

Article

Evaluation of Thermal and Energy Performance in Mosque Buildings for Current Situation (Simulation Study) in Mountainous Climate of Abha City

Ahmed Ali A. Shohan ^{1,*} and Mohamed B. Gadi ²

¹ Department of Architecture and Planning, Faculty of Engineering, King Khalid University, Abha 61411, Saudi Arabia

² Department of Architecture and the Built Environment, University of Nottingham, Nottingham NG7 2RD, UK; mohamed.gadi@nottingham.ac.uk

* Correspondence: ashohan@kku.edu.sa; Tel.: +966-17-241-7815; Fax: +966-17-241-8184

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Abstract: Achieving and maintaining indoor thermal comfort is a crucial factor for energy saving and human health, especially in heavily occupied public buildings, such as mosque buildings. The acceptable level of thermal comfort should not be achieved at the expense of damaging the environment by using preventable energy depletion. This study aims to investigate what level thermal comfort is achieved and related issues in mosque buildings in Abha city, which has a semi-arid moderate/cold mountainous climate. The research involved a computer modelling investigation by using Thermal Analysis Software (TAS). A number of comparisons of the simulation results with actual measurement data in mosque buildings, such as temperature, relative humidity, and energy demand were conducted. Main factors influencing thermal comfort and PMV were investigated for the selected mosques. In addition, thermal performance of mosques' fabrics and envelopes in terms of solar gain and heat loss/gain by conduction and its impacts on thermal comfort and energy demands were also discussed. The outcome showed some discomfort due to heat gain in summer and heat loss in winter. The results also revealed that the main factors behind heat gain or loss were the poor quality of the investigated mosque buildings' envelopes, including walls, roofs, floors, windows, and doors.

Keywords: thermal comfort; thermal performance; energy demand; mosque buildings

1. Introduction

Saudi Arabia has the second-largest crude oil reserves in the world with 22.2% after Venezuela with 24.8% [1]. Therefore, Saudi Arabian's government has subsidized oil and electricity prices inside Saudi Arabia, which has resulted in low prices for petrol and electricity in Saudi markets. Although, the situation has slightly changed since 2010 and since the starting of vision 2030 of Saudi Arabia, however the prices of oil and electricity are still considered subsidized compared to the majority of other countries. This fact, coupled with the shortage of enforceable law and regulations, the lack of awareness of environmental issues among the public, and before that, the harsh and extreme climate that Saudi Arabia have caused high electricity usage in Saudi Arabia. Air-conditioning systems consume around 65% of electric energy in order to maintain the acceptable level of indoor thermal comfort in all types of buildings in Saudi Arabia, compared to some of developed countries, such as the United Kingdom with a percentage of around 22%, and 21% in the United States and Australia [2].

Besides, it is noticed that cutting down the initial costs of buildings, particularly mosque buildings, comes at the expense of buildings' envelopes quality, by cancelling or ignoring some of the important building materials and elements, such as insulation. This in turn causes significant heat loss/gain through the mosque buildings' elements and fabric, therefore increasing cooling and heating demands. Thus, it is highly important to consider insulation and natural high-quality materials in roofs, walls, and doors, and best orientation when designing a building in general, and mosque buildings especially. This could be economically beneficial when considering money saved when reducing the heating and cooling demands, as well as helping preserve the environment by reducing the amount of CO₂ emissions when reducing the energy consumed by heating and cooling systems [3].

As the current study investigates mosque buildings, particularly those in Abha city, one could argue that Mosques as types of buildings form the minority compared to the other types of buildings, such as residential. [4] stated that mosques as a sector have a minority of electrical energy usage 1%, compared to the majority residential sector at 49%, and the industrial sector at 24% respectively. Although, it has been stated in a recent article that mosque buildings in the Kingdom of Saudi Arabia (KSA) are discovered to be one of the biggest types of buildings that consume more energy compared to the other types of buildings such as hospitals and educational buildings [5]. However, this in fact has not given an excuse for investigating the minority buildings for several reasons. One of the most significant reasons is that since the end of the 20th century, sustainability scientists, experts, and the 21 agenda (Rio De Janeiro Summit, 1991) have called for all sectors worldwide, without any exclusion, to take seriously all the issues of sustainability and environmental protection including energy efficiency and the reduction of carbon dioxide through achieving thermal comfort. Another reason is that the results from the literature review showed that other sectors, especially the residential sector in Saudi Arabia, have been extensively over-investigated and studied, unlike mosque buildings.

In addition, mosque buildings are considered as public buildings that accommodate so many worshipers to perform at least five prayers everyday by religious obligations. Besides, in some events, such as Friday congregations, Ramadan (an Arabic blessed month during which Muslims fast), and Eid (special day for Muslims), those mosques will be fully occupied. This could cause significant internal gains by occupancy and therefore could cause significant cooling demands, especially during summer periods and in light of the significant increase in the number of mosque buildings in Saudi Arabia [6]. Since Saudi cities have recently witnessed a boom in urbanization and architecture, consequently the number of mosques has significantly increased from 55,266 in 2008 to more than 94,000 mosque buildings in 2013 [7].

Before that, these sorts of buildings are entitled as "religious buildings" or "Allah Houses," therefore they are deliberated as symbols of Islam. Numerous verses in the Holy Qur'an specify that the Merciful God ordered all of us not to discard and excessively extravagance the natural life assets and sources, and urged all of mankind to preserve the nature. As a result, it is crucial for mosques wide-reaching to imitate the Lord's instructions to include the duties concerning the conservation of the environment at first place [3].

Therefore, unless applying passive cooling and heating techniques and sustainable operation systems based on environmental study results, there will be very large negative impacts on the environment, which is not admirable when considering such sacred buildings and which represent Islamic regulations and policies toward the protection of the environment. Thus, in order to find ways suggesting suitable environmental solutions and achieving sustainability and zero carbon emissions for different sector problems, mosque buildings as a sector of buildings has been targeted and adopted in this study.

The aim of this study is to investigate what level thermal comfort is achieved and related issues in mosque buildings in Abha city, which has a semi-arid moderate/cold mountainous climate by using TAS software. A number of comparisons of the simulation results with actual measurement data were conducted whenever it is applicable. In addition, main variables influencing thermal comfort and PMV were also investigated in this article. Besides, thermal performance of mosques' envelopes in

terms of solar gain and heat loss/gain by conduction and its impacts on thermal comfort and energy demands were also discussed.

2. Literature Review

The interest in studying mosques in relations to thermal comfort and energy saving started around two decades ago in the very end of the 20th century. It seems that the previous researchers did not pay more attention to this topic during the first decade compared to the second decade of this century. During the second decade of this century (since 2011 until 2020), the researchers show more interest in this field as seen in the following sections.

2.1. Thermal Comfort and Energy Performance in Mosque Buildings

A study started during 1998 and published in 2003 investigated different sizes of 20 mosque buildings in hot, arid areas in Saudi Arabia, 19 of which were considered as air-conditioned mosques, and one of which was using a passive and evaporative cooling system by using wind catchers. The aim of the study was to investigate the influence of outdoor weather and temperature (T_{out}) on the energy using the selected mosque buildings in shadow of using different types of air-conditioning systems, including window units, chilled water units, central units, and wind catchers. The researcher utilized a number of assessment methods including questionnaires, interviews, observations, and secondary data collection to gather electricity bills for those mosque buildings as well as the T_{out} for the year 1998. The result of the study was that all of the air-conditioned mosque buildings were consuming significant energy when the T_{out} increased, regardless of size, unlike the one, which used a passive cooling system of wind towers [6].

In another study, which aimed to investigate energy use and thermal comfort conditions in three mosque buildings in the hot, humid city of Dammam in Saudi Arabia, the researchers monitored the energy use of the selected three mosque buildings by using special instruments and gauges to record the energy used by air-conditioning systems, fans, and lights for the year 2002. Another 15 instruments were used to monitor indoor temperature (T_{in}) and relative humidity (RH) in all of the selected mosque buildings for the same whole year. The results revealed that occupants were dissatisfied with thermal comfort levels in the uninsulated mosque buildings, although those mosques showed high-energy usage, unlike the insulated ones, which showed lower energy usage and better thermal comfort [8].

In addition, six of Friday (Juma'ah) prayer air-conditioned mosque buildings from different provinces in Kuwait, which were classified by the researcher as hot, arid areas, were investigated during 2007 in terms of indoor climate and thermal comfort of the selected mosque buildings in another study. The researcher used specific instrument stations to measure T_{in} , RH, air velocity (V_a), and operative temperature (T_{op}), as well as questionnaires to examine the influence of the main factors affecting the acceptable level of thermal comfort for worshippers inside mosque buildings. The result of the study revealed that actual mean vote (AMV) was 26.1 °C, while predicted mean vote (PMV) was 23.32 °C, which gave an underestimation of around 2.8 °C. It is also found that the T_{op} of 26.1 °C showed significant and considerable energy savings when applied on mosque buildings in Kuwait [9].

Another simulation study was conducted to investigate the thermal performance of a typical mosque building and energy conservation in Kuwait by using visual DOE 4.1. About 72% of potential energy savings was obtained when applying improved fabrics and when applying operational strategy [10].

Moreover, a different study examined the effects of the operational zoning strategy on energy consumed by the HVAC systems in many mosque buildings in the hot, humid Eastern province of Saudi Arabia. Visual DOE as simulation software, instruments to monitor energy use, and instruments to record T_{in} were used as evaluation methods for the selected mosque buildings. The result revealed that significant annual reductions in energy could be obtained when operating A/C properly, with around 36% of potential annual energy reduction for uninsulated mosque buildings and about 23% for insulated ones. Another finding showed that there was a significant annual energy reduction when oversizing

and operating A/C an hour before each prayer time and before the arrival of worshippers to perform prayers with an average percentage of around 30% [11].

Furthermore, a study conducted on a mosque building in a hot and humid city, Sarawak in Malaysia, aimed to investigate thermal comfort conditions in light of allegations of high technology design of that mosque building. A number of specific instruments to measure T_{in} , V_a , RH, and MRT, additional to Energy Plus simulation software to investigate thermal performance of the mosque's fabrics, were utilized as evaluation techniques. The result revealed that the high-technology mosque building showed discomfort; since T_{in} exceeded the acceptable level of thermal comfort most of the experiment day hours. It was also found that heat gain through the roof was the main reason behind the discomfort, since it rapidly absorbed solar radiation and then transferred the heat inside the mosque through the roof, causing increases of T_{in} and thus discomfort. Some suggested improvements were recommended, including installing internal roof insulation, since it showed a considerable enhancement for T_{in} [12].

A scientific paper published in 2016 aimed to examine a number of mosques in various types of climates around the world considering the operation systems used for heating or cooling. It analyzes the influence of mosques' features used to cope with the climate for each mosque and the chances to replicate those kinds of features somewhere else were also investigated. It also examined two sorts of methods to include green roof and louver shading and its impacts on indoor temperature for a selected mosque in Riyadh, which has a hot-dry climate by using Design Builder v4.5 for 3D drawings and Energy Plus v8.3 for computer modelling. The researchers found a promising reduction in cooling demands of around 10% when using the combination of green roof and louvers shading [13]. Afterward on 2017, two authors of the previous study's authors published a paper carrying on the same aim of the previous study but investigated different options of roofs' combinations for a new selected mosque in Riyadh. The outcomes display an encouraging reduction in cooling load for the hot arid climate, specifically when applying the combination of insulated roof and green surface compared to other roof options [14].

Moreover, a research paper published in 2018 investigated different types of air distributions and its impacts on the indoor thermal comfort by using Fanger's PMV index. It also examined three systems of air distribution at four diffuser station velocities by utilizing EnergyPlus and CFD software for computer modelling. The results showed significant discrepancies in the performance of air distributor compared to each type of air distribution system and diffuser station velocities. It also showed that the majority of cases indicted that the indoor spaces were overcooling with around -0.66 or lower of PMV [15].

A recent study published early this year (2020) assessed the passive design techniques that were implemented in three selected mosque buildings in Malaysia, especially those in colonial style, and its influences on the indoor environment. The researchers classified the types of mosques styles into three main classifications: vernacular, colonial, and modern. However, the researchers have selected the colonial style. This style affected by western architecture, as it was brought in to Malaysia by western colonialism. Therefore, the study aimed to investigate to what extend those kinds of mosques will cope with the climate in Malaysia. The study used observation method to collect data and a computer modelling to simulate and analyze indoor environment for the selected mosques. The results showed that all of the selected mosques were significantly responsive to the climate of Malaysia. It was found that all of the selected mosques utilized five passive techniques and verandah passive technique has the most noteworthy effect, since it provides shield on the openings from solar radioactivity. It was also found that the dome as a colonial feature forms a great void in the roof which reduces the roof area and thus protects the indoor environment from sun radiation [16].

However, the efforts that have been shown by the previous studies were considered as inadequate and limited, especially for the studies investigating thermal comfort and energy conservation in mosque buildings, and when compared with the other building types. In light of the above, it is found that mosque buildings in hot-humid and hot-arid climates were intensively investigated compared

with the other types of climates. In addition, there are several variables and factors that can influence the acceptable level of humans' thermal comfort and thus energy use, to which previous researchers have not paid enough attention. Therefore, this study aims to be a comprehensive study focusing on a number of methods of assessments related to thermal comfort (to include PMV, DBT, RH, MRT, and T_{Res}). It also investigates thermal performance of mosque buildings' envelope, and the effect of solar radiation on the energy usage and thermal comfort in the selected mosque buildings. As well as, it considers different type of climate on which previous researchers have not paid more attention to, which is called semi-arid moderate/mountainous climate of Abha city. All of the previously mentioned variables and issues related to mosque buildings in one study to allow more comparisons hence make a considerable addition to this field.

2.2. Thermal Analysis of Buildings and Simulation Software

For the purpose of this research, simulation and model as terminologies are treated as identical. Model as a term is utilized to symbolize more than merely exemplifications like a specific scale model of a building. Specifically, it is a reproduction of social-cultural factors and natural regulations that are incorporated in the interfaces of the actual world. It can be used for a diversity of practices that range from scientific and immaterial numerical expressions to physical practices. The theoretical assumption for simulation inquiry is that understanding of a truth can be attained by imitating that actuality in some auxiliary tools to predict the real future [17]. It is identified in four basic sorts of simulation: iconic models for suggested products, analogue models to simulate an environmental condition, operational models that involve life subjects' interfaces, and mathematical models [18].

Selecting appropriate software for simulating the selected mosque buildings can fulfil the aim and objectives of this research is important. Therefore, a number of previous studies have been surveyed to discover the pros and cons of widely used thermal simulation tools and software. Over the previous five decades, some hundreds of building energy and thermal simulation programs have been invented, developed, and are in practice. Since then, the most commonly used programs have been comparatively surveyed and published as reports, papers, and studies [19].

A comparative study conducted by Ahmed and Szokolay (1993) to compare the most commonly used thermal simulation tools in Australia, stated that the package called Thermal Analysis Simulation (TAS) software has full-fledged features, which range from a 3D CAD module for front-end simulation, to computerized fluid dynamics (CFD) for airflow studies [20]. Another significant overview surveyed and compared the features of the 20 major building energy and thermal programs, including TAS software, concluded that TAS is one of the most comprehensive and practical programs among those commonly used programs [19]. Joshua Kates (2010) stated that TAS software offers a precise vision for the response of building fabrics and envelopes, as well as space and surface temperatures, internal loads and energy-use. In a recent PhD study conducted by Saleh (2011) to choose suitable simulation software to carry out her study, she comparatively and intensively investigated in depth two of the commonly used simulation programs, which are Ecotect and TAS software. She conducted many simulation processes and variety examinations for a small and simple cube (9x9x9m) to investigate and compare most of both programs' features, including thermal performance, ventilation, solar gain, and shading. Based on a number of findings, she finally selected TAS software for her major study instead of Ecotect program, as she found it extra inclusive and more precise, although it being more composite [21].

