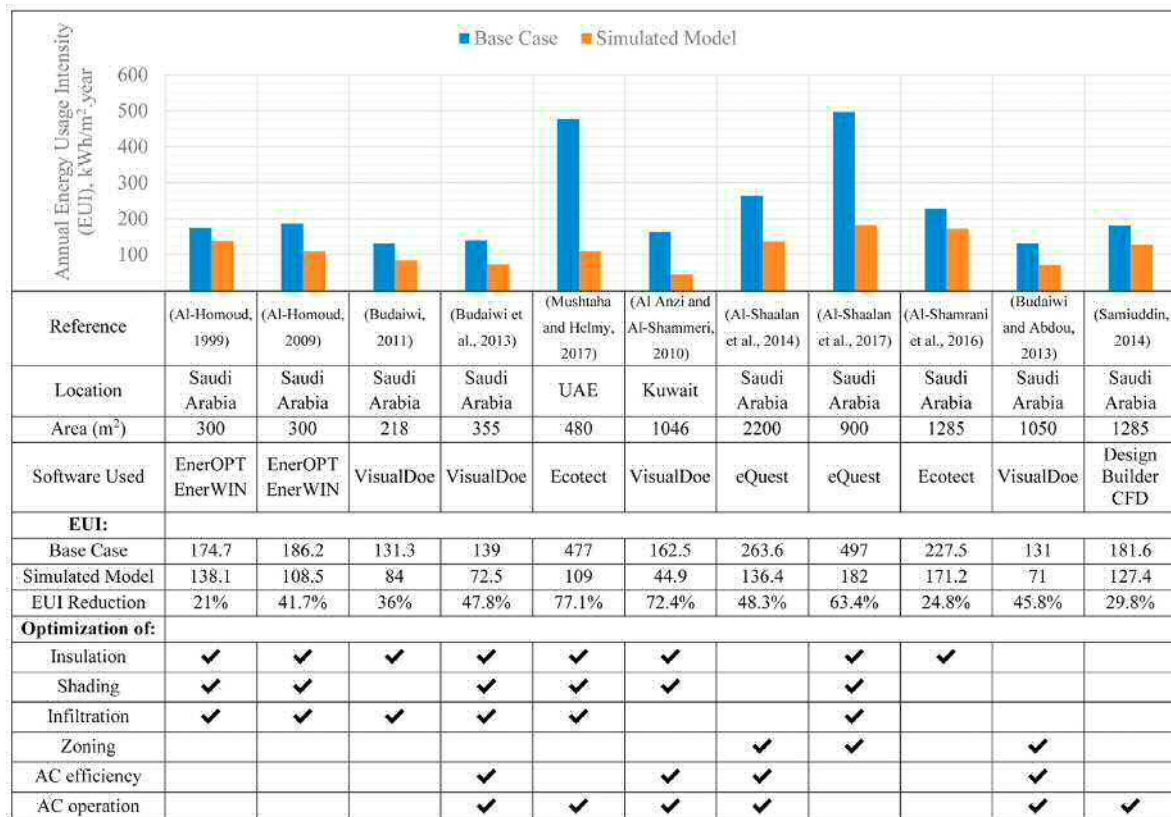


Fig. 10. Comparison between energy optimization experiments in mosques.

reduction but the findings are more practical as the base case parameters have been taken from typical construction practices and the EUI has also been validated through energy audits.

Secondly, in order to optimize the design, some studies have simulated parameters that are practically impossible to achieve. Results from (Al Anzi and Al-Shammeri, 2010) show a very high percentage of reduction, and a very low EUI achieved after optimization. Such a low level of EUI is unrealistic in reality for

buildings with high internal volume and mechanical heating/cooling systems. Similarly, one study (Al-Shaalan et al., 2017) has variables that are not realistic in value whilst another (Al-Shamrani et al., 2016) has logical assumptions yet impractical parameters for the wall dimensions and details. Additionally, studies such as (Al-Homoud, 1999; Al-Homoud, 2009) are based on direct search optimization which yields the optimized output based on defined constraints. It is to be understood that these experiments had

aimed at optimization without considering the finance or practicality of the design and construction. Thus, results from these experiments may not be applicable in realistic scenarios due to various constraints.

Thirdly, some experiments have excluded or ignored certain energy-consuming aspects whilst carrying out optimization studies. In the energy audit for (Al Anzi and Al-Shammeri, 2010), it shows over 40% of the energy used is for lights, hot water system, and equipment. When the optimization of only the building envelope and cooling system is carried out, it is supposed to impact the cooling system and fans with 49% and 10% energy usage, respectively. However, results have been expressed as a percentage reduction of the overall energy usage, which will not be a correct interpretation. Other studies (Mushtaha and Helmy, 2017; Al-Shaalan et al., 2017) with a high percentage of reduction also shows similar tendencies.

Fourthly, experiments such in (Mushtaha and Helmy, 2017; Al-Shaalan et al., 2014; Al-Shaalan et al., 2017; Al-Shamrani et al., 2016) have interpreted the yearly total cooling load as the overall cooling energy without taking into consideration the efficiency of the cooling system. Depending on the COP of the system, the cooling energy and the cooling load may vary considerably. Besides, every machine has an efficiency rating and the performance of a system will gradually decrease over time. Thus, the cooling energy requirements will always be higher than the cooling load of a building. This is a factor that needs to be considered while carrying out optimization experiments.

Lastly, the simulation softwares employ a numerical model of the case study building which must be validated to obtain realistic results. Additionally, each software has a different set of algorithms to determine the optimized output which is subject to limitations as well. For example, Ecotect used in (Mushtaha and Helmy, 2017; Al-Shamrani et al., 2016) and VisualDoe used in (Budaiwi, 2011; Budaiwi et al., 2013; Al Anzi and Al-Shammeri, 2010; Budaiwi and Abdou, 2013) do not take into account ventilation through air movement as a variable that helps towards dissipating the heat. These softwares calculate the ventilation only as a required air change per hour (ACH) for the cooling systems. Other software such as eQuest (Al-Shaalan et al., 2014; Al-Shaalan et al., 2017) has a predefined set of parameters that can influence the outcome of the simulation. This software optimizes the results for different variables of the building envelope and operation parameters but uses California Energy Commission standards which may not be applicable for experiments in other climates.

To ensure that the above-mentioned biases are not present while carrying out optimization experiments, validation of results with respect to real data is a must. This allows scope for calibration and consequently gives realistic data outputs. Studies (Mushtaha and Helmy, 2017; Al-Shaalan et al., 2014; Al-Shaalan et al., 2017; Al-Shamrani et al., 2016) with unrealistic reduction rates or impractical parameters were also the ones that had not carried out any validation or verification for the outputs. On the contrary, experiments like (Al-Homoud, 1999; Al-Homoud, 2009; Budaiwi, 2011; Budaiwi et al., 2013) have validated the results with actual findings from energy audits. Values used for validation such as cooling loads, peak cooling load, or cooling energy were calculated over a span of time, typically for the duration of one or more years. Although these studies yielded lower energy reductions, the results are more practical in terms of construction and energy usage pattern.

6. Conclusions and suggestions for future research

There are numerous mosques around the world, most of which are not energy efficient and have high energy consumption rates.

Yet research in this field is inadequate with regards to identifying the problems and contributing factors as well as analyzing and evaluating the probable solutions. Mosque energy usage is highly impacted due to its unique spatial characteristics as well as the intermittent occupancy pattern. In this paper, the various design and operational parameters that have been found to influence the energy efficiency of mosque buildings are highlighted. A comparison between energy optimization experiments has been drawn and commentary made that may serve as a means to illustrate how the energy efficiency of mosque buildings might be impacted by those factors. Such a review of the contemporary literature provides valuable insights into mosque energy usage patterns and identifies the important aspects to be considered towards reducing energy consumption in mosque buildings. The following conclusions can be drawn from this literature review:

- The envelope thermal design and climatic factors are the most significant aspects of the energy usage of mosques. Consequently, the heating/cooling systems account for the majority of the energy consumption of mosque buildings.
- The defined standards for thermal comfort and temperature settings are not representative of the actual preferences of the users. Maintaining the recommended low temperature leads to energy wastage of the cooling systems.
- Most experiments in this field focus on optimizing energy usage by modifying existing design trends rather than innovative solutions towards passive and low energy buildings. This is a field that is yet to be thoroughly explored in literature yet probably has the most energy saving potential.
- With optimized building design, installation of appropriate thermal control systems, and suitable operation strategies, the energy consumption of mosques can be greatly reduced.
- Zoning of the prayer hall and separate heating/cooling system design for varying occupancy levels combined with suitable operational strategies for high and low occupancy schedules can significantly lower the energy requirements.
- Being an activity-centered building, mosque energy efficiency cannot be fully achieved only through optimizing the design parameters as it is largely dependent on the operational strategies which are controlled by the end-users, both the occupants and management alike.

Mosque energy efficiency is a relatively new research niche and much work remains to be done that will evaluate the comfort conditions and the indoor environmental quality of the mosques as well as explore how current designs and practices are impacting the energy consumption pattern. Through discussing the design and operational parameters, another important criterion has also been identified which can be termed as 'community and policy'. The numerous research gaps that have been illustrated in this review paper should be addressed holistically for a sustainable approach towards energy efficient mosques. Based on the identified research gaps, some probable research scopes are mentioned below as suggestions for future researchers:

- (i) Design parameters:
 - Integrating active or passive energy saving means to traditional design elements.
 - Incorporating passive, low energy solutions for better thermal comfort of the users.
 - Developing zoning strategies to accommodate both the lower and higher occupancy needs.
 - Inspecting how the iconic style of modern mosques impacts the energy usage pattern.