Therefore and based on the previous discussion, TAS software has been adopted in this study. It is considered to be comprehensive, containing most of the features needed for this study. Not only that, but it is an accurate software especially for the variables that have been investigated in this research, compared to the other software discussed earlier.

2.3. Background of Abha City and Its Climate

Saudi Arabia is one of the Middle Eastern countries with an estimated area of 2,331,000 km² [22]. It has a number of different types of topographies that play significant role in determining the dominant climates in Saudi Arabia. It has long two coastal plains including a long western coast (hot/moderate and humid climate) and eastern coast (hot/cold and humid climate). The dominant topographies in Saudi Arabia are sand deserts and plateaus (hot/cold and arid desert climate) in which the capital city of Riyadh city is located. It also has a long chain of mountains called western heights (moderate/cold and mountainous climate) in which Abha is located [22–24].

As far as the current study is concerned, Abha city is the capital city of Asir Region and it is located in the south-western part of the country, to the south-west of the Western Heights with a longitude of 52.5° E and a latitude of 18.2° N. The climate of Abha (moderate/cold and mountainous) is influenced by the location, since it is located above the mountains at a height ranging from 2200 m to 3200 m above sea level. The climate in Abha is characterized by moderate temperatures and being a little humid, especially in the winter. There are also large diurnal temperature swings between daytime and night-time, since the maximum mean of temperature ranges from 27 °C to 33 °C, and occasionally reaches 35 °C, while the minimum ranges from 15 °C to 20 °C, forming diurnal summer temperature swings with an average ranges from 12 °C to 15 °C. In addition, the humidity ranges from 40% to 82% in the summer. The solar radiation reaches a maximum of around 6.9 kWh/m² when the days' lengths become longer with an average length of about 13:40 h during the month of June in the summer. In terms of precipitation and rain, the rain falls during the whole year and increases during the summer, since it is influenced by subtropical high pressure, reaching its peak of around 11 cm during August [25].

On the other hand, during the winter, it is considered as cold, since the maximum temperature ranges from 15 °C to 23 °C, and the minimum ranges from 5 °C to 13 °C, and occasionally falls below 0 °C, forming also large differences of winter temperature swings with an average ranges from 10 °C to 13 °C. The humidity usually increases during the winter, since it ranges from 48% to 92% and sometimes reaches 95%. The solar radiation may decline to be as low as 4.5 kWh/m² when the days are as short as 11:10 h. As mentioned previously, rainfalls during the whole year and increases during the summer, however it falls during the winter influenced by Atlantic winds causing rainfall to peak around 4 cm during March. Moreover, Abha city is affected by the cloud cover and fog during the winter season, reducing the visibility to be as low as 5 km [25].

2.4. Background of Mosques Buildings

What distinguishes these buildings is that, in addition to the sacredness of mosque buildings, the architectural features and parts, these buildings are characterized by the importance of religion for around a billion-and-a-half Muslims in the world. Furthermore, the importance of mosque buildings lies in the importance of the activities that are performed in such sacred and holy places, such as the five daily prayers. Therefore, feeling comfortable is very important to reach peace and serenity by worshippers inside mosque buildings [12].

The architectural design of mosque buildings is usually affected by various factors and considerations including religious, cultural, and climatic variables [8,11]. In term of religious or worshipping influences, there are two main styles inside the mosque buildings. The first style is the prayer, which involves a number of actions including standing, bowing, prostrating, and sitting [8,12]. Worshippers while praying should stand in straight and parallel rows with spaces between one row and another of about 1.2 m facing the qiblah. The second style is sitting for the worshippers while the Imam stands on the pulpit (minbar) and delivers the speech (Khutbah). Therefore, the capacity or the area necessary for each worshipper to comfortably execute the prayers in the prayer hall can be estimated as $0.8 \times 1.2 = 0.96 \text{ m}^2$ [8].

Most mosque buildings are built simply in large, rectangular shapes [8,9,11]. One of the most important architectural parts of the mosque is the prayer hall, which is occasionally presumed as the

holy space. Usually, the prayer hall area is enormous and open to allow more worshippers in so they can perform their daily five-time prayers, Eid festival prayers, or Friday (Juma'ah) prayers [26,27]. In addition, the prayer hall usually consists of a vast, open-plan, high-ceiling, and enclosed room. The longest wall of the rectangular area is usually called the qiblah wall, since it is oriented to the direction of Makkah [8,9,11] as all mosque buildings worldwide must face the qiblah, which is Al-Ka'abah in Makkah city [28]. Therefore, for Abha mosque buildings, normally the qiblah walls are the Northern walls (Figure 1).

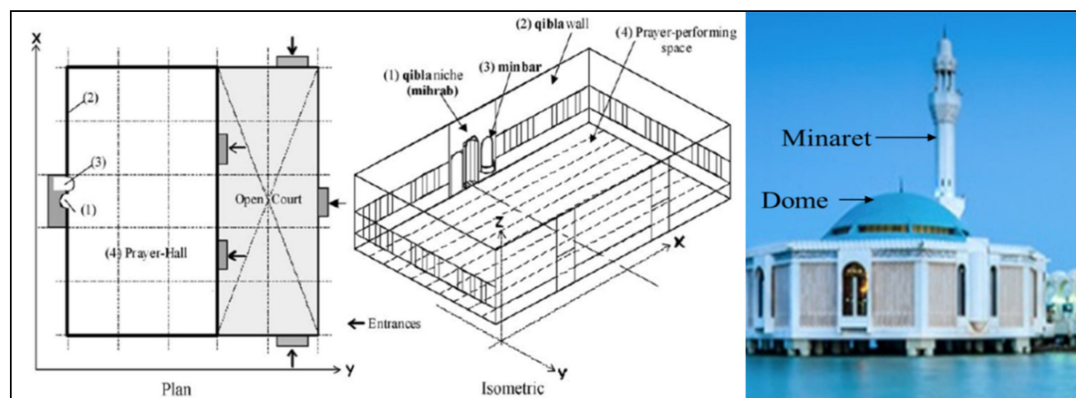


Figure 1. Architectural design elements of a simple mosque building. Reproduced figure based on [29].

The qiblah wall has an important architectural element, namely niche (mihrab). It is usually located in the middle of the qiblah wall and it denotes the qiblah. It is usually built in different sizes and shapes, such as semi-circular or square plans. It is basically used by the leader (Imam) of the congregation when performing the prayers [8,9,28]. To the right of the niche (mihrab) and in the same qiblah wall, there is another element called the pulpit (minbar), which should be the highest place inside the prayer hall [8,9]. It should be raised around 1–2 m above the floor level of the prayer hall [8,12]. It is normally used by the Imam during Juma'ah, Eid, and Estisga' prayers to deliver a speech or what is called khutbah [30] (Figure 1).

With regard to the mosque building's external appearance, most mosque buildings are covered by different shapes and sizes of domes or attics, which are usually located in the middle and on top of the roofs [9]. A dome is usually structured to form half a sphere, which is usually used for several reasons. One of the reasons is that domes are used to reduce the number of columns inside the prayer hall [28] allowing more space for the worshippers and allowing eye contact with the leader (Imam) while delivering the speech (khutbah). Another reason is to allow more natural daylight to penetrate through the skylights that are designed on those domes. The other reasons may refer to the ornamentation and symbolization (Figure 1).

Another important architectural element, which is considered as the symbol of mosque buildings, is the minaret. Most mosque buildings have at least one minaret located on one corner of the mosque building [9]. It is considered as the highest point of the mosque and should be the highest in the district, since it is usually used to deliver the sound of prayers call (Atha'n) as far as possible to remind Muslims with the times of prayers (Figure 1).

3. Research Framework and Methodology

The following sections present the adopted research method in this study, which is TAS simulation software, and the criteria that have been considered to select this software. Section 3.3 for the criteria has been considered to select those mosque buildings and the description of the case studies. Section 3.4 presents the constructions, materials, and the input data that have been used in TAS software for the simulation processes based on real data collected from the authorities responsible for building those mosques as follows.

3.1. Research Method

The strategy and research method that has been adopted in this research, is a computer modelling study using TAS simulation software. The selection of this software came after a number of investigations as discussed earlier in Section 2. In addition, some simulation programs have been generally investigated by researcher before adopting any simulation programs. Those programs include EDSL Tas, Ecotect, Energy Plus, and IES. A number of interviews have been conducted with a number of PhD students who have experienced such programs. Moreover, the following criteria are considered as the base for the selection procedures. These major guidelines have been taken into account, in addition to the previous discussions, as follows:

- The ability of the software and its features.
- Its accuracy in carrying out the output and simulation results.
- Ease of use and clarity of the application interface of the software.
- The databases that the software has, such as the building materials database and the ability to upload new data.
- The novelty and modernity of the software.
- The cost of the software.
- The possibility of being installed by the IT department at the University.
- To what extent learning this software can be beneficial in the future.

In conclusion, after the previous discussion, TAS software has been adopted in this study. It is considered to be comprehensive, meeting most of the previous criteria and containing most of the features needed for this study. Not only that but, it is an accurate software especially for the variables investigated in this research. Factors and parameters such as DBT, RH, and MRT that influence occupants' thermal comfort, additional to the mosque buildings' thermal performance will be investigated and assessed. Thermal comfort, load breakdown, and demand for each mosque building will be predicted and estimated by using this (TAS) software.

Before starting to discuss the outcomes of the major simulation study, it is worth to highlight the description of the case studies and the input data have been used and entered in the TAS simulation software, as presented in the next sections. Then in a number of sections, the results and outcomes of the simulation processes will be discussed.

3.2. The Selection of the Case Studies

In order to select mosque buildings as case studies in Abha city, there are a number of criteria that have been considered as sampling procedures. These criteria helped and guided the researchers to determine the case studies of mosque buildings and are listed as follows:

- The size and capacity of mosque buildings.
- Design considerations.
- The age of mosque buildings.
- The availability of information for the selected mosque buildings.
- Problems which have been discovered by people in charge who are responsible for operating mosque buildings, such as increased electricity bills for some mosques compared to others.
- Based on the city map, main roads and the city's nature, the city has been divided into different regions from which the researchers can determine at least three for each region to be adopted as case studies, and then select three for the city as seen in Figure 2.

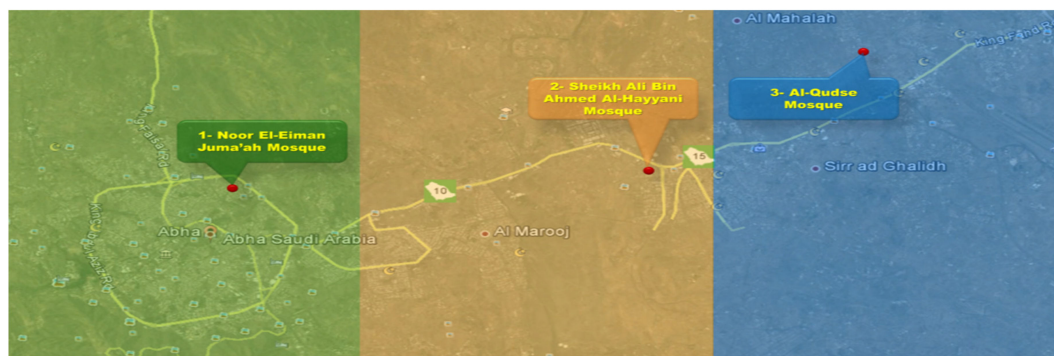


Figure 2. The location of the selected mosque buildings in Abha city.

3.3. The Description of Case Studies

With regard to the case studies, three of large and small mosque buildings in Abha city were selected and investigated in this study (two of which are considered as daily prayers mosques and one Juma'ah or Friday mosque), as seen in Table 1 (and Supplementary Materials). The areas of these selected mosque buildings range from the smallest mosque building, called Al-Qudse mosque building (QA-3) with an area of around 180 m² to the largest area for Noor El-Eeman mosque building (NEA-2), which is about 625 m². The capacity of these mosque buildings, measured in people, ranges from the smallest (five daily prayers) QA-3 mosque building of around 155 people to 650 people for NEA-2 the largest (Friday and five daily prayers) mosque building's capacity (Table 1).

Table 1. Details for the selected case studies of mosque buildings in the selected city of Abha.

	Mosque Name	Mosque Image	City	District	Type of Mosque	Capacity (People)		Area (m ²)
						Full Capacity	Reality of Occupation	
1	Al-Sheikh Ali Al-Hayyani (AHA-1)		Abha	Al-badee	Regular for five daily prayers	375	55	20 × 20 = 400
2	Noor El-Eeman (NEA-2)			Assamer	Juma'ah or Friday prayer + Regular	650	650	25 × 25 = 625
3	Al-Qudse (QA-3)			Hijlah	Regular for five daily prayers	155	45	15 × 12 = 180

3.4. Input Data for Simulation Process

Input data are considered an important stage in any thermal simulation process of a building, since the quality of the input data for any building of interest will determine the precision of the outcomes of its simulation processes [21,31–33]. Therefore, during the field studies and experiments, the envelope, fabrics, materials, windows, doors, internal gain (occupants, lighting, and equipment), and HVAC systems for the previously mentioned mosque buildings (Table 1) were identified by observing or by interviewing mosque authorities as seen on (Appendix A). The thermal properties for all mosque buildings, such as the types of insulation and the thicknesses of walls etc., were obtained from the Ministry of Islamic Affairs (MOIA) and some other architecture agencies.

In addition, the electricity bills for all mosque buildings were obtained from SCECO. The internal gains (occupant, equipment, and lighting) were calculated based on TAS requirements (W/m²) and according to those provided by CIBSE guide-A [33]. The limits for the thermostat have been placed at 20 °C for the lower limit and 24 °C for the upper limit according to ASHRAE standard [34] and

SBC [35,36]. Abha weather file in the extension of IWECC provided by ASHRAE was used. The default calendar is that provided in the TAS database and is used with some changes to match Saudi weekend days.

In terms of the construction of a mosque building and its thermal properties, the external walls are constructed from concrete blocks without any insulation; therefore, it is considered as a thermally lightweight building. In addition, there is no thermal insulation in the roof, although it does have water insulation. It should be mentioned here that the materials described previously are considered as the typical materials that are used in each mosque building as seen on (Tables A1 and A2). However, there are some small alterations in some materials depending on each mosque's building design and specifications, including some changes in the materials' thicknesses and colors, and that was considered in this study.

4. Results and Discussion

This part discusses the outcomes of the simulation processes that have been conducted to investigate major parameters that influence occupants' level of thermal comfort in the main prayer zones for all mosque buildings in both seasons by using TAS simulation software. Comparisons between the outcomes of the winter and the summer will be discussed. In addition, comparisons between the outcomes of the simulation processes and the field studies results (previous studies that have been done by the researchers, see Appendix A for the instruments have been used) will be discussed wherever possible.

4.1. Dry Bulb Temperature (DBT)

Dry bulb temperature (DBT) is one of the variables that TAS software can analyze and it is considered as one of the main factors affecting the thermal comfort. Figure 3 presents DBT compared with T_i result from field studies in the main prayer zones for all mosque buildings and T_{out} in Abha city for days in both seasons (winter and summer).