- Exploring the orientation and asymmetric layout of mosques for better thermal performance.
- (ii) Operational strategies:
 - Investigating energy efficiency for mosques in temperate or cold climates.
 - Determining energy efficiency with respect to life cycle cost and sustainability.
 - Identifying suitable heating/cooling system that is appropriate for intermittent occupancy.
 - Establishing suitable set-point temperature range and operation timings that will cater to the thermal comfort of users while maintaining energy efficiency.
- (iii) Community and policy:
 - Training of end users and management of mosques to ensure awareness.
 - Exploring the concept of smart mosques and testing its viability.
 - Establishing regulations and policies on the energy usage of mosques.
 - Incorporating renewable and clean energy sources to reduce carbon footprint.

This list is not exhaustive but has been put forward since these are critical aspects yet to be explored in mosque literature. It is envisioned that these identified research prospects would create potential research scopes for future researchers. Based on such research, suitable design and operational guidelines should also be developed in order to assist architects, engineers and governments to design more energy efficient mosques.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Nabeeha Amatullah Azmi: Conceptualization, Methodology, Formal analysis, Investigation, Software, Visualization, Writing - original draft, Writing - review & editing. **Müslüm Arıcı:** Methodology, Formal analysis, Investigation, Supervision, Writing - review & editing. **Azhaili Baharun:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX C

The list of relevant literary articles, along with details such as publication year, research type, research focus etc., in the context of Malaysia.

Reference	Title	Year	Type of Publication	Source/publication	Research Focus	Type of Research	Type pf Mosque
(Omar et al., 2020)	Energy consumption and potential saving in MSI complex	2020	Journal article	Journal of Advanced Research in Fluid Mechanics and Thermal Sciences	Energy audit	Field study	Air-conditioned
(Hussin et al., 2020a)	Energy Consumption Control of An Air-Cooled Chiller from the Use of An Automatic ON/OFF Timer System: A Real Case Study of the Penang State Mosque	2020	Journal article	Jurnal Kejuruteraan (Journal of Engineering) - UKM	Energy usage optimization	Field study	Air-conditioned
(Yusoffa, 2020)	Initial assessment of indoor environmental condition and thermal comfort of Malaysia heritage mosque	2020	Journal article	Jurnal Kejuruteraan (Journal of Engineering) - UKM	Thermal performance of building	Field study	Naturally ventilated
(Munir et al., 2020)	Association between thermal comfort condition and worshippers' satisfaction in timber and concrete of suburban religious buildings	2020	Conference proceedings	International Conference on Urban Sustainability, Environment, and Engineering (CUSME 2020), Bali, Indonesia	Thermal comfort assessment	Field study	Air-conditioned
(Hussin et al., 2020b)	Using CFD to optimizing comfort and energy using different air temperatures and velocities for air conditioning (AC) in Penang State Mosque	2020	Conference proceedings	Proceedings of the 11th Windsor Conference on Thermal Comfort: Resilient Comfort	Thermal comfort optimization	Numerical experiment	Air-conditioned

(Hussin et al., 2019)	Air conditioning energy profile and intensity index for retrofitted mosque building: A case study in Malaysia	2019	Journal article	Alam Cipta International Journal on Sustainable Tropical Design Research and Practice	Energy audit	Field study	Air-conditioned
(Azmi & Kandar, 2019)	Factors contributing in the design of environmentally sustainable mosques	2019	Journal article	Journal of Building Engineering	Thermal performance of building	Field study	Air-conditioned
(Kamar et al., 2019)	Enhancement of thermal comfort in a large space building	2019	Journal article	Alexandria Engineering Journal	Thermal comfort optimization	Numerical experiment	Naturally ventilated
(Hussin et al., 2018b)	Energy usage and energy saving potential of air conditioning Mosque in Penang Malaysia	2018	Conference proceedings	Proceedings of the 2nd Malaysia University-Industry Green Building Collaboration Symposium (MU-IGBC 2018), Selangor, Malaysia	Energy audit	Field study	Air-conditioned
(Hussin et al., 2018a)	Indoor Thermal Performance of a Retrofitted Air-Conditioned Mosque: Case Study for Penang State Mosque	2018	Journal article	Jurnal Kejuruteraan (Journal of Engineering) - UKM	Thermal performance of building	Field study	Air-conditioned
(Nordin & Misni, 2018)	Evaluating the interior thermal performance of mosques in the tropical environment	2018	Conference proceedings	Proceedings of the 3rd International Conference on Research Methodology for Built Environment and Engineering 2017	Thermal performance of building	Field study	Naturally ventilated

				(ICRMBEE 2017), Selangor, Malaysia			
(Omar et al., 2018)	Green Mosque: A Living Nexus	2018	Conference proceedings	Proceedings of the 6th AMER International Conference on Quality of Life (AicQoL 2018), Terengganu, Malaysia	Thermal performance of building	Discussion paper	Naturally ventilated
(Nordin & Misni, 2017)	A Comparative Study on the Indoor Thermal Performance of New and Old Mosques	2017	Conference proceedings	Proceedings of the 5th AMER International Conference on Quality of Life (AicQoL 2017), Bangkok, Thailand	Thermal performance of building	Field study	Naturally ventilated
(Noman et al., 2016)	Improvement of thermal comfort inside a mosque building	2016	Journal article	Jurnal Teknologi (Sciences and Engineering)	Thermal comfort optimization	Numerical experiment	Naturally ventilated
(Baharudin & Ismail, 2016)	Aspect of Design Functionality on Communal Mosque in Muslim and Non-Muslim Country	2016	Journal article	Asian Journal of Quality of Life	Thermal performance of building	Discussion paper	Air-conditioned
(Aziz, 2016)	Execution of contemporary Islamic architecture through design: the Cyberjaya Green Platinum Mosque Project in Malaysia	2016	Conference proceedings	Proceedings of the 1st International Conference on Islamic Heritage Architecture and Art (IHA 2016), Valencia, Spain	Thermal performance of building	Discussion paper	Air-conditioned

(Abdullah et al., 2016)	Defining Issue of Thermal Comfort Control through Urban Mosque Façade Design	2016	Conference proceedings	Proceedings of the 4th AMER International Conference on Quality of Life (AicQoL 2016), Medan, Indonesia	Thermal performance of building	Discussion paper	Air-conditioned
(Eusof et al., 2015)	An Assessment of Green Mosque Index in Peninsular Malaysia	2015	Journal article	American-Eurasian Journal of Agricultural & Environmental Sciences	Energy audit	Field study	Air-conditioned
(Hussin et al., 2015)	The reliability of Predicted Mean Vote model predictions in an air-conditioned mosque during daily prayer times in Malaysia	2015	Journal article	Architectural Science Review	Thermal comfort assessment	Field study	Air-conditioned
(Maarof, 2014)	Roof Designs and Affecting Thermal Comfort Factors in a Typical Naturally Ventilated Malaysian Mosque	2014	Unpubliished phd Thesis	Department of Architecture, Cardiff University	Thermal performance of building	Field study	Naturally ventilated
(Ibrahim et al., 2014)	Assessment of thermal comfort in the mosque in Sarawak, Malaysia	2014	Journal article	International Journal of Energy and Environment	Thermal performance of building	Field study	Naturally ventilated
(Hussin et al., 2014)	Thermal comfort during daily prayer times in an air-conditioned mosque in Malaysia	2014	Conference proceedings	Proceedings of the 8th Windsor Conference: Counting the Cost of	Thermal comfort assessment	Field study	Air-conditioned

				Comfort in a Changing World, Windsor, UK			
(Baharudin & Ismail, 2014)	Communal Mosques: Design Functionality Towards the Development of Sustainability for Community	2014	Conference proceedings	Proceedings of the 2nd AMER International Conference on Quality of Life (AicQoL 2014), Sabah, Malaysia	Thermal performance of building	Discussion paper	Naturally ventilated
(Ariff et al., 2012)	The impact of external environment on the internal thermal environment of the main prayer of Putra Mosque, Putrajaya	2012	Conference proceedings	Proceedings of UMRAN2012: Green Wave, IIUM Gombak, Selangor, Malaysia	Thermal performance of building	Field study	Air-conditioned
(Bakhlah & Hassan, 2012)	The Study of Air Temperature When the Sun Path Direction to the Ka'abah	2012	Journal article	International Transaction Journal of Engineering, Management & Applied Sciences & Technologies	Thermal performance of building	Field study	Naturally ventilated
(Hassan, 2010)	Concept of Prostration in Traditional Malay Mosque Design to the Surrounding Environment with Case Study of Tranquerah Mosque in Malacca, Malaysia	2010	Journal article	Journal of Techno-Social	Thermal performance of building	Discussion paper	Naturally ventilated

APPENDIX D

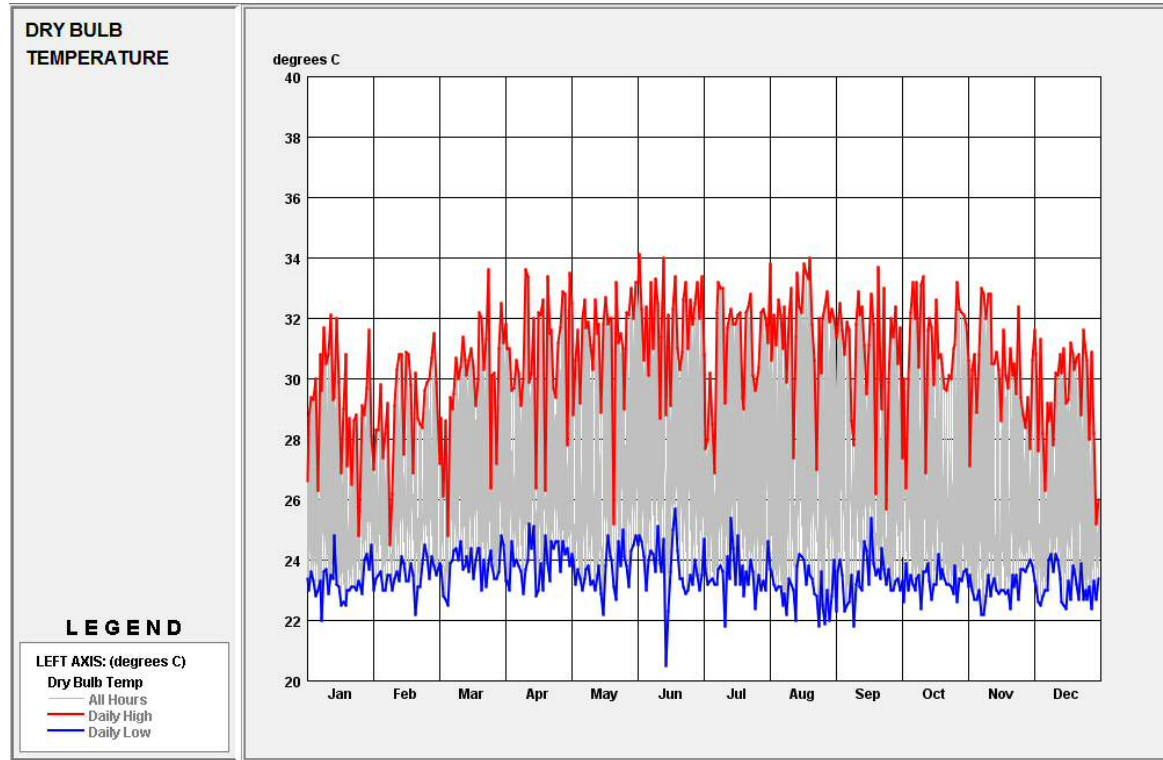


Figure 1: Yearly dry-bulb temperature of all hours showing daily high and low.

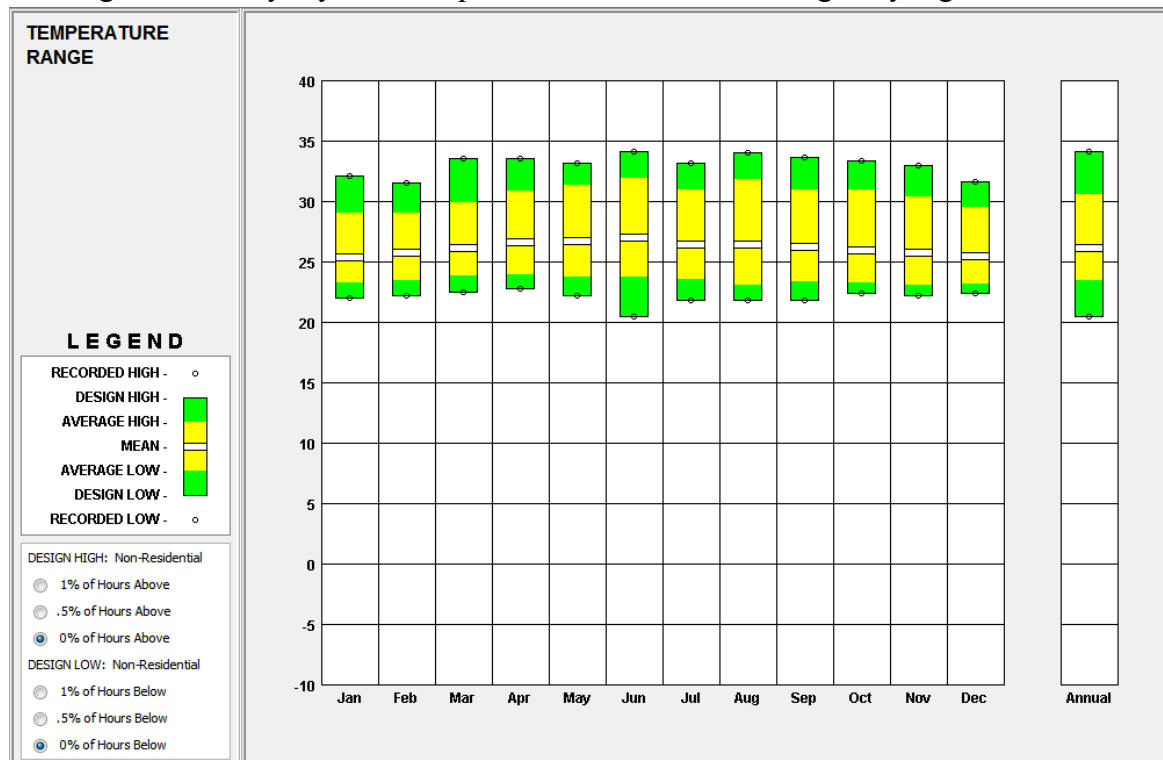


Figure 2: Daily average dry-bulb temperature range.

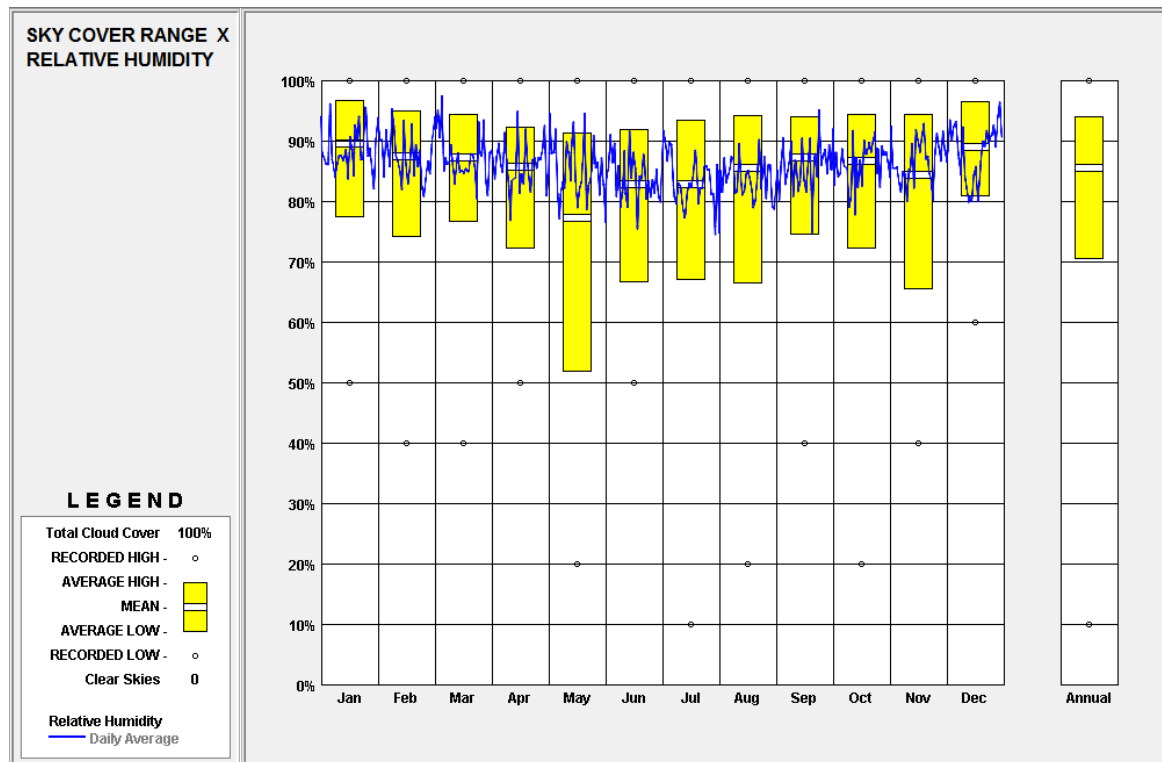


Figure 3: Yearly sky cover and relative humidity range.

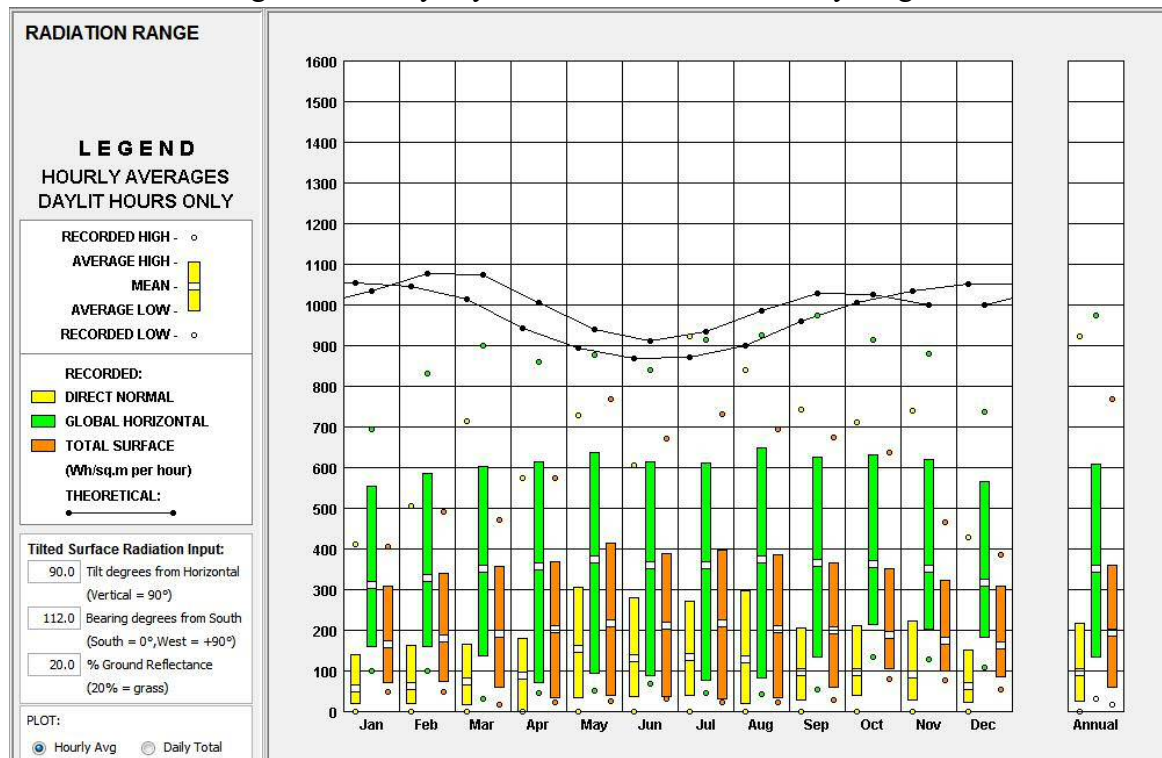


Figure 4: Yearly expected and observed solar radiation.