The outcomes display that there are significant discrepancies between DBT (from the simulation processes) and T_i (based on collected data from the field studies using a thermometer with data logger with an accuracy of ± 1.8 °F/1.0 °C, see Table A3 for the instruments have been used) in all mosque buildings, especially in the winter (Figure 3a), except in Al-Qudse (QA-3) mosque building (Figure 3e), where the results were close to each other, although there is not a large divergence between TAS DBT and field study T_i in the summer (Figure 3b). There are also noticeable discrepancies between TAS T_{out} and field studies T_{out} in both seasons for all experiment days, which could be a possible reason behind the discrepancies. In addition, the number of occupants as an input was not matching the reality in all prayers in all of the selected mosque buildings. As it is known that the number of users (internal gain by occupancy) coupled with outdoor weather affect significantly the results of indoor temperature. This is the problem when studying public buildings such as mosque buildings, where the number of occupants vary and cannot be anticipated as the same as reality. Since it really varies and differs from time to time compared to other type of buildings such as residential office, or school buildings, in which we can predict the same number of users as in reality. Another reason is that the conditions in all of the mosques were entirely controlled during the prayer times and then they were on free running modes (without using active cooling/heating systems, which is the opposite of controlled mode) out of the prayer times when using TAS simulation processes to assess the indoor environments and that could explain the fluctuation trends of the DBTs for all of the mosques. On the other hand, the conditions were also fully controlled during the prayer times, and partly controlled out of the prayer times (one A/C unit was operated for the working team), especially during the summer experiments' days in all of the mosques.

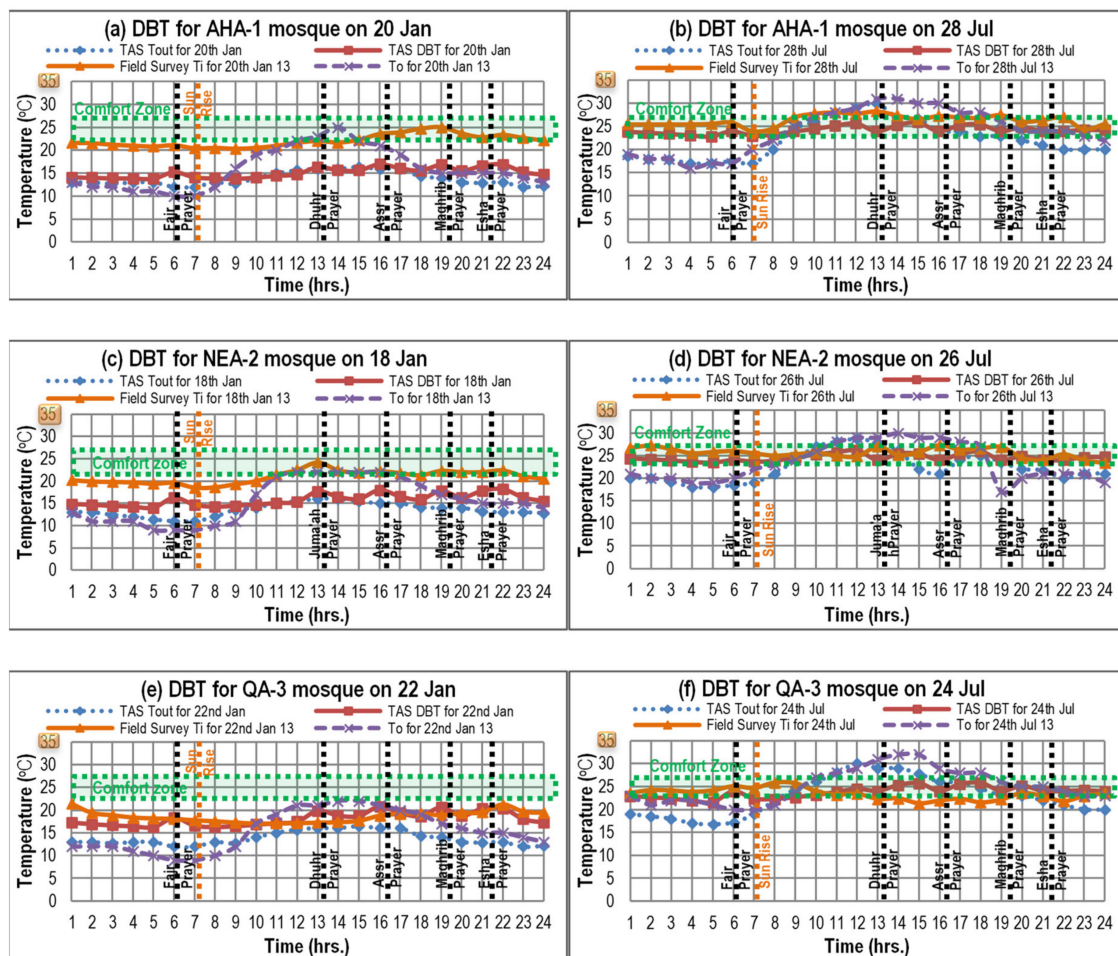


Figure 3. DBT compared with T_i from field studies in both seasons in: (a) AHA-1 mosque on 20 January, (b) AHA-1 mosque on 28 July, (c) NEA-2 mosque on 18 January, (d) NEA-2 mosque on 26 July, (e) QA-3 mosque on 22 January and (f) QA-3 mosque on 24 July.

The DBT ranges from 14 °C (out of prayer hours) to 21 °C (during the operation hours) in all mosque buildings in the winter, while it ranges from 21 °C to 26 °C in the summer. It is also noticed that the trend of DBT is influenced significantly by the internal gain and conditions, since it increases dramatically during the prayer times in the winter days, while it declines radically during the prayer times in the summer days, except in all Fajr prayers in the early morning hours, since no air conditioning systems were operating (Figure 3).

In addition, it is noticed that DBTs in all mosque buildings were out and below the thermal comfort zone, particularly in the winter (Figure 3a), while it was within thermal comfort limits, especially during prayer times in the summer (Figure 3b). Moreover, the results may also indicate the poor quality of the mosque buildings' envelopes in Abha mosque buildings, because of the simultaneous and significant changes in DBT during the operation hours (prayer times) and closing hours of the mosque buildings. This may indicate great heat gains and losses through mosque buildings' fabrics.

4.2. Relative Humidity (RH)

Relative humidity (RH) is one of the variables that TAS software can investigate and it is considered as one of the main factors that affect thermal comfort. Figure 4 presents the indoor and outdoor RH (%) from TAS compared with indoor and outdoor RH from field studies in the main prayer zones for all mosque buildings in Abha city in both seasons' days (winter and summer) as follows.

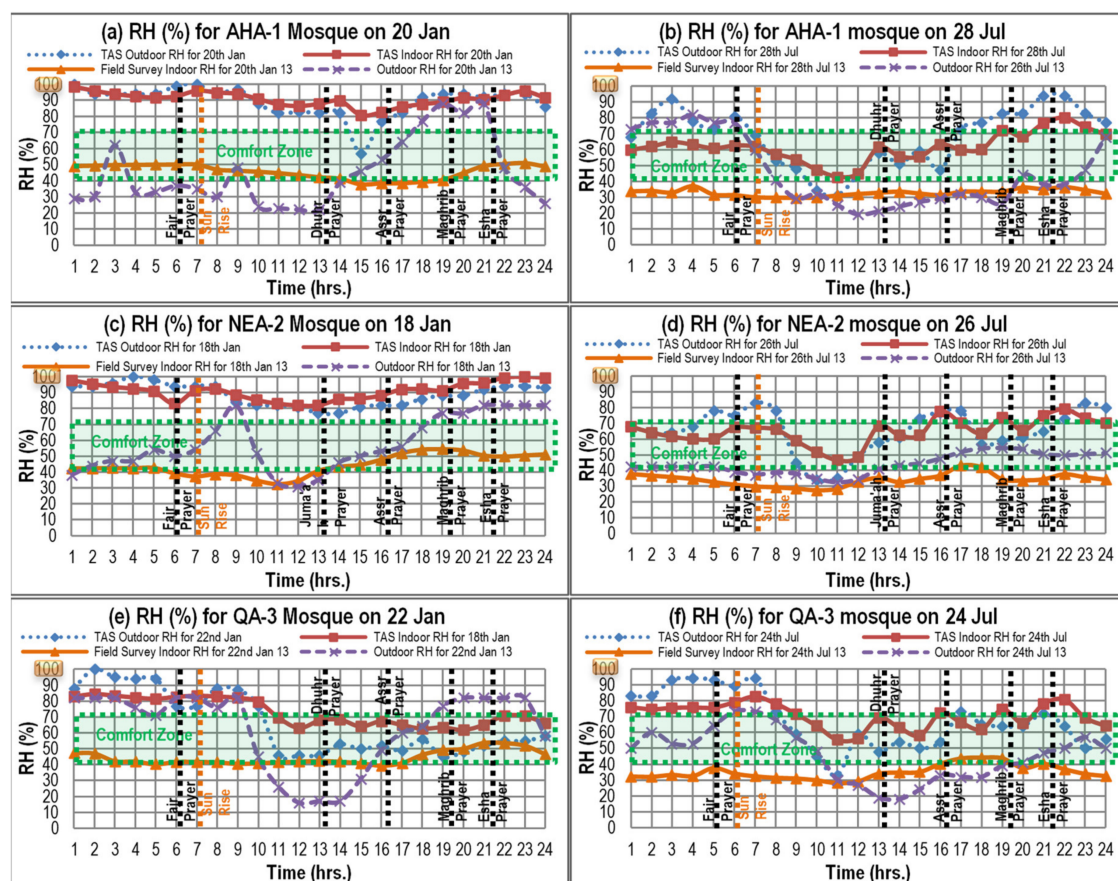


Figure 4. RH (TAS) compared with RH (field studies) for both seasons in: (a) AHA-1 mosque on 20 January, (b) AHA-1 mosque on 28 July, (c) NEA-2 mosque on 18 January, (d) NEA-2 mosque on 26 July, (e) QA-3 mosque on 22 January and (f) QA-3 mosque on 24 July.

The outcomes display that there are significant discrepancies between TAS and field studies indoor RH in all of the mosque buildings in both seasons. There are also great divergences between TAS and field studies outdoor RH in all mosque buildings in both seasons and this may explain the large discrepancies for indoor RH. In addition, the number of occupants as an input was not matching the reality in all prayers in all of the selected mosque buildings. As it is known that the number of users (internal gain by occupancy) coupled with the outdoor RH affect significantly the results of indoor RH. This is the problem when studying public buildings such as mosque buildings, where the number of occupants vary and cannot be anticipated as the same as reality. Since it really varies and differs from time to time compared to other type of buildings such as residential office, or school buildings, in which we can predict the same number of users as in reality. Another reason is that the conditions in all of the mosques were entirely controlled during the prayer times and then they were on free running modes (without using active cooling/heating systems, which is the opposite of controlled mode) out of the prayer times when using TAS simulation processes to assess the indoor environments and that could explain the fluctuation trends of the DBTs for all of the mosques. On the other hand, the conditions were also fully controlled during the prayer times, and partly controlled out of the prayer times (one A/C unit was operated for the working team), especially during the summer experiments' days in all of the mosques.

It also revealed that TAS indoor RH was mostly above the upper limit of RH comfort (70%), particularly during prayer hours in the winter (Figure 4a), although most of the times it was within the limits of RH comfort in the summer experiment days (Figure 4b). This means that most of the indoor environments in all mosque buildings may experience wetness, especially in the winter (Figure 4a,c,e) and some hours in the summer.

It is also noticed that outdoor RH is a bit higher in the winter (Figure 4a,c,e) than it is in the summer (Figure 4b) and the effect on indoor RH was noticeable in both seasons. In addition, it is seen that indoor RH was also influenced significantly by the internal gain and conditions, since it increased dramatically during mosque buildings' opening hours and dropped immediately after closing the mosques buildings (Figure 4).

4.3. MRT and T_{Res}

It is believed that mean radiant temperature (MRT) is considered as one of the key influences manipulating thermal comfort. Resultant temperature (T_{Res}) is also considered as an important temperature index for thermal environment, which is operative temperature T_{op} . MRT is the result of glob temperature (T_g) subtracted by 0.6 and multiplied by T_i divided by 0.4. It has also a great impact on T_{Res} as an important thermal comfort index. The impact of MRT on T_{Res} is subject to clothing, since its effect would be around twice as great as T_i with light clothing in a warm environment (summer), whereas it has the same influence of T_i with heavier clothing during a cold period [37].

It is worth highlighting that the plan was to conduct the field studies in free-running buildings in both seasons (winter and summer). However, harsh weather was the main reason behind not conducting the field studies in the mosque buildings without switching on the air conditioning systems, especially in the summer. Additionally, the authorities did not allow conducting the field studies in the mosque buildings without switching on the air conditioning systems, especially during prayer hours particularly in the summer period, since the indoor environment were not bearable inside the mosques without thermal control and that may affect the worshipers negatively. Therefore, free-running MRT and T_{Res} for all mosque buildings were estimated in this part using TAS simulation software as presented in the following Figure 5 in different days in the winter (shortest day, coldest day, and typical day) and the summer (longest day, hottest day, and typical day).

The results display that there are no significant differences between MRT and T_{Res} in both seasons' days in all mosque buildings. It is also noticed that internal gains affected both MRT and T_{Res} , especially in the winter in all mosque buildings, since both temperatures increased during opening hours and declined in closing hours. In addition, MRT and T_{Res} were just below the acceptable ranges (which ranges from 19–21 °C for winter and from 22–24 °C for summer considering the activity and I_{clo} based on CIBCE Guide). Since both temperatures ranged from 13 °C to 20 °C in the winter days, they were within the acceptable ranges with an average of around 25 °C for both temperatures in the summer days. Moreover, it is also observed that MRT was almost equal or very close to T_{Res} during all of the experiment days in both seasons, the winter and the summer, considering the impact of low T_g or surrounding surfaces temperatures (Figure 5).

4.4. The Predicted Mean Vote (PMV)

Several key parameters need to be addressed in order to estimate the predicted mean vote (PMV), which is associated with predicted percentage of dissatisfied (PPD). These parameters include metabolic rate (met), clothing value (I_{clo}), and air velocity (V_a). For metabolic rate, 1.2 met is set for a sedentary person. With regard to clothing value and air velocity parameters, there are two values for each of these two parameters required by TAS, one to be used for the winter and the other for the summer. Therefore, 0.95 clo and 0.15 m/s were set for the winter values, while 0.6 clo and 0.3 m/s were set for the summer values, as also explained previously.

The results indicate that the highest PMV is estimated during the summer, whereas the lowest PMV is predicted in the winter for both modes (free running and conditioned) in all of the three mosque buildings. It is also found that PMV in all mosque buildings was out of the acceptable limits ($-0.5 < PMV < +0.5$), especially with free-running modes (Figure 6).