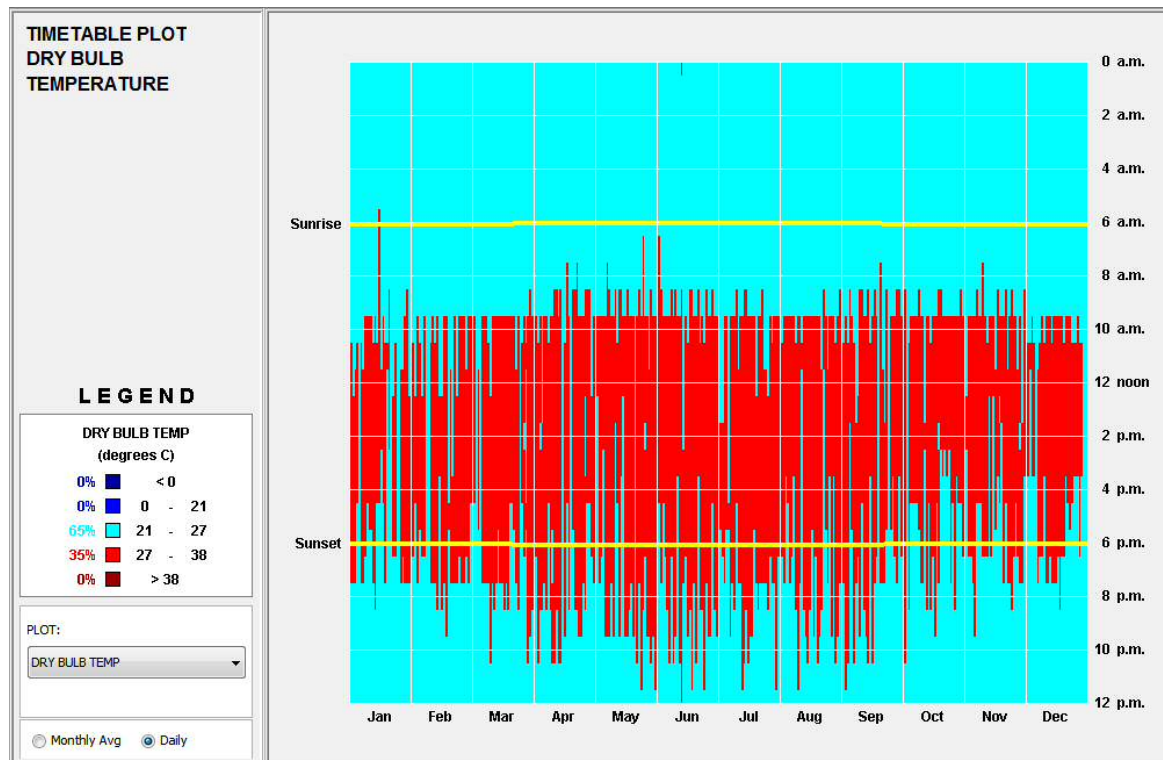


Figure 5: Timetable plot for dry-bulb temperature.

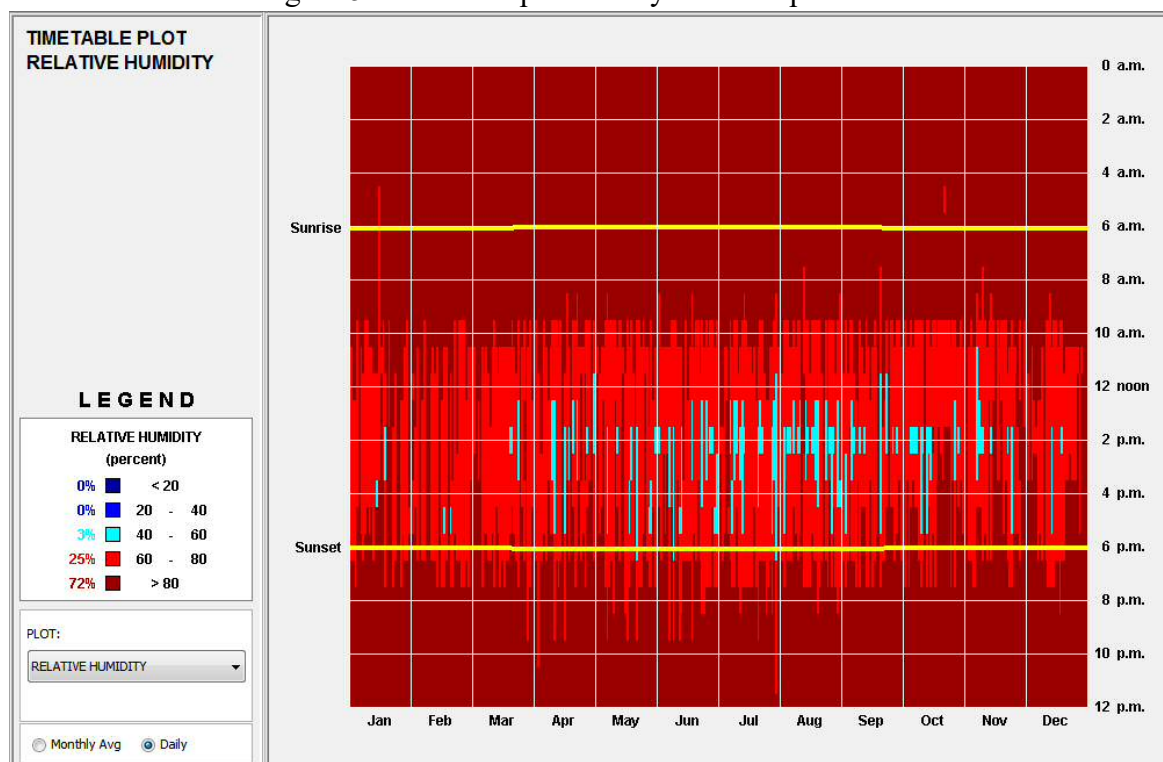


Figure 6: Timetable plot for relative humidity.

APPENDIX E

CFD-generated 2D and 3D diagrams comparing the different design scenarios for different wall configurations. The comparisons are provided for all the five prayer timings.

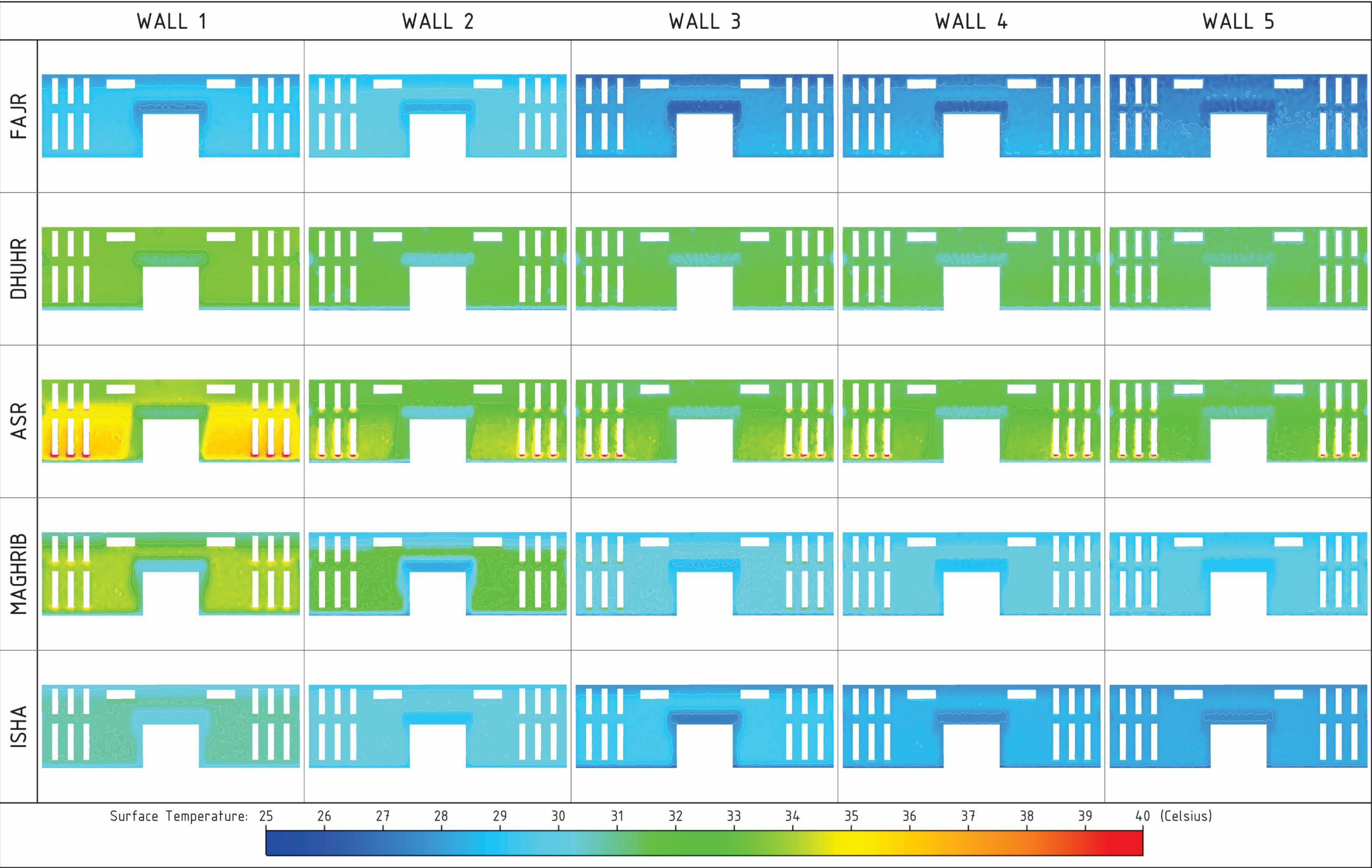


Figure 1: 2D Temperature profile of the *Qiblah* wall.

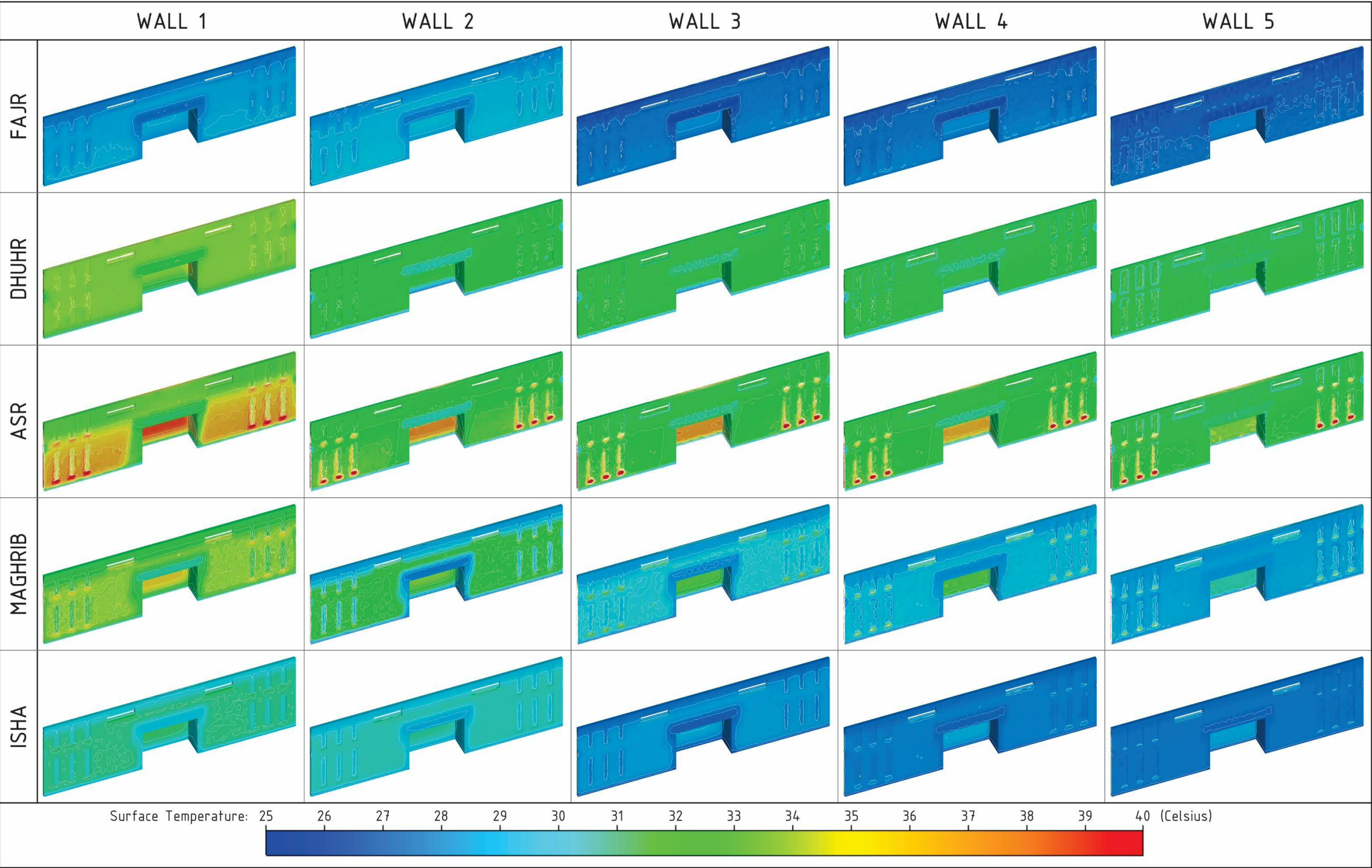


Figure 2: 3D Temperature profile of the *Qiblah* wall.

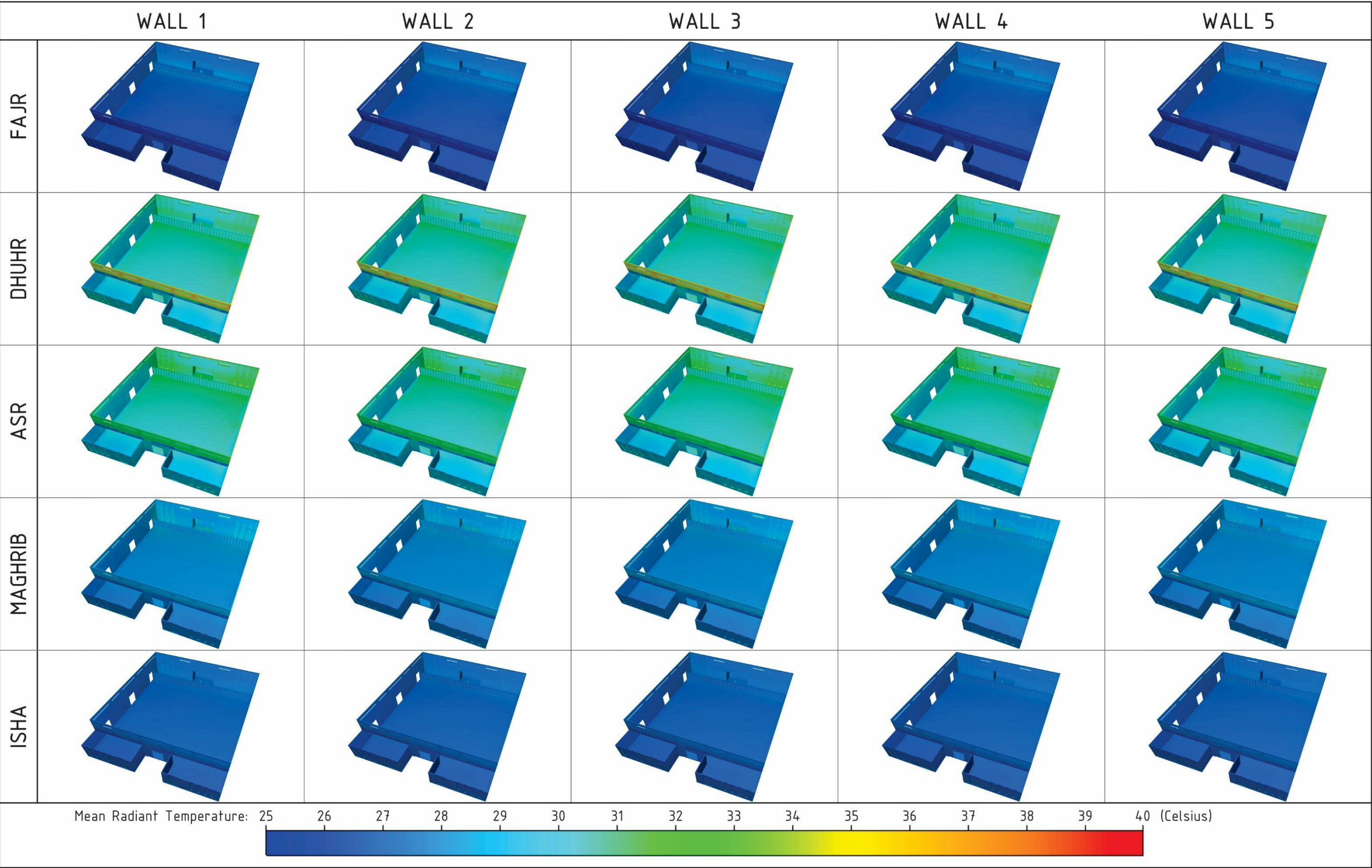


Figure 3: CFD image of MRT of the prayer hall.