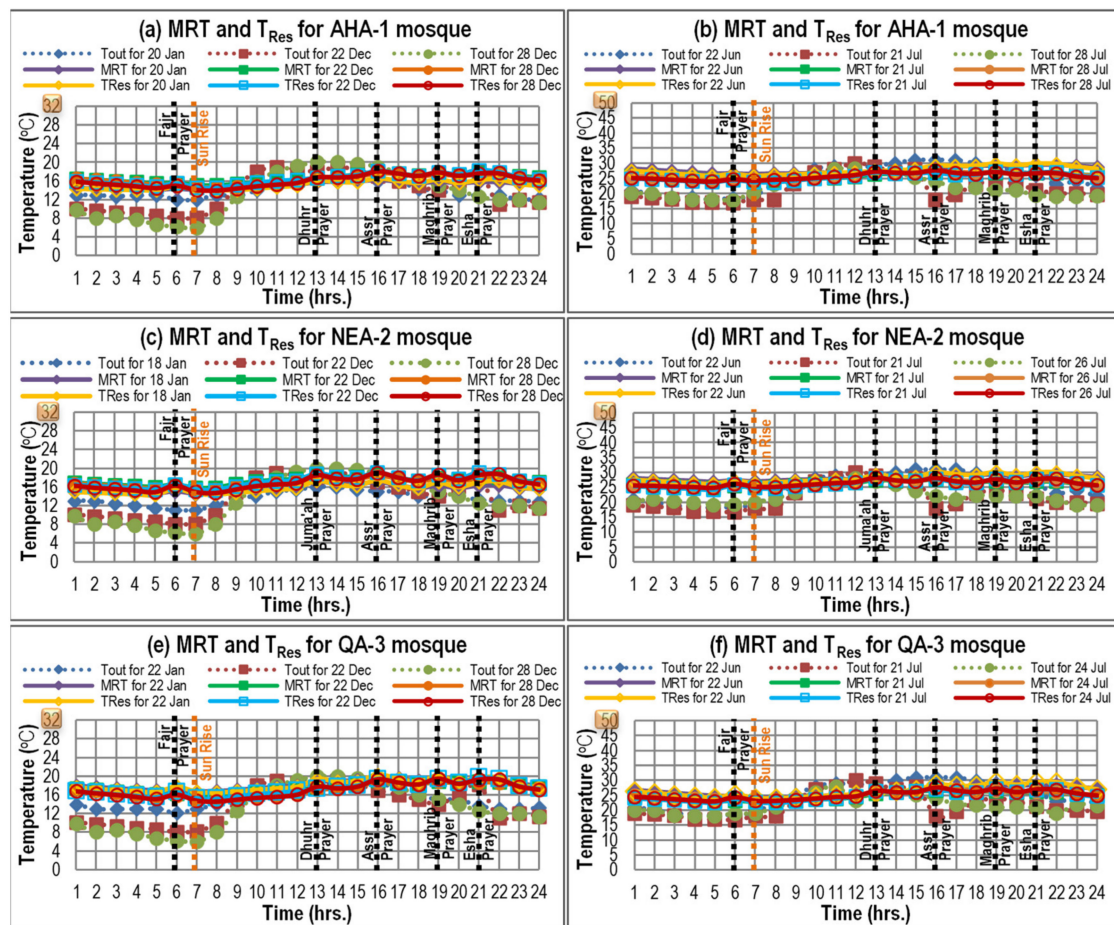


Figure 5. MRT compared with T_{Res} for different days in winter and summer in: (a) AHA-1 mosque, (b) AHA-1 mosque, (c) NEA-2 mosque, (d) NEA-2 mosque, (e) QA-3 mosque and (f) QA-3 mosque.

The results show that there are significant discrepancies between PMV in controlled mode (cases a, c, and e) and in free-running mode (cases b, d, and f). It is observed that PMV in controlled mode for all mosque buildings ranged from -1.69 (in the AHA-1 and the NEA-2 mosques) to $+0.59$ (in the NEA-2 mosque case c), while it ranged from -1.95 (in the AHA-1 mosque case b) to $+1.70$ (in the NEA-2 mosque case d) in free-running mode (Figure 6).

It is also found that the best PMV estimated was in the QA-3 mosque building (case e), since it ranged from -0.94 (out of the acceptable limits) to $+0.41$ (within the acceptable limits) in controlled mode. In addition, the best PMV estimated was also in the QA-3 mosque (case f), since it ranged from -1.45 to $+1.27$, followed by -1.95 to $+1.38$ in the AHA-1 mosque (case b), and the highest PMV was in the NEA-2 mosque (case d) where it ranged from -1.72 to $+1.70$ in free-running mode; however, all of them were out of the acceptable limits (Figure 6).

Furthermore, the minimum average of PMV estimated was in the AHA-1 mosque building (case a) with an average of -0.38 followed by -0.28 in the NEA-2 mosque building (case c) and the maximum average was -0.23 in the QA-3 mosque building (case e) in controlled mode. Whereas, the minimum average of PMV estimated was -0.21 in the AHA-1 mosque building (case b) followed by -0.06 in the QA-3 mosque building (case f) and the maximum average was $+0.04$ in the NEA-2 mosque building (case d) in free-running mode (Figure 6).

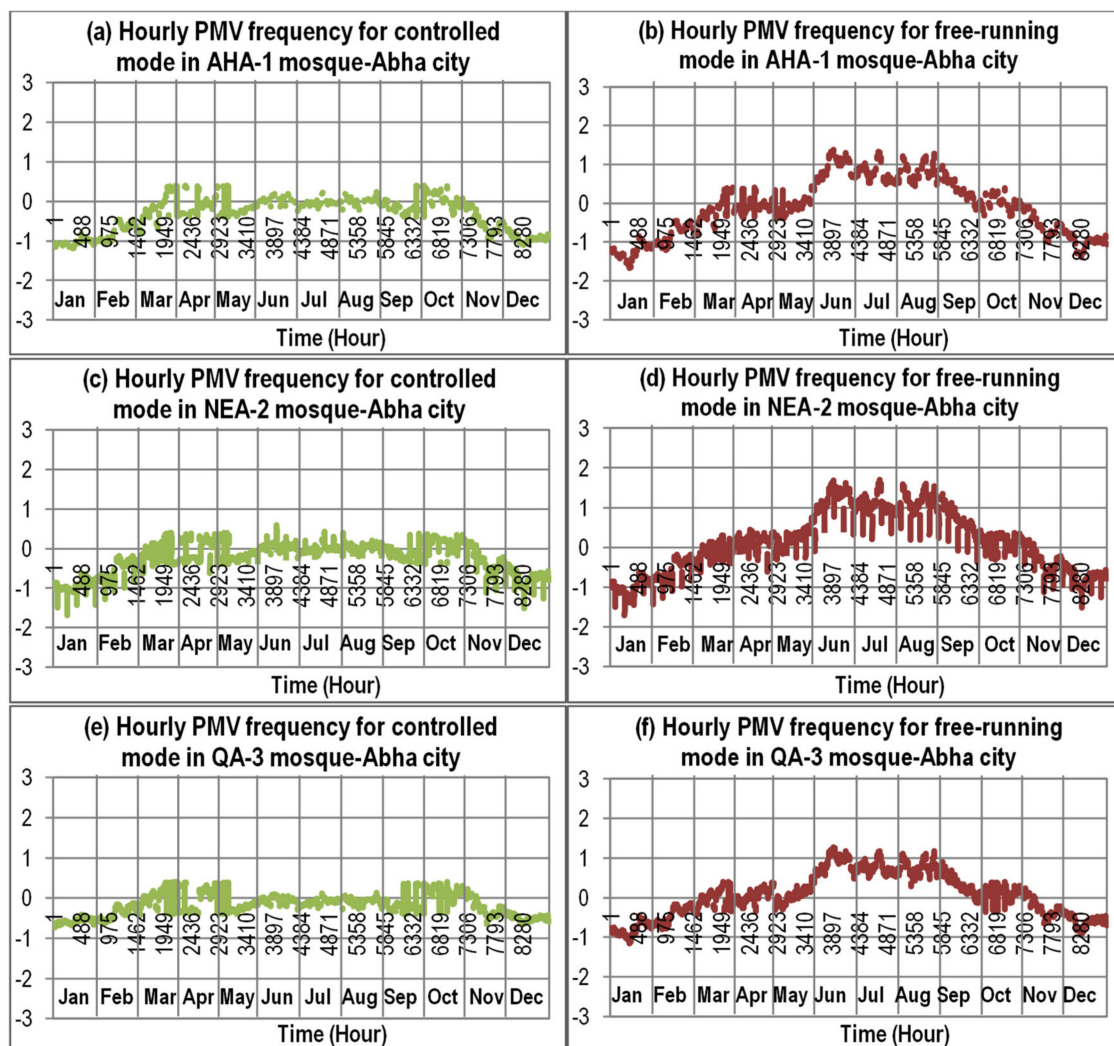


Figure 6. Hourly PMV by using TAS in: (a) AHA-1 mosque (controlled mode), (b) AHA-1 mosque (free-running mode), (c) NEA-2 mosque (controlled mode), (d) NEA-2 mosque (free-running mode), (e) QA-3 mosque (controlled mode) and (f) QA-3 mosque (free-running mode).

4.5. Annual Loads Breakdown

In TAS software, load is broken down into nine variables; however, these nine variables can be re-categorized into six variables instead of nine by gathering lighting, occupant, and equipment gains together to be one variable called internal gain, and external opaque conduction with external transparent conduction together to be under one variable named fabric gain [38]. The following sections discuss estimated loads breakdown and annual loads demand for all mosque buildings.

The outcomes revealed that the significant issue experienced by all mosque buildings is the significant amount of heat gain, which caused significant demands on cooling to remove that heat and to maintain the indoor mosque buildings within the acceptable thermal levels. However, both heat gain and loss were issues that were experienced, although heat gain was more significant than heat loss, therefore the cooling demand was also greater than heating demand in all mosque buildings (Figure 7). It is worth highlighting that the mosque buildings investigated in this study have different sizes and occupant capacities as explained earlier in this thesis.

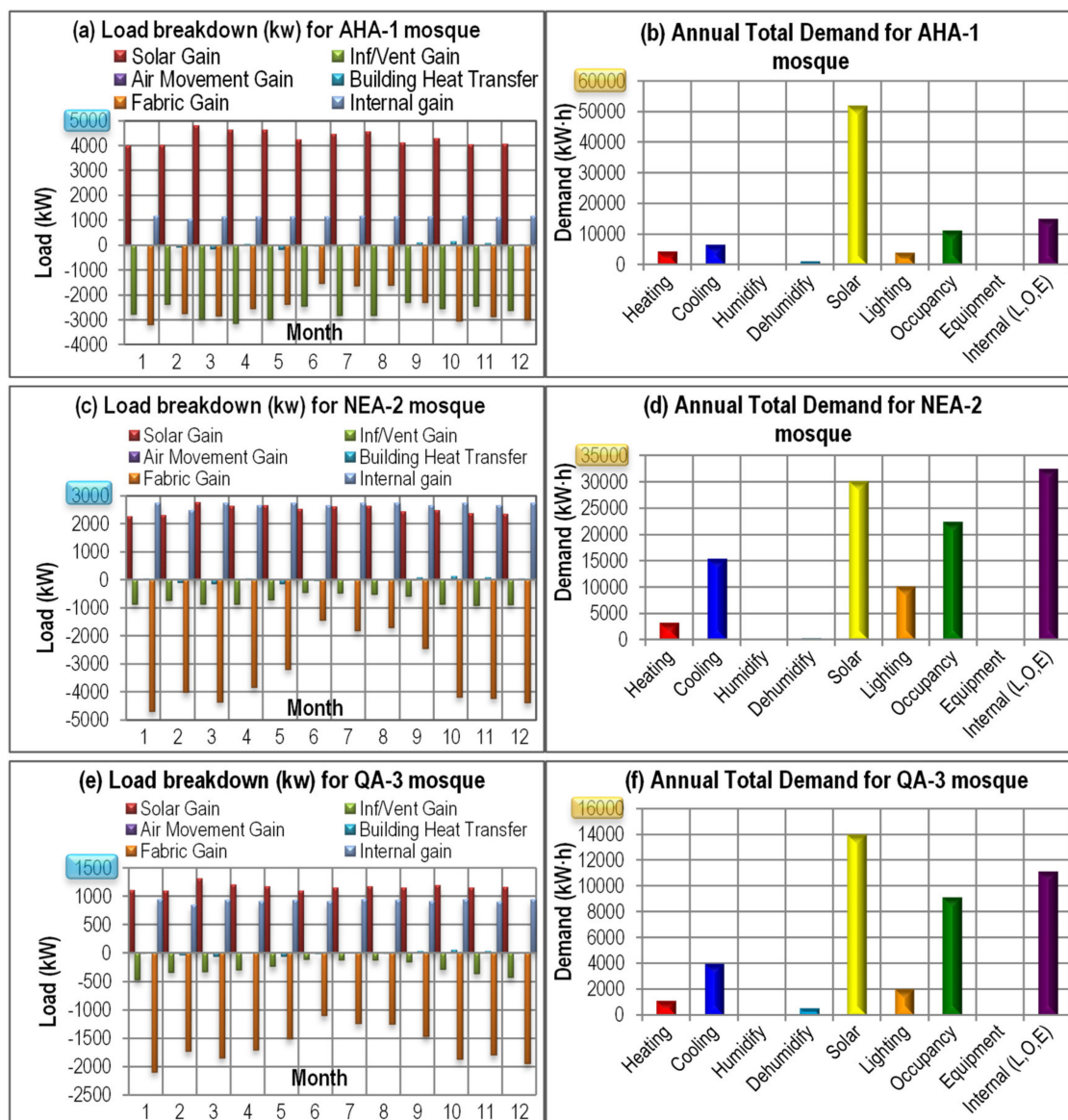


Figure 7. Estimated loads breakdown and annual total demands by using TAS in: (a) AHA-1 mosque (load breakdown), (b) AHA-1 mosque (annual total demand), (c) NEA-2 mosque (load breakdown), (d) NEA-2 mosque (annual total demand), (e) QA-3 mosque (load breakdown) and (f) QA-3 mosque (annual total demand).

In AHA-1 mosque building (cases a and b), the results show that the amount of heat gain (with an average of 5491 kW) during a whole year was slightly higher than heat loss (with an average of 5182 kW) from all of the six categories in this mosque building. The highest heat gain in this mosque building was around 4821 kW caused by solar gain and occurred in March, with an average of around 4333 kW for each month in the whole year (case a). The highest amount of heat loss was around 3187 kW via the building's fabrics (external conduction opaque and glazing) and occurred in January, with an average of around 2485 kW for each month in the year. The second significant amount of heat gain was caused by internal gain in all months with an average of around 1156 kW. However, the amount of heat gain or loss in this mosque building was not a significant problem, since the heating demand of 4233 kW·h caused by heat loss and cooling demand of 6388 kW·h caused by heat gain (case b) were not great compared with the other mosque buildings (Figure 7).

In NEA-2 mosque building (cases c and d), the results display that the amount of heat gain (with an average of 25,291kW) during a whole year was also greater than heat loss (with an average of

23,070kW) from all of the six categories in this mosque building. The greatest amount of heat gain in this mosque building was caused by internal gain (occupancy and lighting) with an average of around 2708 kW and by solar gain with an average of about 2511 kW for each month in the whole year (case c). The highest amount of heat loss was caused by the building's fabrics (external conduction opaque and glazing) with an average of around 3363 kW followed by infiltration and ventilation gain with an average of about 735 kW for each month in the whole year. Therefore, the cooling demand of 15,419 kW·h caused by the significant heat gain was far greater than the heating demand of 3233 kW·h caused by heat loss as seen in case d (Figure 7).

In QA-3 mosque building (cases e and f), the outcomes show that the amount of heat gain (with an average of 63,162kW) during a whole year was also greater than heat loss (with an average of 49,655kW) from all of the six categories in this mosque building (case e). The greatest amount of heat gain in this mosque building was caused by solar gain with an average of around 1169 kW followed by internal gain (occupancy and lighting) with an average of about 924 kW for each month in the whole year. The highest amount of heat loss was caused by the building's fabrics (external conduction opaque and glazing) with an average of around 1633 kW followed by infiltration and ventilation gain with an average of about 274 kW for each month in the whole year. Therefore, the cooling demand of 3927 kW·h caused by the significant heat gain was far greater than the heating demand of 1089 kW·h caused by heat loss as seen in case f (Figure 7).

4.6. The Total Demands and Actual Energy Use

The total monthly demands are estimated for all mosque buildings using TAS simulation software, and are compared with solar radiation and the actual annual usage of electricity in each mosque building. Figure 8 presents the outcomes of this investigation as follows.

Mosque building and 180 m² for the QA-3, the smallest mosque.

The results display that there are some discrepancies in the trends of all variables (demand, solar radiation, and actual electricity usage and the prices) involved in this comparison, especially in the AHA-1 mosque building (case a and b). However, the trends of demand and energy use were to some extent the same. The results also indicate that the demands are influenced by solar radiation and outdoor temperatures accordingly. However, it seems there were some other factors affecting the amount of demand, such as internal gains and heat loss from mosque buildings' fabrics, which caused high heating demands in some months in all mosque buildings.

The highest demands were estimated for the NEA-2 mosque building (case c) with a maximum load of 10,531 kW·h in August, and therefore it has the highest energy use (case d), since the maximum energy use was 10,680 kW·h in September. The lowest demand was estimated in the QA-3 mosque (case e) with a maximum load of 2840 kW·h in August, and therefore it has the lowest energy use (case f) with a maximum energy use of around 2890 kW·h in July (Figure 8). This is due to the differentiation in term of size and capacity between these mosque buildings, since the NEA-2 mosque building (625m²) is significantly bigger than the other two mosque buildings, with an area of 400 m² for the AHA-1

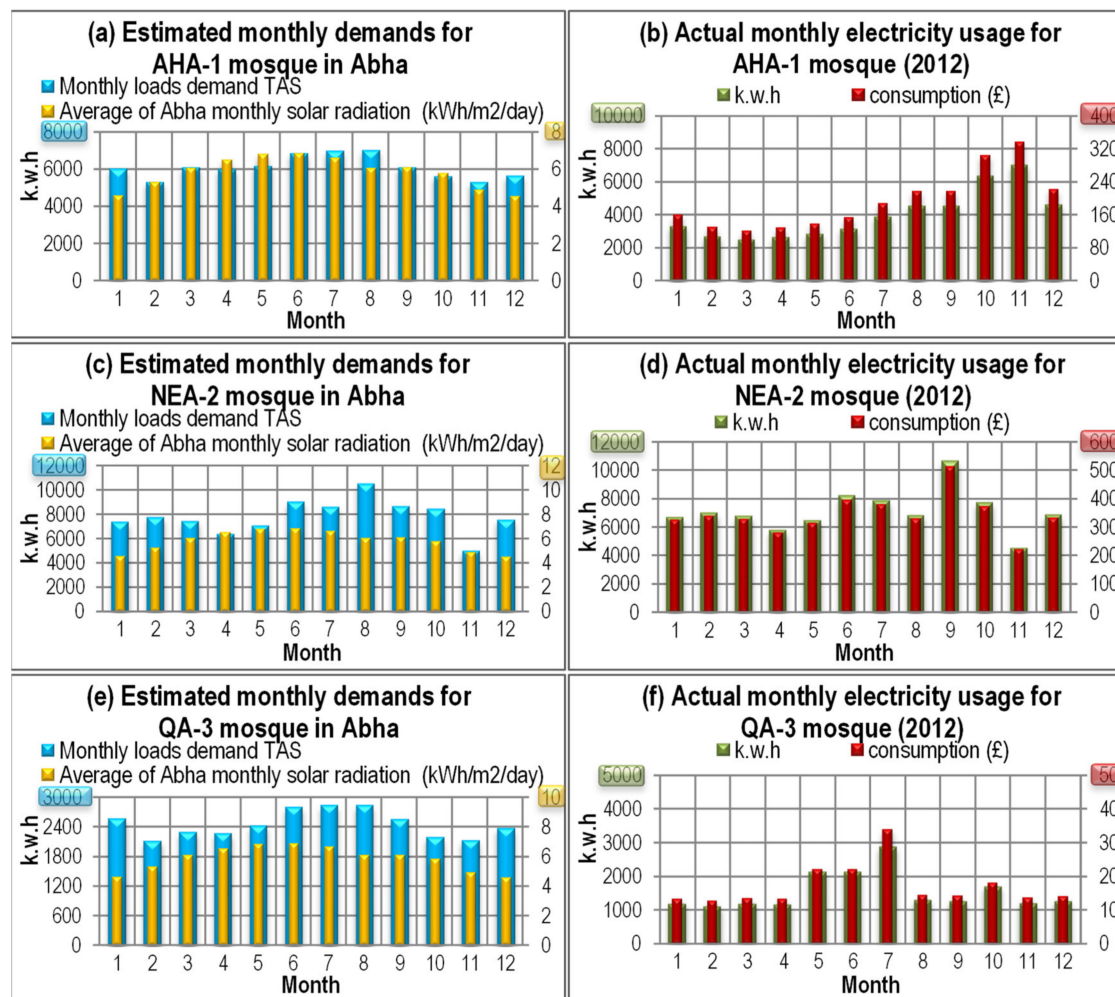


Figure 8. Estimated total demands (TAS) compared to the actual energy use for: (a) AHA-1 mosque (monthly demand by TAS), (b) AHA-1 mosque (monthly electricity for actual usage), (c) NEA-2 mosque (monthly demand by TAS), (d) NEA-2 mosque (monthly electricity for actual usage), (e) QA-3 mosque (monthly demand by TAS) and (f) QA-3 mosque (monthly electricity for actual usage).

4.7. Thermal Performance of Mosque Buildings' Fabrics (Solar Gain)

A building's envelope and fabrics have a great impact on the indoor environments and conditions, since they help maintaining the indoor spaces to be within the acceptable level of human thermal comfort when it is of high quality. It should be mentioned here that because of the huge number of charts, exceeding 800, and figures that have been produced for only this part, it is difficult to discuss all in this part. Therefore, the charts of the NEA-2 mosque building will be presented and discussed based on some criteria as explained earlier. The following sections discuss thermal performance of the envelope and fabrics for the selected mosque building for days in the winter and the summer.

According to TAS manual, solar gain is the amount of solar radiation absorbed by the selected surface (TAS manual, 2014). Solar radiation is considered as the main source of any building's heat gains depending on the quality of the building's fabrics and materials. In addition, the previous discussions show significant solar gains caused great demands in all of the selected mosque buildings. Thus, solar gains for roofs, floors, windows, doors, and the external walls for the selected mosque building in both winter and summer days are predicted to see that most elements were responsible for the solar heat gains in the selected mosque building as follows.

4.7.1. Solar Gain of Roof and Floor Surfaces

An exposed flat roof or floor of a building typically receives the greatest amount of solar radiation, since they expose more area to solar radiation than the other building's fabrics and materials. Unless they have high quality or are well designed, they will have great impacts on the indoor spaces of the buildings. Therefore, an investigation has been conducted to examine the floors and roofs of the selected mosque building in term of solar gain, as seen in Figure 9. The outcomes displayed that the trends of solar gains for the selected mosque building was almost the same in the winter and in the summer, although was higher in the summer than in the winter.

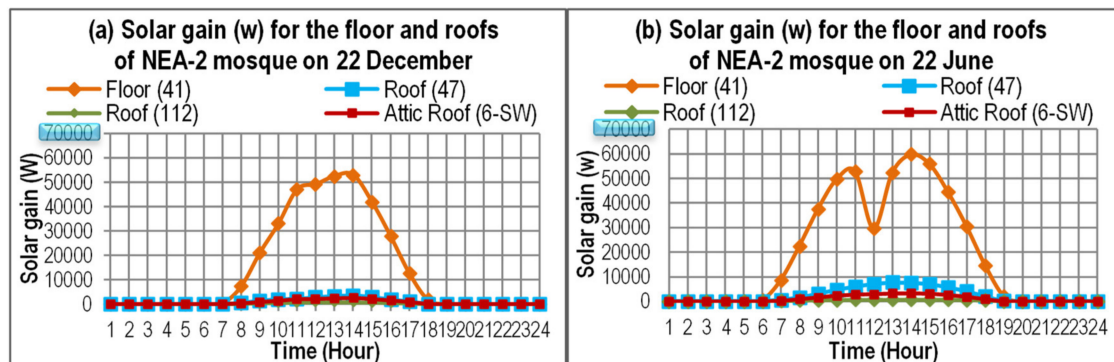


Figure 9. Solar gain for floors and roofs for both seasons in: (a) NEA-2 mosque on 22 December and (b) NEA-2 mosque on 22 June.

The outcomes display that solar gain movements take place from 7:00 h to after 18:00 h in the winter (case a), where the day is shorter than in the summer (case b) when the movements take place from 6:00 h to after 19:00 h. The greatest amount of solar gain was surprisingly observed for the ground floor surface (41) with a maximum of around 53 kW in the winter (case a), while it was around 60 kW in the summer (case b) and both occurred at the middle of the day (14:00 h). This may be due to the large areas of glazing that this mosque building has on each side and even the dome, which allows solar radiation to penetrate and reach the ground floor surface. It is also noticed that the solar gain increased dramatically until 11:00 h and then declined significantly to below 30 kW at around 12:00 h and then turned back and increased until reaching its maximum of 60 kW in the summer (case b). This could be because of the altitude of the sun being close to 90°, the zenith, at around 12:00 h on June 22. Therefore, the solar radiation could not penetrate except through the southern facing windows and reaching only small areas of the ground floor, and thus the solar gain declined significantly during that hour before the sun moved, increasing the solar gain again, this time through the western and southern sides.

The second greatest amount of solar gain was for the staircase roof surface (47) with maximum of about 4 kW in the winter (case a), while it was around 77 kW in the summer (case b), which is far lower than the ground floor surface (41), and both occurred in the middle of the day (14:00 h). In addition, the lowest solar gain was observed for the main building's roof (112) with a maximum of about 2 kW in the winter (case a) and around 0.7 kW in the summer (case b) (Figure 9). This may be due to the surrounding buildings shading the mosque building's main roof (112) and in spite of the great discrepancy of these surfaces' areas, since the main building's roof surface (112) has a significantly bigger area (around 638 m²) than the staircase roof surface (around 13 m²). Another possible reason is that the floor is covered by carpet with higher absorptance than the white terrazzo tiles covering the roof, which has greater reflectance than absorptance. Therefore, the floor absorbed more solar radiation than the roof.

4.7.2. Windows Surfaces (Solar Gain)

An investigation has been conducted to examine the windows and glazing areas of the selected mosque building in term of solar gain as seen in Figure 10. The outcomes revealed that there were significant discrepancies between the winter and the summer for the trends of solar gain in the selected mosque building.

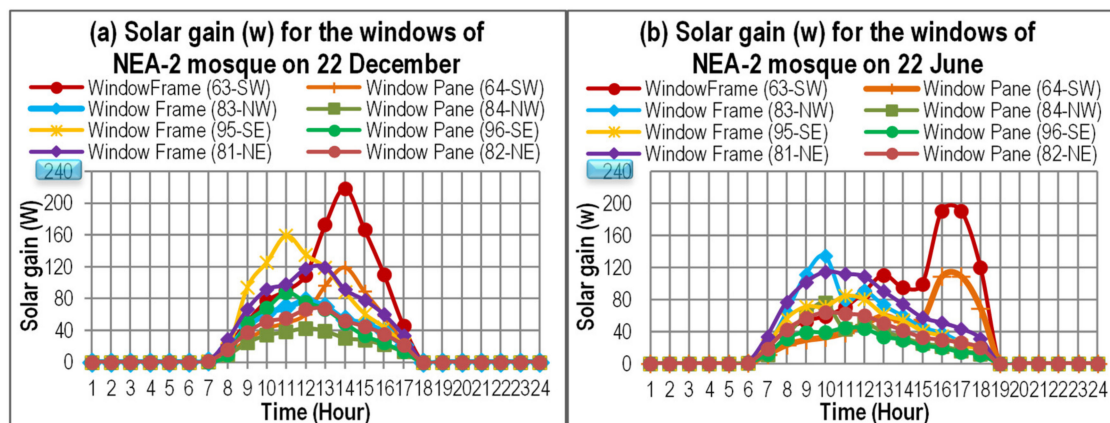


Figure 10. Solar gain for windows for both seasons in: (a) NEA-2 mosque on 22 December and (b) NEA-2 mosque on 22 June.

The results display that solar gain movements also take place from after 7:00 h to after 18:00 h in the winter (case a), where the day is shorter than in the summer (case b) when the movements take place from 6:00 h to after 19:00 h. It should be mentioned here that this mosque building has windows in all four walls. The results show that window-frames 63 (SW) and 95 (SE) showed the highest solar gains with a maximum of around 219 W occurring at 11:00 h and 159 W occurring at 14:00 h respectively, which were higher than the other window-frames and panes in the winter (case a). The highest solar gains found in the summer were for window-frames 63 (SW) and 83 (NW) with a maximum of around 191 W occurring at 10:00 h and 135 W occurring at 17:00 h respectively, which were also higher than the other window-frames and panes (case b). This may also be because the aluminum window-frames have higher absorptance than the transparent window-panes, which may have higher reflectance than absorptance (Figure 10).

Therefore, the aluminum window-frames absorbed more solar radiation than the transparent window-panes. In addition, it is observed that window' frames and panes in NW, SE, and NE walls showed higher solar gains during the period from 7:00 h to 13:00 h in the winter and from 6:00 h to 10:00 h in the summer when facing the sun; then the gains declined slowly after those periods. In comparison, window-frames and panes in the SW wall displayed the reverse of those windows, which were higher in solar gains from afternoon hours, when facing the sun, and were lower in the morning hours (Figure 10).

4.7.3. Doors' Surfaces (Solar Gain)

Another investigation has been conducted to examine the doors of the selected mosque building in term of solar gain as seen in Figure 11. The outcomes revealed that there were significant discrepancies between the winter and the summer in the trends of solar gains in the selected mosque building.

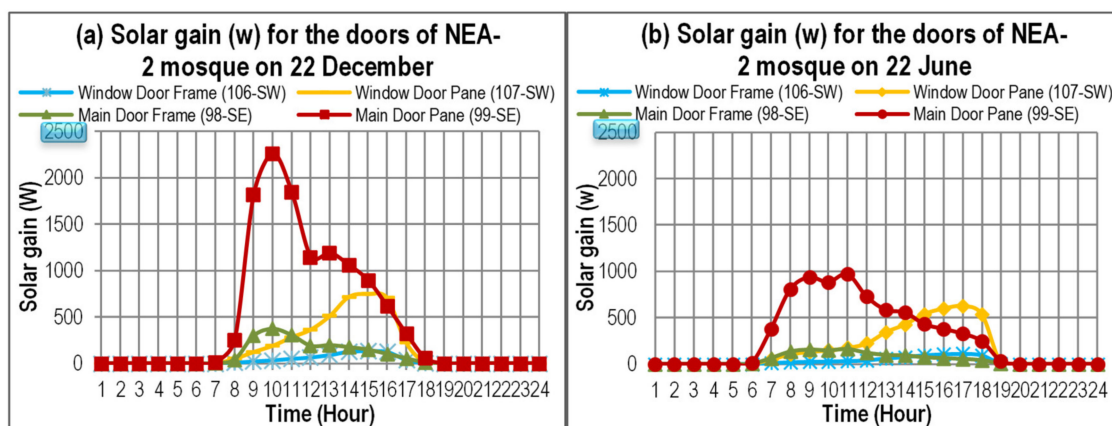


Figure 11. Solar gain for doors for both seasons in: (a) NEA-2 mosque on 22 December and (b) NEA-2 mosque on 22 June.

The outcomes display that there are no significant discrepancies for the trends of doors' solar gain between the winter (case a) and the summer (case b), although it was greater in the winter than in the summer. It also shows that SE doors' frames and panes showed higher solar gains in the morning hours when facing the sun, while SW door's frame and pane displayed increases in solar gains during afternoon hours when facing the sun in both seasons. In addition, door's pane 99 (SE) indicated greater solar gains than other doors' frames and panes with a maximum of around 2,264W, although it declined significantly after 10:00 h in the winter (case a). On the other hand, door's pane 99 (SE) was also greater during the hours from 8:00 h to 12:00 h with a maximum solar gain of 971 W at 11:00 h in the summer (case b). After that, it declined significantly, swapping with door's pane 107 (SW), which increased dramatically to become greater during the period from 15:00 h to 18:00 h with a maximum solar gain of 624W at 17:00 h in the summer (case b). Furthermore, it is also observed that solar gain was influenced by the orientation of the mosque buildings and the location of each material. It is noticed that all doors' frames showed lower solar gains than doors' panes in both seasons (Figure 11); this may be because doors' panes were facing the sun more than the door frames, and therefore indicating discrepancies in solar gain.