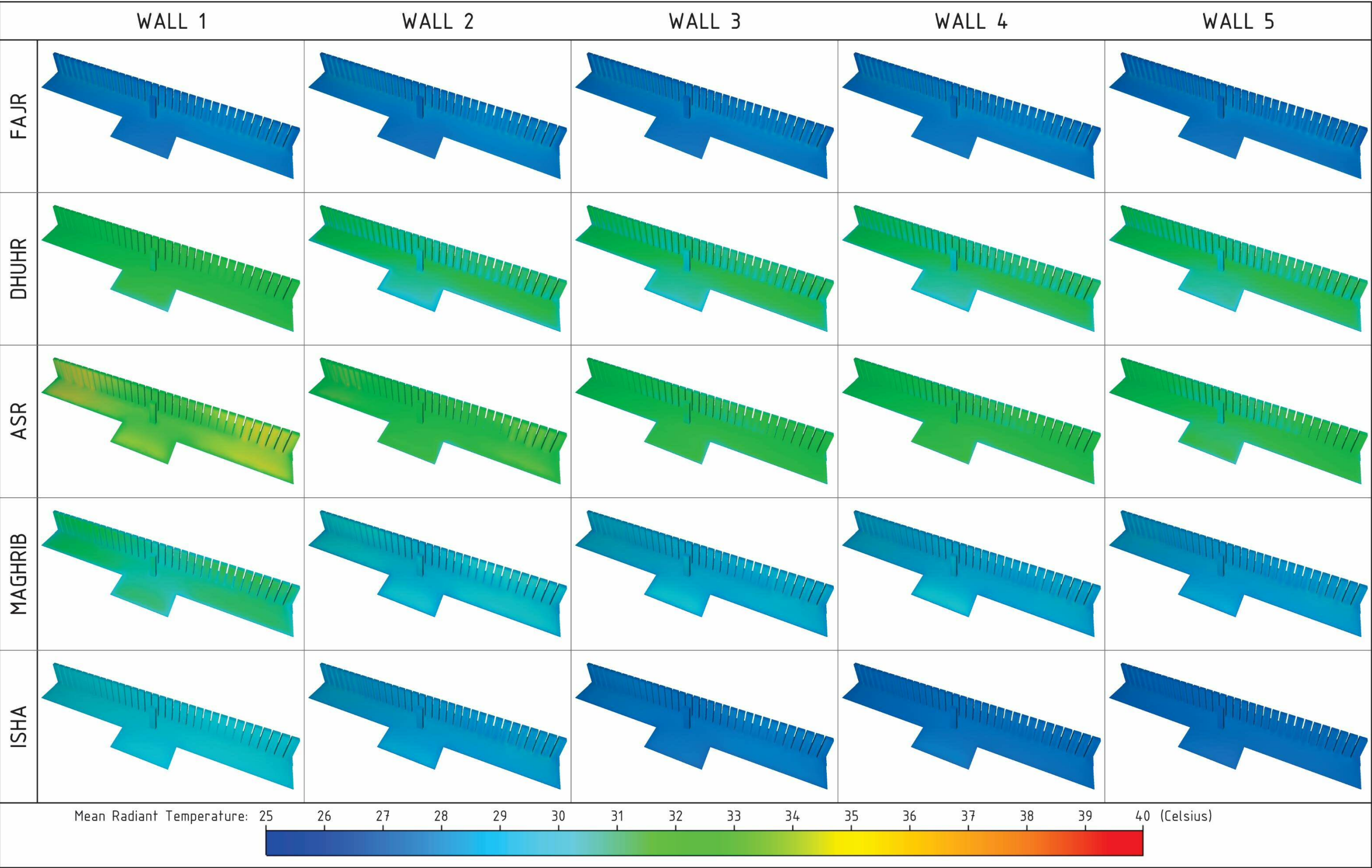


Figure 4: CFD image of MRT for a row of congregants.

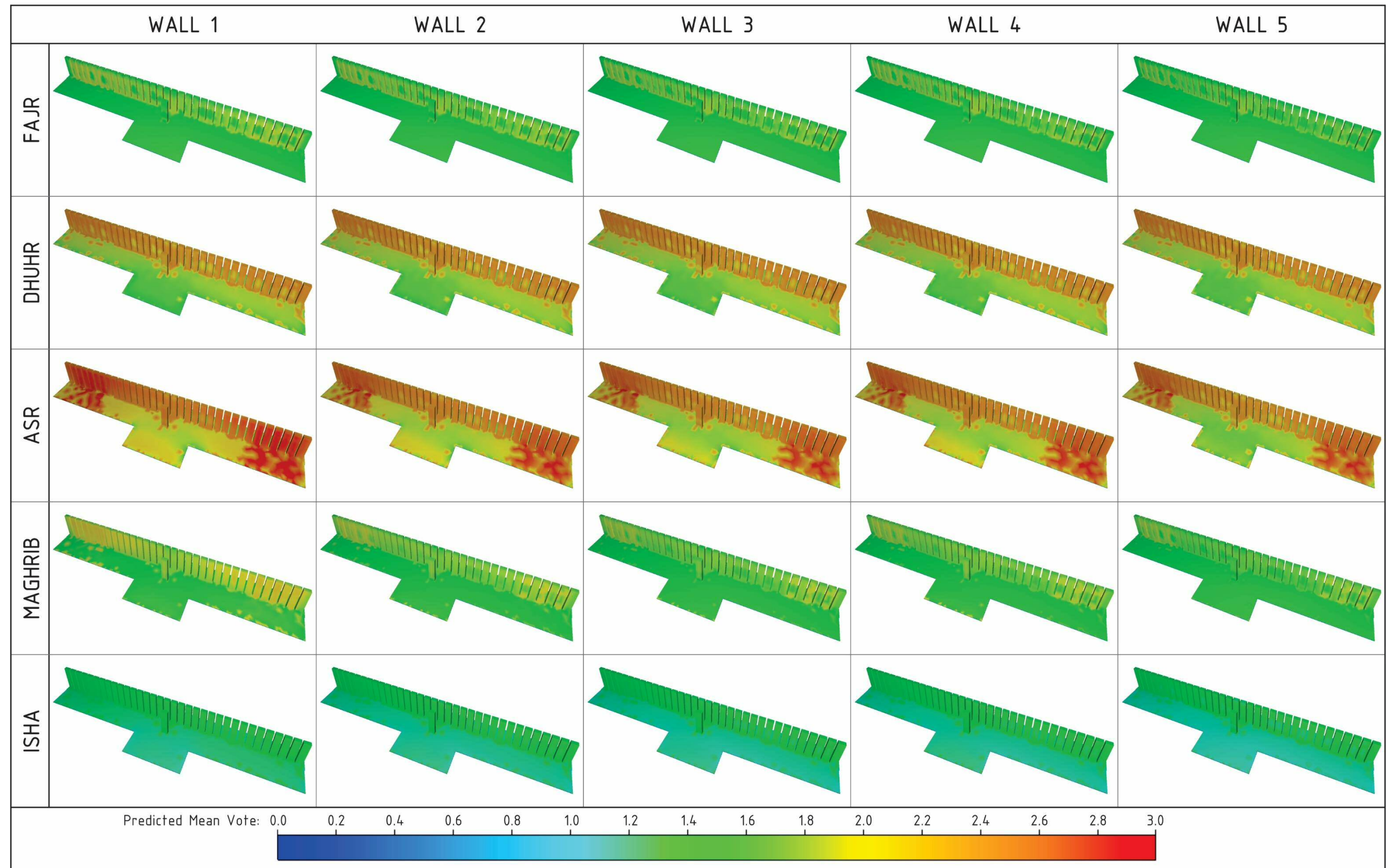


Figure 5: CFD image of PMV for a row of congregants.

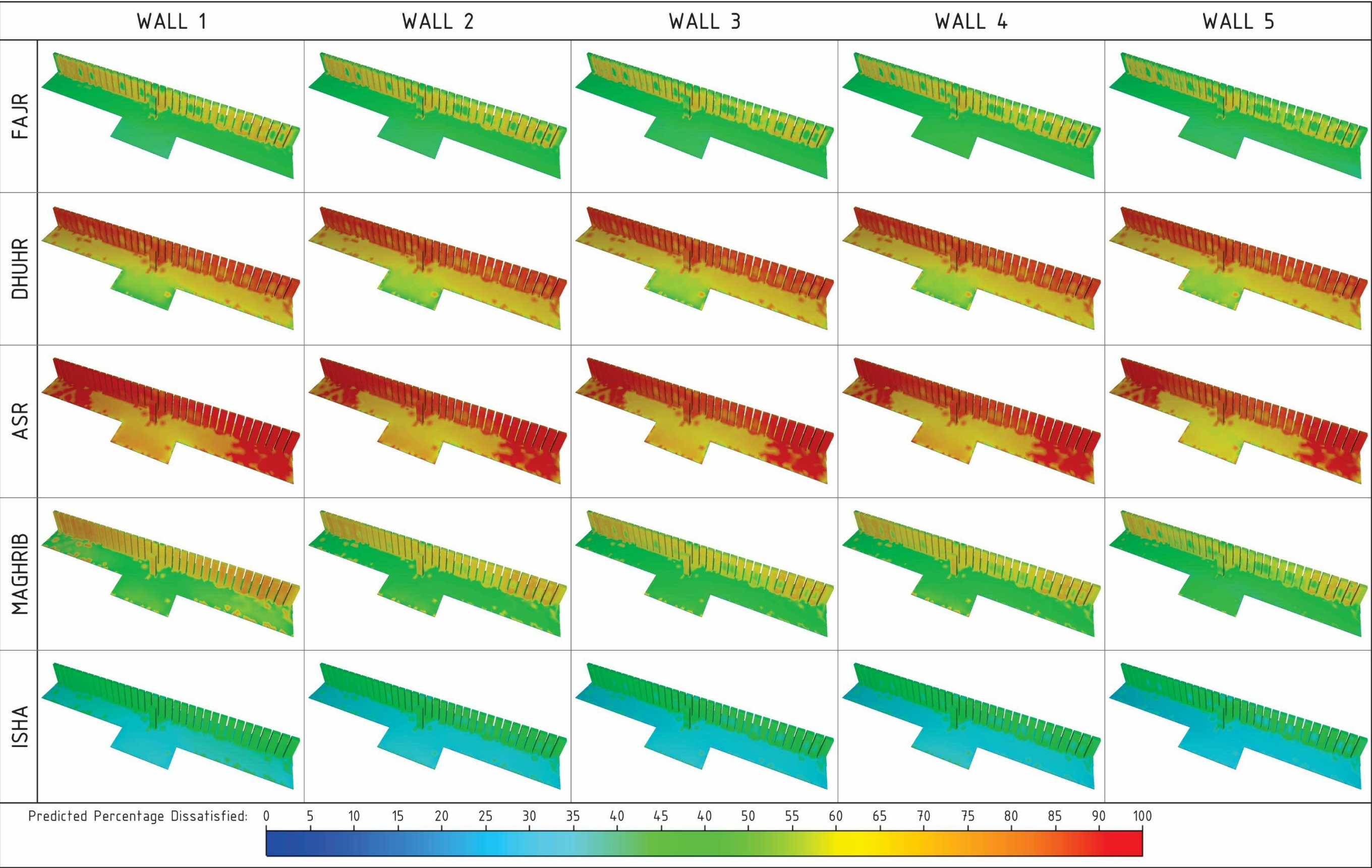


Figure 6: CFD image of PPD for a row of congregants.