4.7.4. External Walls' Surfaces (Solar Gain)

This section aims to study the external walls of the selected mosque building in terms of solar gain. The outcomes revealed that there were significant discrepancies between the winter and the summer in the trends of solar gains in the selected mosque building (Figure 12).

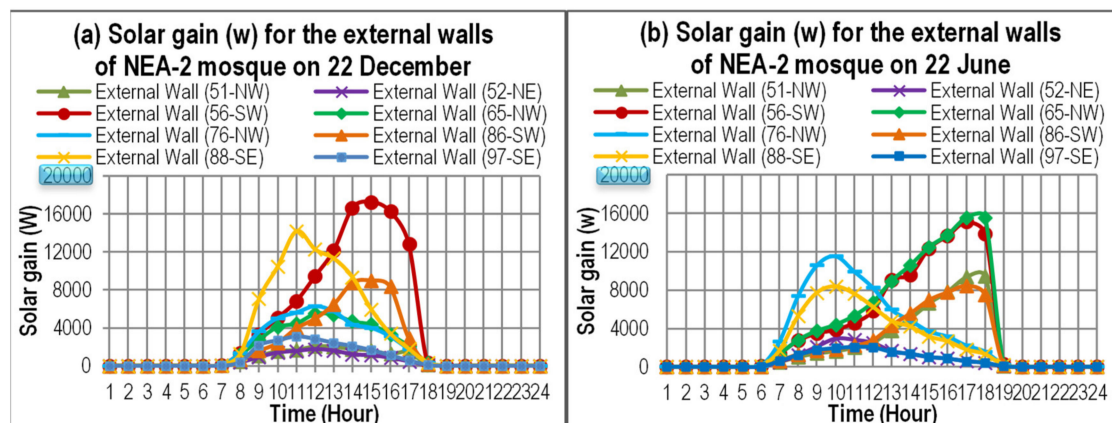


Figure 12. Solar gain for external walls for both seasons in: (a) NEA-2 mosque on 22 December and (b) NEA-2 mosque on 22 June.

The outcomes display that solar gain was influenced by the position of the sun and the orientation of the mosque buildings' elements, since there were some discrepancies between solar gain in the winter (case a) and in the summer (case b). It also shows that SE walls showed sharp increases in solar gains in the morning hours when facing the sun, with a maximum of 14.2 kW for the external wall 88 (SE) occurring at 11:00 h in the winter (Figure 12a).

In comparison, SW walls displayed greater solar gains during afternoon hours when facing the sun with a maximum of 17.2 kW for the external wall 56 (SW) and 9 kW for the external wall 86 (SW), both occurring at 15:00 h in the winter (case a). On the other hand, the external wall 76 (NW) and the external wall 88 (SE) showed significant increases in solar gains in the morning hours when facing the sun with a maximum of 11.5 kW for the external wall 76 (NW) and 8.4 kW for the external wall 88 (SE), both occurring at 10:00 h in the summer (case b). The external walls of 56 (SW), 65 (NW), 51 (NW), and 86 (SW) displayed great increases in solar gains during afternoon hours when facing the sun. The external wall 65 (NW) showed the greatest solar gain with a maximum of around 15.6 kW occurring at 18:00 h, with 15.1 kW for wall 56 (SW) at 17:00 h, 9.5 kW for wall 51 (NW) at 18:00 and 8.5 kW for wall 86 (SW) at 17:00 in the summer (Figure 12b).

Furthermore, the shadings by surrounding buildings were noticeably influencing the walls' solar gains; those walls affected by the shading showed lower or some reductions in solar gain. For example, the external walls 52 (NE) and 97 (SE) showed lower solar gain when facing the sun during morning hours in both seasons' days, because it was affected by the shading (Figure 12).

4.7.5. Attic/Dome Fabrics' Surfaces (Solar Gain)

Another investigation was conducted to examine the attic or dome fabrics' surfaces of the selected mosque building in terms of solar gain. The outcomes revealed that there were significant discrepancies between winter and summer in the trends of solar gain in the selected mosque building (Figure 13).

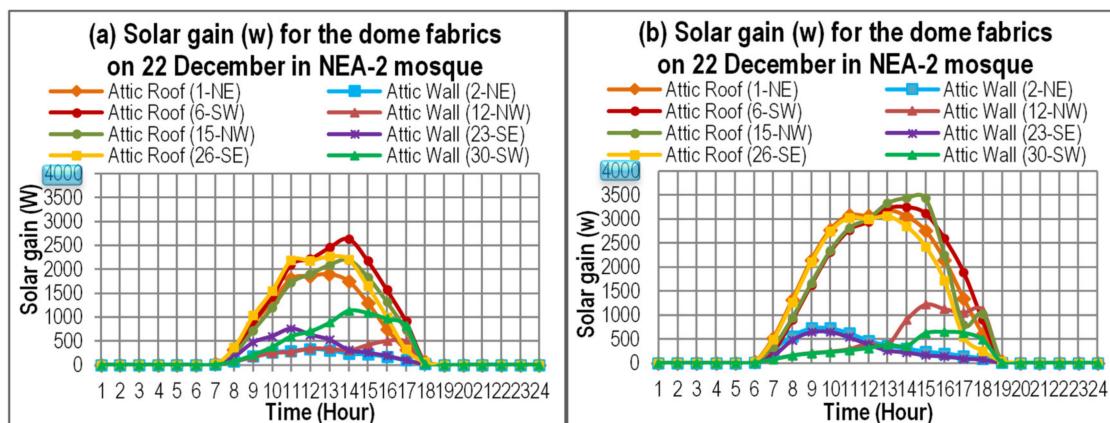


Figure 13. Solar gain for attic/dome fabrics for both seasons in: (a) NEA-2 mosque on 22 December and (b) NEA-2 mosque on 22 June.

The outcomes display that solar gain was influenced by the position of the sun and the orientation of the mosque buildings' elements, since there were some discrepancies between solar gain in the winter (case a) and in the summer (case b). It also shows that dome's roof 6 (SW) indicated the highest solar gain with a maximum of around 2.6 kW occurring at 14:00 h, and the lowest solar gain was for dome's roof 1 (NE) with a maximum of about 1.9 kW at 13:00 h in the winter (Figure 13a).

In comparison, dome's roof 15 (NW) indicated the highest solar gain with a maximum of around 3.4 kW occurring at 14:00 h, and the lowest solar gain was for dome's roof 26 (SE) with a maximum of about 3 kW at 13:00 in the summer (case b). In addition, dome's wall 23 (SE) showed an increase in solar gains in the morning hours when facing the sun with a maximum of 758 W occurring at 11:00 h

in the winter (case a), while dome's wall 30 (SW) displayed greater solar gains during the afternoon hours when facing the sun with a maximum of 1,137W occurring at 14:00 h in the winter (Figure 13b).

On the other hand, dome's walls 2 (NE) and 23 (SE) showed increases in solar gains in the morning hours when facing the sun with maximums of 727 W and 648 W respectively, both occurring at 09:00 h in summer (case b), while dome's walls 12 (NW) and 30 (SW) displayed greater solar gains during afternoon hours when facing the sun with a maximum of 1220 W for wall 12 (NW) occurring at 15:00 h and 650 W for wall 30 (SW) occurring at 16:00 h in the summer (case b) (Figure 13).

4.7.6. Attic/Dome Windows' Surfaces (Solar Gain)

This section aims to study the attic/dome windows' surfaces of the selected mosque building in term of solar gain. The outcomes revealed that there were significant discrepancies especially between the winter and the summer in the trends of solar gains in the selected mosque building (Figure 14).

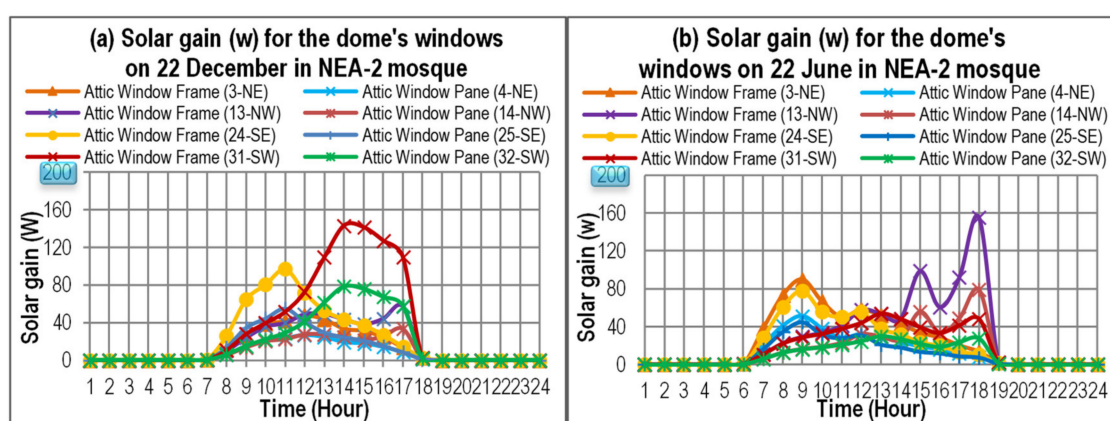


Figure 14. Solar gain for attic/dome windows for both seasons in: (a) NEA-2 mosque on 22 December and (b) NEA-2 mosque on 22 June.

The results display that window-frame 24 (SE) and window-pane 25 (SE) showed higher solar gains during the period from 07:00 h to 11:00 h when facing the sun, with a maximum solar gain of around 97W for the frame and 55W for the pane and both occurred at 11:00 h, and then declined in the winter (case a). Whereas, window-frame 31 (SW) and window-pane 32 (SW) showed higher solar gains during afternoon hours from 13:00 h to 17:00 h when facing the sun with a maximum solar gain of around 143 W for the frame and 78W for the pane and both occurred at 14:00 h in the winter (Figure 14a).

On the other hand, window-frames 3 (NE) and 24 (SE) showed higher solar gains during the period from 06:00 h to 11:00 h when facing the sun, with a maximum solar gain of around 90 W and 78 W respectively and both occurred at 09:00 h, and then declined in the summer (case b). Whereas, window-frame 13 (NW) and window-pane 14 (NW) showed higher solar gains during afternoon hours from 15:00 h to 18:00 h when facing the sun, with a maximum solar gain of around 155 W for the frame and 79 W for the pane and both occurred at 18:00 h in the summer (Figure 14b).

Furthermore, it is also observed that window-frames had far greater solar gains than window-panes in both seasons during the day (Figure 14). This may also be because the aluminum window-frames have higher absorptance than the transparent window-panes, which may have higher reflectance than absorptance. Therefore, the aluminum window-frames absorbed more solar radiation than the transparent window-panes, as explained earlier.

4.8. Heat Gain/Loss by Conduction

Heat gain or loss by conduction is defined as the sum of heat transferred through a building's construction fabrics, and this value is measured in Watts (TAS manual, 2014). Positive values mean the

building gains heat, since the heat is being transferred through the building's construction to the inside surfaces, whereas negative values indicate heat loss, as the heat is being transferred away through the building's construction to the outside surfaces. Therefore, heat gain or loss by conduction for roofs, floors, windows, doors, and the external walls for the selected mosque building in both the winter and the summer days are predicted as follows.

4.8.1. Heat Gain/Loss by Conduction of Roof and Floor Surfaces

An investigation has been conducted to examine the floors and roofs of the selected mosque building in terms of heat gain or loss by conduction. Figure 15 presents the outcomes of this investigation as follows.

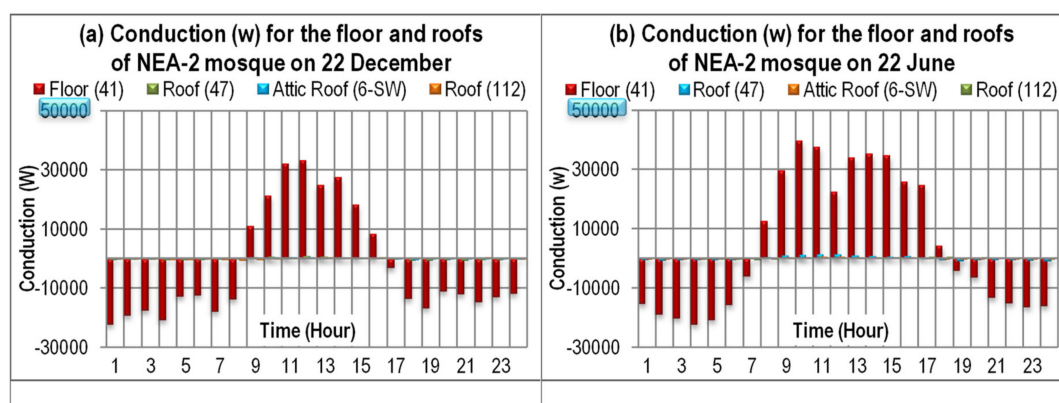


Figure 15. Heat loss/gain by conduction for attic/dome roofs and floors for both seasons in: (a) NEA-2 mosque on 22 December and (b) NEA-2 mosque on 22 June.

The results showed that there are a few discrepancies between the trends of conduction in the winter (case a) and in the summer (case b), since the results showed that this mosque building experienced great heat loss by conduction through its floor and roofs (particularly through floor 41) during the periods from 01:00 h to 08:00 h and from 17:00 h to 24:00 h, with a maximum heat loss of about 22.3 kW at 01:00 h for floor 41 in winter (case a). Also, it experienced heat gain by conduction during the period from 09:00 h to 16:00 h with a maximum heat gain of around 33.4 kW at 12:00 h for floor 41 in the winter (case a) (Figure 15).

On the other hand, the results also showed that this mosque building experienced great heat loss by conduction through its floor and roofs (particularly through floor 41) during the periods from 01:00 h to 07:00 h and from 19:00 h to 24:00 h, with a maximum heat loss of about 22.2 kW at 04:00 h for floor 41 in the summer (case b). Additionally, it experienced heat gain by conduction during the period from 08:00 h to 18:00 h, with a maximum heat gain of around 39.8 kW at 10:00 h for floor 41 in the summer (case b) (Figure 15). The results surprisingly showed significant heat gain and loss by conduction through the floor 41. This may be due to the great glazing areas in each side and even the dome of this mosque building, as explained in the solar gain investigation. It allows solar radiation to penetrate and be absorbed by the ground floor surface and then conducted again to the indoor environment or away to the soil depending on the differences between the indoor temperatures and the floor's surface temperature.

Another possible reason is that the floor is covered by carpet with higher absorptance than white terrazzo tiles covering the roof, which has a greater reflectance than absorptance. Therefore, the floor absorbed more solar radiation than the roof, and hence caused great heat gain by conduction through the floor 41. In addition, these discrepancies and trends may also refer to the influence of solar radiation as explained earlier, since it is noticed that when there is no solar radiation and when the indoor temperatures become higher than the outdoor temperatures, the building experienced heat loss. This may be supported by the poor quality of the building's fabrics and construction. When

the indoor temperatures become lower than outdoor temperatures, during the day when there is great solar radiation, the building experienced heat gain.

4.8.2. Windows' Surfaces (Heat Gain/Loss by Conduction)

This part aims to examine the windows of the selected mosque building in terms of heat gain or loss by conduction. Figure 16 presents the outcomes of this investigation.

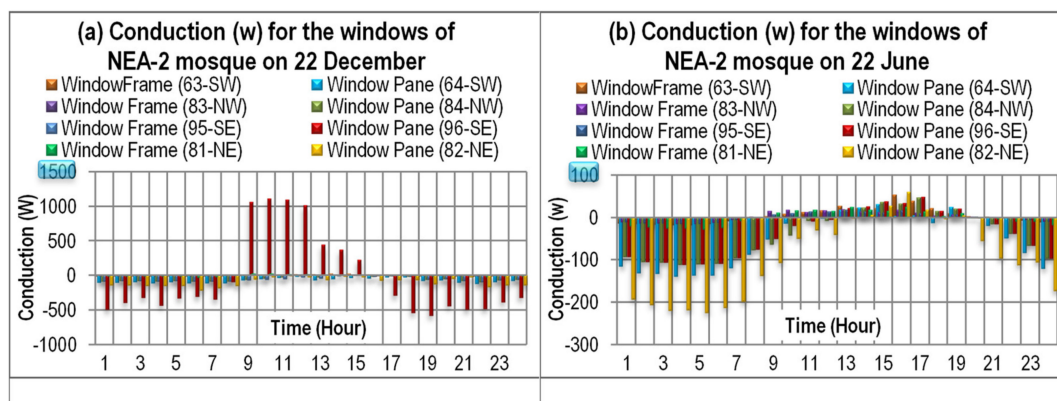


Figure 16. Heat loss/gain by conduction for the windows for both seasons in: (a) NEA-2 mosque on 22 December and (b) NEA-2 mosque on 22 June.

The results displayed that there are also significant discrepancies between the trends of conduction in the winter (case a) and in the summer (case b). It shows that this mosque building experienced heat loss by conduction through all the windows during the periods from 01:00 h to 08:00 h and from 16:00 h to 24:00 h in the winter (case a). The greatest heat loss by conduction was found through window-panes 96 (SE) and 82 (NE), with a maximum heat loss of about 587 W at 19:00 h and 218 W at 06:00 h respectively in the winter (case a). During the period from 09:00 h to 14:00 h, the mosque building experienced significant heat gain by conduction particularly through window-pane 96 (SE), with a maximum heat loss of about 1109 W at 10:00 h in the winter (case a) (Figure 16).

On the other hand, the mosque building indicated great heat loss by conduction through all the windows during the periods from 01:00 h to 07:00 h and from 20:00 h to 24:00 h with a maximum heat loss of about 225 W at 05:00 h for window-pane 82 (NE) in the summer (case b). In addition, the period from 08:00 h to 12:00 h experienced greater heat loss, especially through window-panes 82 (NE), than heat gain through the other windows in the summer (case b). Whereas, the last period from 13:00 h to 19:00 h showed heat gains by conduction through all windows, with a maximum heat gain of around 60 W for window-pane 82 (NE) occurring at 16:00 h in the summer (Figure 16). The reasons for these discrepancies and trends may also refer here to the influence of solar radiation, since it is noticed that when there is no solar radiation and when the indoor temperatures become higher than the outdoor temperatures, the building experienced heat loss in the summer. This may be supported by the poor quality of the building's windows. On the other hand, when the indoor temperatures become lower than outdoor temperatures, during the day when there is great solar radiation, the building experienced heat gain.

4.8.3. Doors' Surfaces (Heat Gain/Loss by Conduction)

Another investigation has been conducted to examine the doors of the selected mosque building in terms of heat gain or loss by conduction. Figure 17 presents the outcomes of this investigation. The results displayed that there are also significant discrepancies between the trends of conduction in the winter (case a) and in the summer (case b). It shows that this mosque building experienced heat loss by conduction through all the doors during the period from 01:00 h to 08:00 h with a maximum heat loss of about 537 W for the door's window pane 107 (SW) at 08:00 h in the winter (case a). During the

period from 09:00 h to 24:00 h the mosque building experienced greater heat gain than heat loss by conduction, particularly through main door's pane 99 (SE) with a maximum heat gain of about 1082 W at 09:00 h in the winter (case a) (Figure 17).

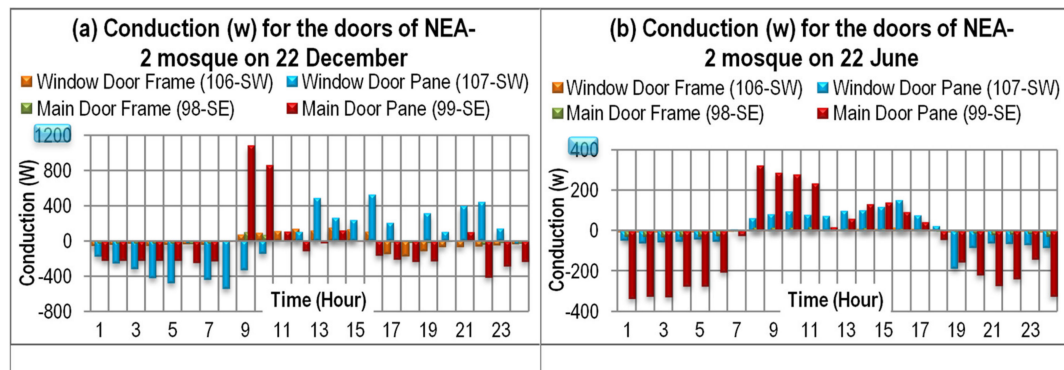


Figure 17. Heat loss/gain by conduction for the doors for both seasons in: (a) NEA-2 mosque on 22 December and (b) NEA-2 mosque on 22 June.

On the other hand, the mosque building indicated a great heat loss by conduction through all the doors during the periods from 01:00 h to 07:00 h and from 18:00 h to 24:00 h with a maximum heat loss of about 335 W at 01:00 h for the main door's pane 99 (SE) in the summer (case b). In addition, the periods from 08:00 h to 17:00 h experienced significant heat gain, especially through the main door's pane 99 (SE), with a maximum heat gain of around 322 W at 08:00 h in the summer (case b) (Figure 17). The reasons for these differences and trends may also refer here to the influence of solar radiation, since it is noticed that when there is no solar radiation and when the indoor temperatures become higher than the outdoor temperatures, the building experienced heat loss in the summer. This may be supported by the poor quality of the building's doors. When the indoor temperatures become lower than the outdoor temperature, during the day when there is great solar radiation, the building experienced heat gain.

4.8.4. External Walls' Surfaces (Heat Gain/Loss by Conduction)

This section aims to study the external walls of the selected mosque building in terms of heat loss or gain by conduction. The outcomes also revealed that there were some discrepancies between the winter and the summer in the trends of conduction in the selected mosque buildings (Figure 18).

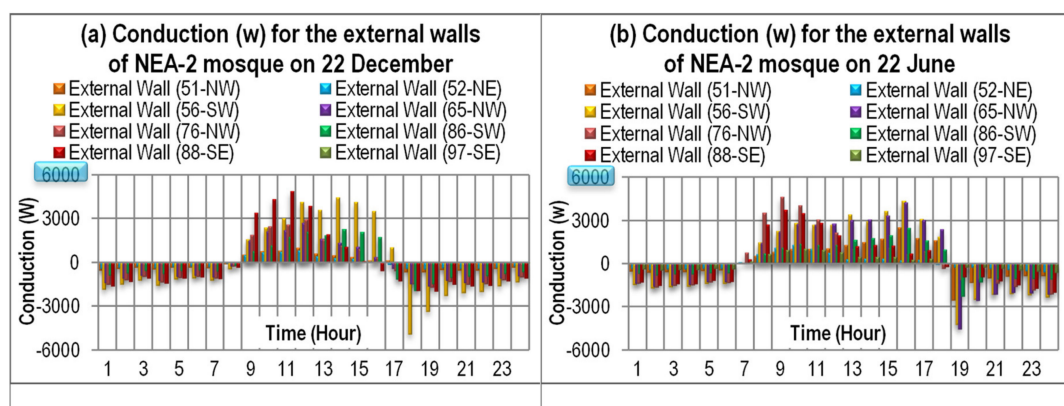


Figure 18. Heat loss/gain by conduction for the external walls for both seasons in: (a) NEA-2 mosque on 22 December and (b) NEA-2 mosque on 22 June.

The outcomes displayed that this mosque building experienced heat loss by conduction through all of the external walls during the periods from 01:00 h to 08:00 h and from 17:00 h to 24:00 h with a maximum heat loss of about 4920 W for the external wall 56 (SW) at 18:00 h in the winter (case a). During the period from 09:00 h to 16:00 h in the winter (case a), the mosque building experienced great heat gain by conduction. During this period the heat gain by conduction of the external wall 88 (SE) was greater than for the other walls before 11:00 h, when facing the sun, with a maximum heat gain of around 4886 W occurring at 11:00 h in the winter (case a). It dropped down, exchanging with the external wall 56 (SW), which had a greater heat gain than the other walls during afternoon hours, with a maximum heat gain of around 4480 W occurring at 14:00 h in the winter (case a) (Figure 18).

On the other hand, the mosque building indicated great heat loss by conduction through all of the external walls during the periods from 01:00 h to 06:00 h and from 19:00 h to 24:00 h, with a maximum heat loss of about 4525 W at 19:00 h for the external wall 65 (NW) in the summer (case b). In addition, the period from 07:00 h to 18:00 h experienced significant heat gain by conduction in the summer (case b). During this period, the heat gains by conduction of the external walls 76 (NW) and 88 (SE) were greater than the other walls before 11:00 h, when facing the sun, with maximum heat gains of around 4627 W and 3713 W respectively occurring at 09:00 h in the summer (case b). It then dropped down, exchanging with the external walls 56 (SW) and 65 (NW), which had a greater heat gain than the other walls during afternoon hours, with maximum heat gains of around 4338 W and 4226 W respectively occurring at 16:00 h in the summer (Figure 18).

The reasons for these divergences and trends may also refer here to the influence of solar radiation, since it noticed that when there is no solar radiation and when the indoor temperatures become higher than the outdoor temperatures, the building experienced heat loss in the summer. This may be supported by the poor quality of the building's fabrics and construction. When the indoor temperatures become lower than outdoor temperatures, during the day when there is great solar radiation, the building experienced heat gain.

4.8.5. Attic/Dome Fabrics' Surfaces (Heat Gain/Loss by Conduction)

Another investigation has been conducted to examine the attic or dome's fabrics surfaces of the selected mosque building in terms of heat loss or gain by conduction. The outcomes revealed that there were no big discrepancies between the winter and the summer in the trends of heat loss or gain by conduction in the selected mosque building (Figure 19).

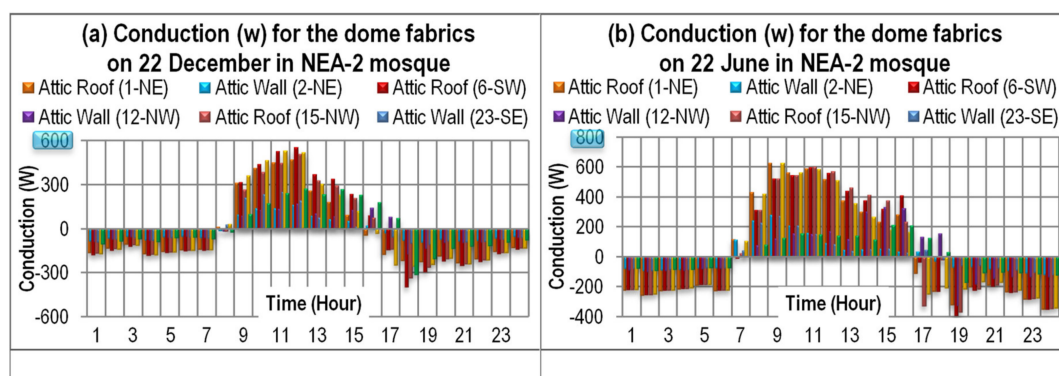


Figure 19. Heat loss/gain by conduction for the attic/dome fabrics for both seasons in: (a) NEA-2 mosque on 22 December and (b) NEA-2 mosque on 22 June.

The outcomes displayed that this mosque building experienced heat loss by conduction through all of the dome's fabrics during the periods from 01:00 h to 07:00 h and from 17:00 h to 24:00 h, with a maximum heat loss of about 398 W for the dome's roof 6 (SW) at 18:00 h in the winter (case a). During the period from 08:00 h to 16:00 h the mosque building experienced great heat gain by

conduction, with a maximum heat loss of about 553 W for the dome's roof 6 (SW) at 12:00 h in the winter (case a) (Figure 19).

On the other hand, the mosque building indicated great heat loss by conduction through all of the external walls during the periods from 01:00 h to 06:00 h and from 17:00 h to 24:00 h, with a maximum heat loss of about 393 W occurring at 19:00 h for the dome's roof 6 (SW) in the summer (case b). In addition, the period from 07:00 h to 16:00 h experienced significant heat gain by conduction, with a maximum heat gain of about 630 W for the dome's roof 1 (NE) and 628 W for dome's roof 26 (SE), both occurring at 09:00 h in the summer (case b) (Figure 19).

The reasons for these discrepancies and trends may also refer here to the influence of solar radiation and the surface location and orientation. Since a building's roof normally receives more solar radiation than the other building's elements, therefore it may show greater heat gain by conduction accordingly. It is also noticed that when there is no solar radiation and when the indoor temperatures become higher than the outdoor temperatures, the building experienced heat loss in the summer. This may be supported by the poor quality of the building's fabrics and construction. When the indoor temperatures become lower than outdoor temperatures, during the day when there is great solar radiation, the building experienced heat gain.

4.8.6. Attic/Dome Window Surfaces (Heat Gain/Loss by Conduction)

This is the last part in this chapter and it aims to examine the attic/dome's windows of the selected mosque building in terms of heat gain or loss by conduction. Figure 20 presents the outcomes of this investigation.

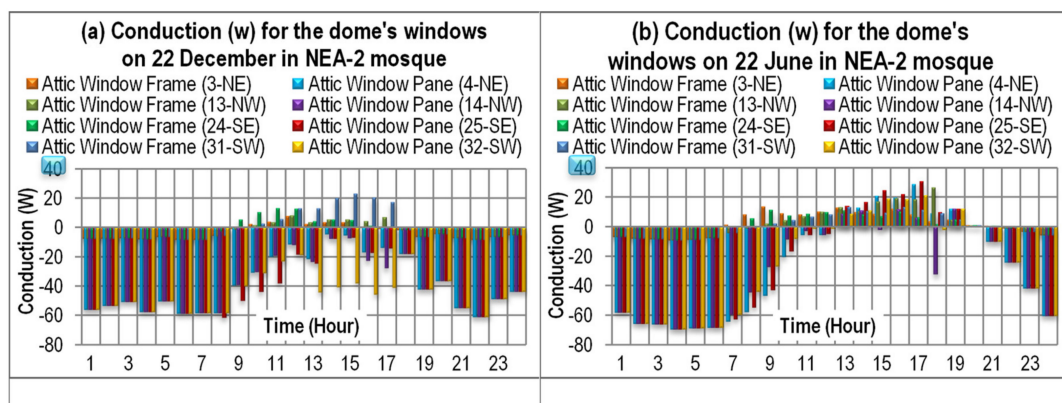


Figure 20. Heat loss/gain by conduction for attic/dome windows for both seasons in: (a) NEA-2 mosque on 22 December and (b) NEA-2 mosque on 22 June.

The results displayed that there are also significant discrepancies between the trends of conduction in the winter (case a) and in the summer (case b). It shows that this mosque building experienced heat loss most of the time by conduction through all of the dome's windows during the periods from 01:00 h to 08:00 h and from 18:00 h to 24:00 h in the winter (case a). It is also noticed that dome's window panes of 4 (NE), 14 (NW), 25 (SE), and 32 (SW) showed almost the same amount of heat conduction in the winter (case a). The maximum heat loss by conduction was observed to be about 61 W for dome's window pane 25 (SE), which was little bit higher than the other dome's windows panes (4 NE, 14 NW, 25 SE, and 32 SW), which were all almost the same, being around 58 W at 08:00 h in the winter (case a). During the period from 09:00 h to 17:00 h, the mosque building experienced greater heat loss than heat gain by conduction, particularly through the dome's window pane 32 (SW) with a maximum heat loss of about 45 W at 16:00 h in the winter (case a) (Figure 20).