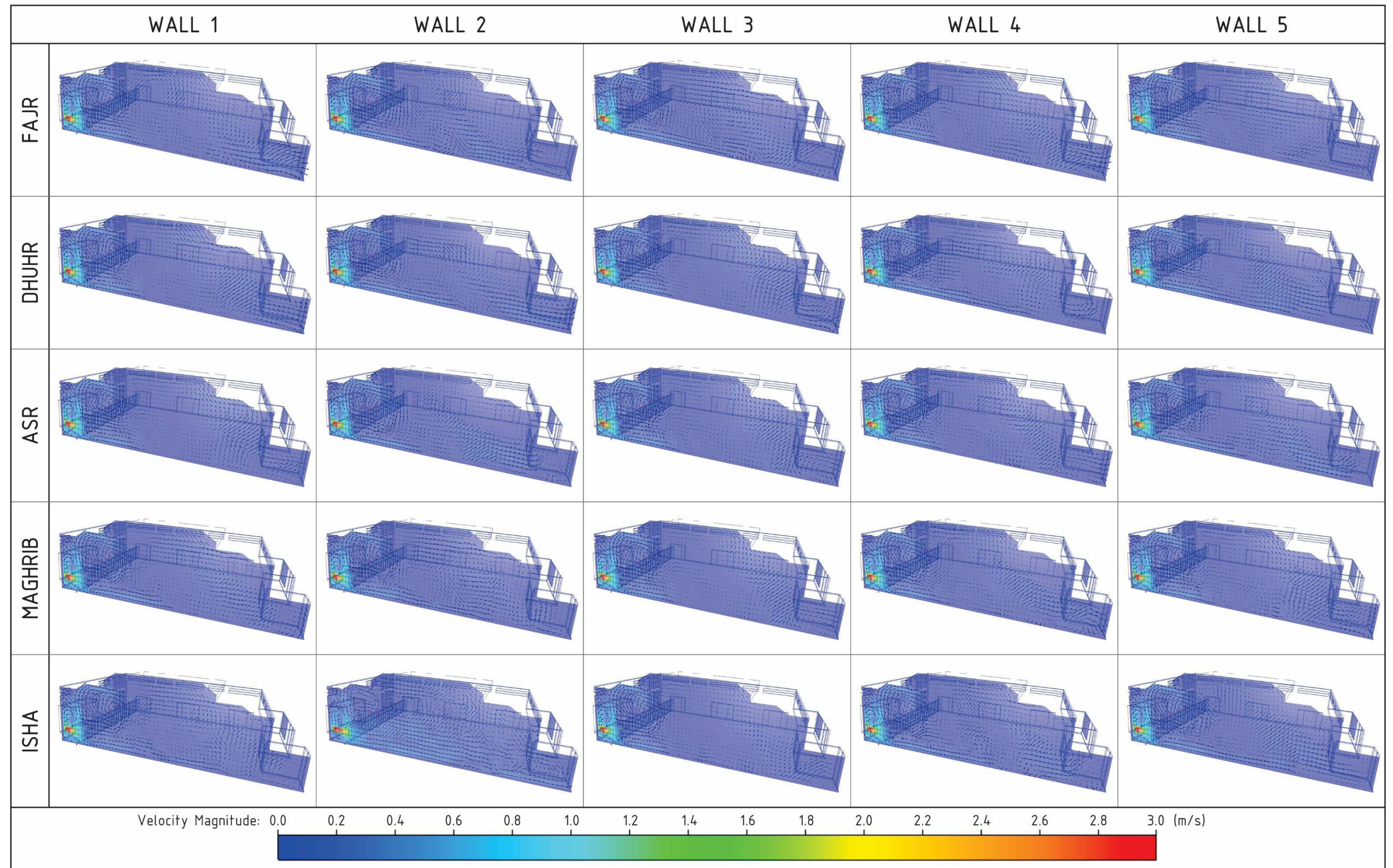


Figure 7: Velocity profile for the different simulation cases.

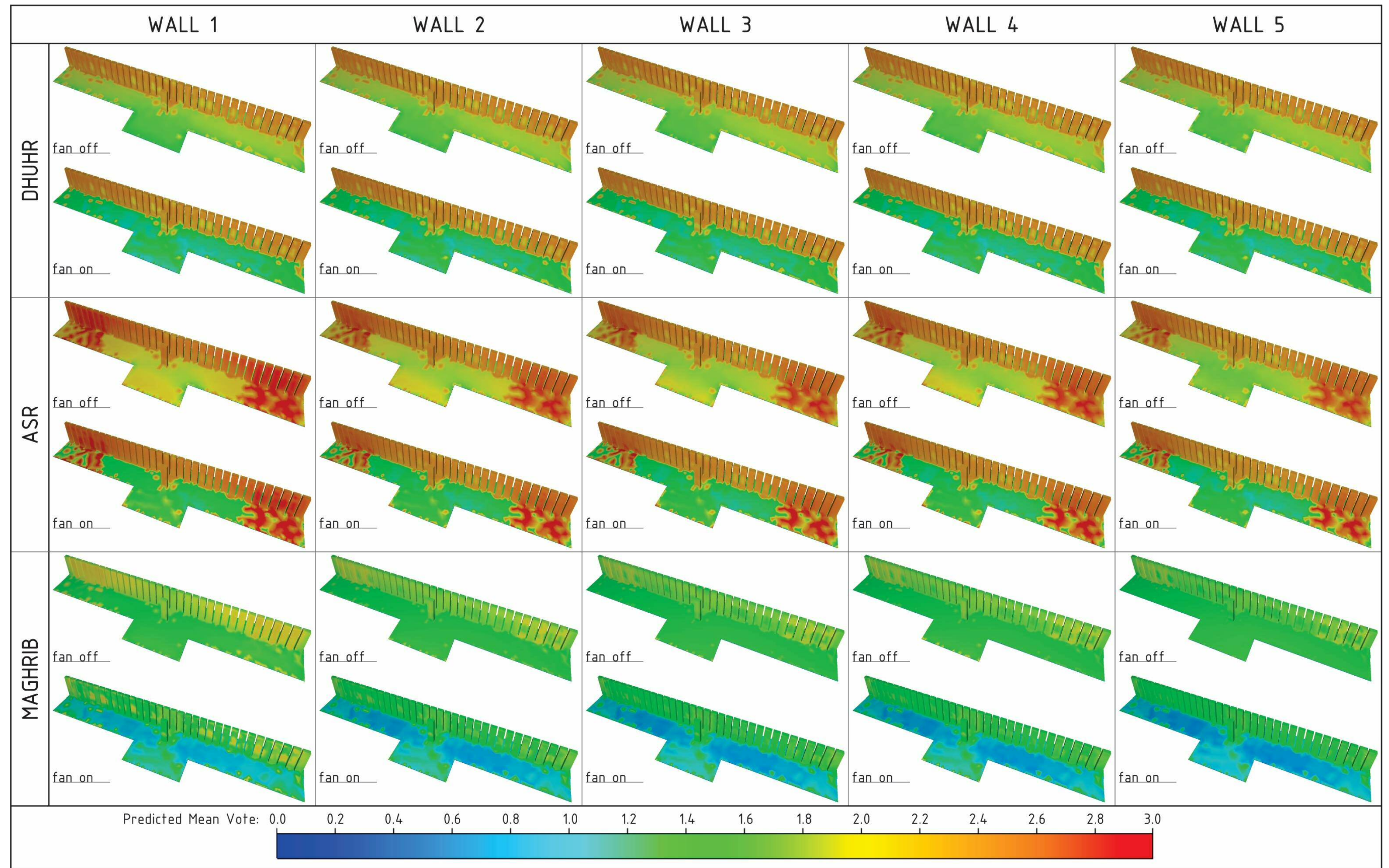


Figure 8: CFD image of PMV of occupants with fans switched off and on.

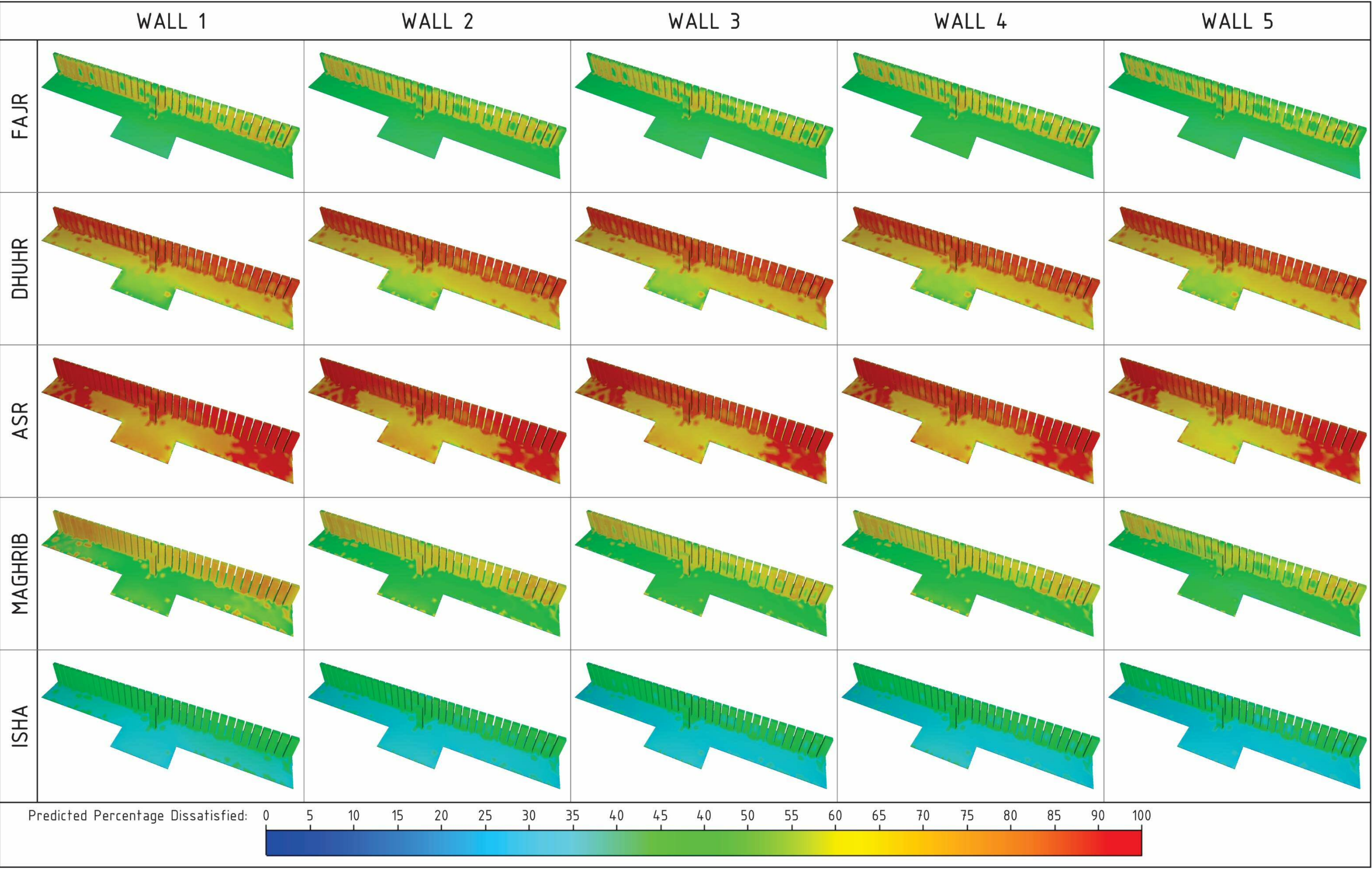


Figure 9: CFD image of PPD of occupants with fans switched off and on.

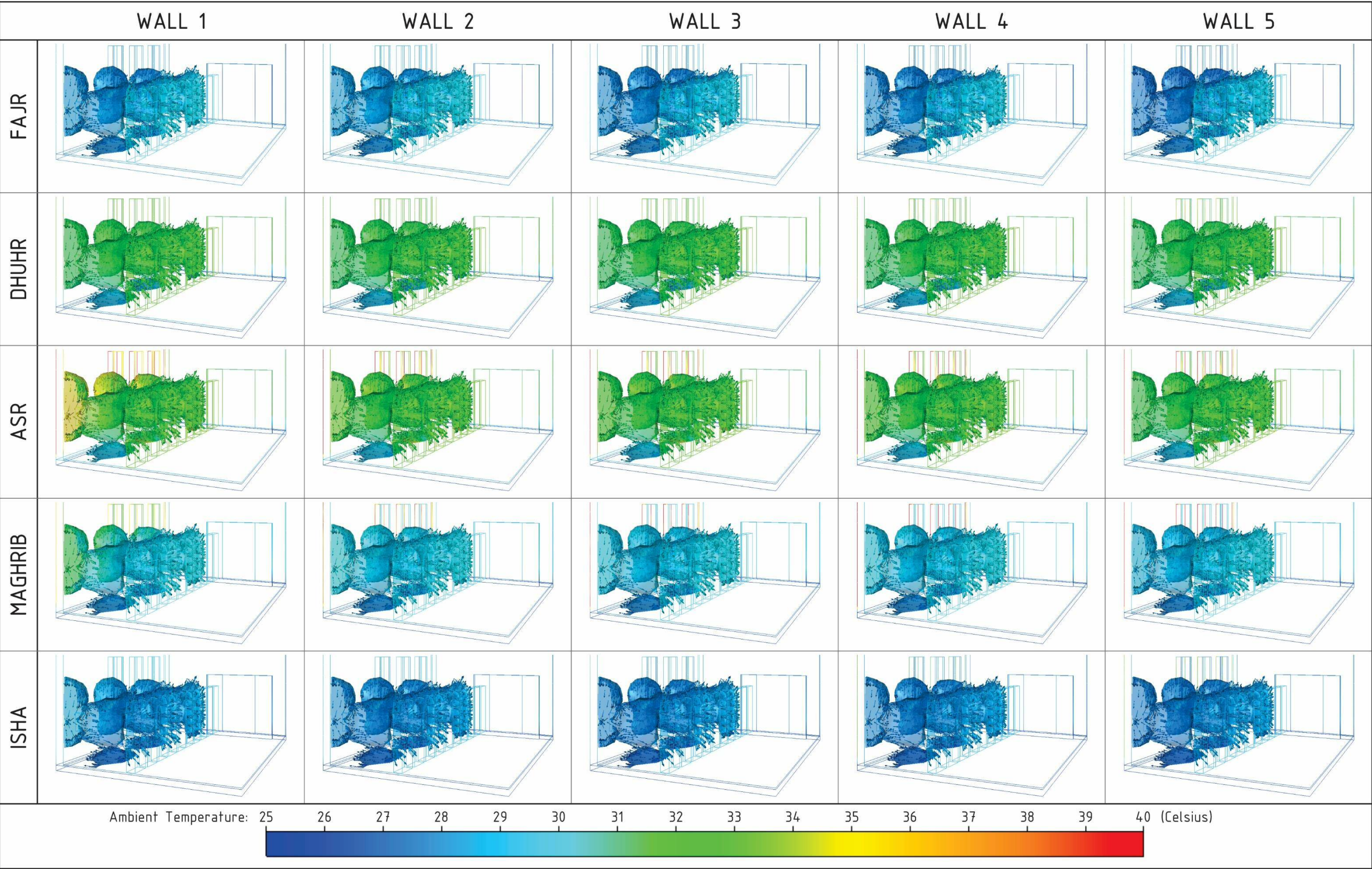


Figure 10: Ambient air temperature when fans are operating.

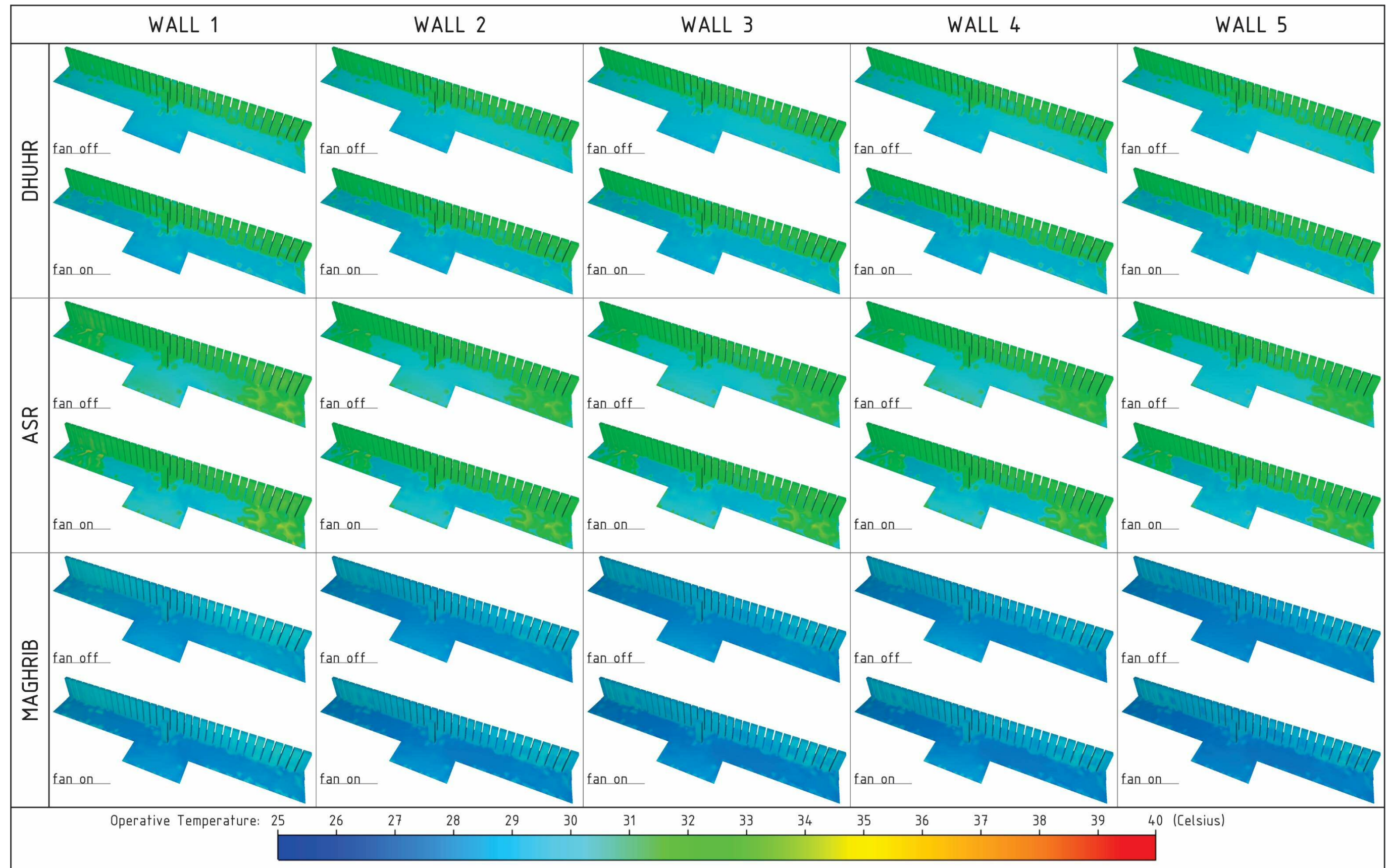


Figure 11: CFD image of OT of occupants with fans switched off and on.