On the other hand, the mosque building indicated great heat loss by conduction through all of the dome's windows during the periods from 01:00 h to 07:00 h and from 21:00 h to 24:00 h in the summer (case b). The maximum heat loss was found to be about 69 W occurring at 04:00 h for the dome's

windows panes 4 (NE), 14 (NW), 25 (SE), and 32 (SW), which also showed almost the same trends during most of these periods in the summer (case b). In addition, the period from 08:00 h to 20:00 h experienced greater heat loss than heat gain, especially during the period from 08:00 h to 12:00 h in the summer (case b). Furthermore, it is found that dome's windows panes of 25 (SE) and 4 (NE) showed greater heat gain by conduction than the other dome's windows, with maximum of about 31 W and 29 W respectively occurring at 17:00 h in the summer (case b) (Figure 20).

The reasons for these discrepancies and trends may also refer here to the influence of the solar radiation and the surface location and orientation. Since it is also noticed here that when there is no solar radiation and when the indoor temperatures become higher than the outdoor temperatures, therefore the building experienced heat loss in the summer. This may be supported by the poor quality of the building's fabrics and construction. When the indoor temperatures become lower than outdoor temperatures, during the day when there is great solar radiation, the building experienced heat gain.

5. Conclusions

This research paper investigated a number of small and large mosque buildings in term of thermal comfort in Abha city, which has a semi-arid/moderate and mountainous climate. A computer modelling assessment method was used to achieve the aim of this study. This research paper aimed to assess thermal comfort for all the selected mosque buildings' indoor environments and the thermal performance for their fabrics and constructions by using the thermal modelling of TAS simulation software. The factors, variables and parameters investigated in this chapter included DBT, RH, MRT, PMV, loads breakdown and annual demands, which influence occupants' thermal comfort, additionally to the mosque buildings' thermal performance (heat gain by solar radiation, and heat loss/gain by conduction). Loads breakdown and demand for each mosque building were predicted and estimated and compared with the actual energy-use.

The results showed that the temperatures as main factors affecting thermal comfort level were hardly within the acceptable limits of thermal comfort, especially when applying free running mode in the selected mosque buildings particularly in the summer and hot periods when there are great diurnal differences, since the indoor DBT for all mosque buildings ranged from 14 °C to 19 °C in the winter, while it ranged from 19 °C to 26 °C in the summer. The results also showed that all types of temperatures including DBT, MRT, and T_{Res} were lower or close to the lower limit of thermal comfort in all of the selected mosque buildings with a minimum temperature of 14 °C in the winter experiments. Whereas, they were higher or close to the upper limit of thermal comfort with a maximum temperature of 30 °C in the summer.

With regards to RH, the results revealed that TAS's indoor RH were mostly above the upper limit of RH comfort (65%), especially during winter. However, TAS's indoor RH for all mosque buildings was below the lower limit of RH comfort (30%) all the time in the summer experiment days. Since, it ranged from the lowest RH of 42% during summer to the highest RH of 100% during winter days. This means indoor environments in all mosque buildings experienced wetness in the winter, although most of the times it was within the limits of RH comfort in the summer experiment days.

In terms of PMV, the results showed that there were significant discrepancies between PMV in controlled mode and in free-running mode in all of the selected mosque buildings. It was observed that PMV in controlled mode for all mosque buildings ranged from −1.46 to +1.47, which were out of the acceptable thermal comfort limits. Yet, it ranged from −1.95 to +1.70, which were also out of the acceptable thermal comfort's limits when applying free-running mode. However, the results showed that in all of the selected mosque buildings around 75% of the year, PMV were in the range of $-1.0 < PMV < +1.0$, which is also considered as the acceptable limit, except during the summer period (for free running mode). Furthermore, in terms of load breakdown and annual demands, it was found that there were significant heat gains because of the great amount of solar radiation that mosque buildings' surfaces received, especially when facing the sun in the summer, and in light of the poor fabrics and construction for the mosque buildings. Solar gain ranged from 13,995 W to 51,906 W for

all of the selected mosque buildings. This significant solar gain, together with other types of gain (such as internal gains), caused great cooling demands in all mosque buildings, especially in the summer periods. The cooling demand ranges from the minimum of 3927 kW·h to 15,419 kW·h for all mosque buildings.

Although, the results displayed that the amount of heat gain during a whole year was greater than the heat loss through all of the loads' categories in all of the selected mosque buildings. However, poor quality of the mosque buildings' fabrics and construction (roofs, floors, windows, doors, and external walls) caused great heat loss, which in turn caused considerable heating demands in all of the selected mosque buildings. The heating demand caused by the amount of heat loss ranges from 1089 kW·h to the maximum estimated heating demand of 4233 kW·h for all mosque building.

In addition, it is really hard to find the correlation of loads breakdown and demand from the results obtained by simulation method and the actual results except in the large mosque building (NEA-2 mosque), in which the correlation was well noticed. The other small mosques were not operated and used in all prayers in all days during the whole year and the electricity bills for those mosques were calculated based on real usage. Thus, there were discrepancies between loads breakdown and demand from the results obtained by simulation method and the actual results for the small mosque buildings.

The outcomes from the field studies revealed that the main factors behind the heat gain or loss were the poor quality of the investigated mosque buildings' envelopes to include roofs, windows, doors, floors, and walls in the winter and the summer. The thermal simulation processes using TAS software came to support the findings from the field studies, since it also indicated that all of the investigated mosque buildings experienced significant heat gain and loss in the summer and the winter through their poor fabrics and constructions. It is also found that from both methods of assessments (Field studies and TAS simulation), the differentiations in the climates, locations, and orientations of the selected mosque buildings showed different conclusions. Solar radiation and because of the previous mentioned reasons affect different elevations (outdoor and indoor) of the selected mosque buildings differ from one location to another. Therefore, the designs and solutions for those elevations should be addressed and designed differently. To conclude this article, unless applying passive cooling/heating techniques and sustainable operation systems based on environmental study results, there will be very large negative impacts on the environment. Thus, a number of suggested improvements including different materials, designs, sustainable techniques and systems (based on the problems have been found from both methods of assessments) should be explored in the next studies, and comparing the results obtained after the improvements with the results obtained from the field studies and from the simulation studies (for the current situation). This is in order to see to what extend the suggested improvements fulfil the sustainability and reduction in CO₂ emissions in this type of buildings.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/10/4014/s1>.

Author Contributions: Conceptualization, A.A.A.S.; methodology, A.A.A.S. and M.B.G.; software, A.A.A.S. and M.B.G.; validation, A.A.A.S.; formal analysis, A.A.A.S.; investigation, A.A.A.S.; writing—original draft preparation, A.A.A.S.; writing—review and editing, M.B.G.; supervision, M.B.G.; project administration, A.A.A.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

DBT	Dry Bulb Temperature	(°C)
TAS	Thermal Analysis Software	
MRT	Mean Radiant Temperature	(°C)
Met/M	metabolic rate	(W/m ²)
RH	Relative Humidity	(%)
HVAC	Heating, Ventilation, and Air Conditioning	
DOE	Design of Experiments	
A/C	Air Conditioning	
SCECO	The Saudi Consolidated Electric Company	
OPEC	Organization of the Petroleum Exporting Countries	
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	
ISO	International Organization for Standardization	
PMV	Predicted Mean Vote	
PPD	predicted percent of dissatisfied	
CIBSE	Chartered Institution of Building Services Engineers	
EN	European Union	
ANSI	American National Standards Institute	
MOIA	The Saudi Ministry of Islamic Affairs	
SBC	Saudi Building Code	
CFD	Computerized Fluid Dynamics	
EDSL	Environmental Design Solutions Limited	
IES	Integrated Environmental Solutions	
CAD	Computer aided design	
AHA	Al-Sheikh Ali Al-Hayyani in Abha	
NEA	Noor El-Eeman in Abha	
QA	Al-Qudse in Abha	
SW	South western	
NE	North eastern	
SE	South eastern	
NW	North western	

Table A1. Details of opaque constructions and the component materials for the selected mosque buildings. Produced table based on data collected from the MOIA and TAS software [3].

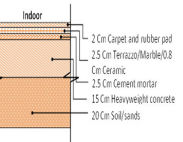
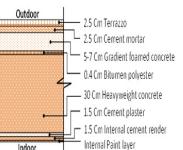
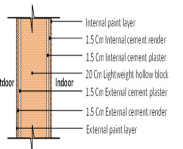
Envelope Type	Material Type	Based on the Ministry of Islamic Affairs (MOIA)				Based on TAS Programme					
		Description of Materials	Thickness (cm)	Conductivity (W/m. °C)	Specific Heat (J/kg. °C)	Density (kg/m ³)	Solar Reflectance		Emissivity		
							External	Internal	External	Internal	
Ground floor	Opaque		Carpet and layer of rubber pad	2	0.06	1382	288	0.30	0.30	0.90	0.90
		Terrazzo tiles or Ceramic or Marble	2.5	1.75	850	2400	0.35	0.35	0.90	0.90	
		Cement mortar	0.8	1.30	1000	2300	0.30	0.30	0.90	0.90	
			2.5	2.40	840	2600	0.55	0.55	0.95	0.95	
			2.5	0.94	1000	1750	0.30	03.0	0.90	0.90	
		Heavyweight concrete of 0.8m ³ , 0.4 m ³ sands, and 250kg/m ³ Portland cement	15	1.95	921	2243	0.35	0.35	0.90	0.90	
		Clean sands for filling the ground spaces under the concrete layer	20	0.81	837	1800	0.18	0.18	0.91	0.91	
Roof	Opaque		Terrazzo tiles	2.5	1.75	850	2400	0.35	0.35	0.90	0.90
		Cement mortar	2.5	0.94	1000	1750	0.30	03.0	0.90	0.90	
		Gradient foamed lightweight (L.W.) concrete of Portland cement 500 kg/m	5–7	0.53	837	1281	0.35	0.35	0.90	0.90	
		Cement plaster	3	0.42	837	1200	0.60	0.60	0.90	0.90	
		Bitumen polyester 180/m ² for waterproofing	0.4	0.50	1000	1700	0.26	0.26	0.91	0.91	
		Heavyweight concrete 0.8 m ³ , 0.4 m ³ sands, and 250 kg/m ³ Portland cement	30	1.95	921	2243	0.35	0.35	0.90	0.90	
		Cement plaster	1.5	0.42	837	1200	0.60	0.60	0.90	0.90	
		Internal cement render	1.5	0.50	769	1300	0.60	0.60	0.90	0.90	
		Internal paint layer	0.2	999.9	0.001	0.001	0.64	0.64	0.92	0.92	
External wall	Opaque		Internal paint layer	0.2	999.9	0.001	0.001	0.64	0.64	0.92	0.92
		Internal cement render	1.5	0.50	769	1300	0.60	0.60	0.90	0.90	
		Cement plaster	1.5	0.42	837	1200	0.60	0.60	0.90	0.90	
		L.W. hollow concrete block	20	0.50	880	465	0.35	0.35	0.90	0.90	
		Cement plaster	1.5	0.42	837	1200	0.60	0.60	0.90	0.90	
		External cement render	1.5	0.57	1000	1300	0.30	0.30	0.90	0.90	
		External paint layer	0.2	999.9	0.001	0.001	0.64	0.64	0.92	0.92	

Table A1. Cont.

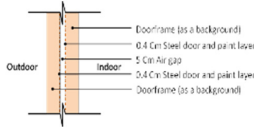
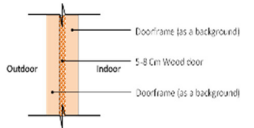
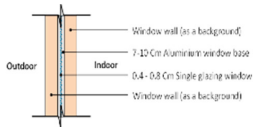
Envelope Type	Material Type	Based on the Ministry of Islamic Affairs (MOIA)				Based on TAS Programme					
		Description of Materials	Thickness (cm)	Conductivity (W/m. °C)	Specific Heat (J/kg. °C)	Density (kg/m³)	Solar Reflectance		Emissivity		
							External	Internal	External	Internal	
Door & Window	Opaque										
			Steel and paint	0.2	43	500	7800	0.47	0.47	0.25	0.25
			or Wood Aluminum of 1.5mm for window frame	5 10	0.15 204	1633 896	609 2700	0.40 0.50	0.40 0.50	0.90 0.22	0.90 0.22

Table A2. Details of transparent materials and the component materials for the selected mosque buildings. Table based on data collected from the MOIA and TAS software [3].

Material Type	Description of Materials	Conductivity (W/m. °C)	Solar Reflectance		Solar Transmittance	Light Transmittance		Light Reflectance	Emissivity	
			External	Internal		External	Internal		External	Internal
Window	Transparent	Window glass	1.73	0.10	0.10	0.69	0.08	0.08	0.89	0.84
	Transparent	Light blind	1.00	0.50	0.50	0.40	0.50	0.50	0.40	0.85
	Transparent	Or dark curtain	1.00	0.38	0.38	0.11	0.38	0.38	0.11	0.85

Table A3. The description of the instruments were used for the field studies.

Specifications	Infrared Thermometer DT-8862 	WBGT Meter 	CEM AAVM-8880 CAL Kit - Hot Wire USB Logging Anemometer 	CEM USB Temperature and Humidity Datalogger-DT-172 	MP-100 Pyranometer Solar Radiation Shortwave 
Range	−50~650 °C (−58~1202 °F) 0 to 50 °C (32 to 122 °F) −10 to 60 °C (−14 to 140 °F) 10%~90%RH	32 to 122 °F (0 to 50 °C) 32 to 176 °F (0 to 80 °C) 32 to 122 °F (0 to 50 °C) 0 to 100%RH	0.1 to 25 m/s × 0.01 0 to +50 °C, 32 to 122 °F 1 °C/1.8 °F	0 to 100%RH, −40 to 70 °C	Spectral Range: 380 to 1120 nm
Resolution	0.1 °C (0.1 °F) <1000 1 °F >1000		0.01	0.1%RH, 0.1 °C	
Accuracy	±2.5 °C (−50 °C to +20 °C) ±1.0% of reading ±1 °C (+20 °C to 300 °C) ±1.5% of reading (+300 °C to 650 °C)	±3%RH ±1.8 °F/1.0 °C ±4 °F/2 °C	±5%	+2%RH, +1 °C	± 5%
Response time	Less than 150 ms Spectral response = 8~14 um Digitally adjustable from 0.10 to 1.0			2 s to 24 h	Less than 1 s Cosine Response: 45° Zenith angle: ± 1% 75° Zenith angle: ± 4%
Weight	163 g	136 g	323 g	295 g	150 g
size	146 × 104 × 43 mm	10 × 1.9 × 1.1" (254 × 48.7 × 29.4 mm) Ball: 1.6" dia, 1.4" high (40 mm diameter, 35 mm high)	210 × 75 × 50 mm unit 0.3 × 1 m probe	94 × 50 × 32 mm	2.4 cm diameter by 2.75 cm height

Table A3. Cont.

	Infrared Thermometer DT-8862	WBGT Meter	CEM AAVM-8880 CAL Kit - Hot Wire USB Logging Anemometer	CEM USB Temperature and Humidity Datalogger-DT-172	MP-100 Pyranometer Solar Radiation Shortwave
Specifications					
Safety	"CE" complies with EMC				
Accessories and Features	- Supplied with 9V battery - Carrying case and box.	- Auto power off with override - Built-in RS-232 interface with optional Windows® compatible software - Complete with two AAA batteries	- USB interface for real-time transfer of readings to a PC - Supplied with USB connection cable, software, hard carry case, telescopic hot wire probe, battery and AC/DC Mains power adaptor 9V PP3 alkaline battery (ALR-61) or AC/DC mains power adaptor (supplied)	- Manual 2 × screws - Battery typically 3 years - Holster - USB lead & Windows software - Padlock - Memory: 32000(16000 each for temperature and humidity) - Analysis software: Windows 98/2000/XP/Vista/Windows 7 32&64 Bit	3V coin cell battery (included) 99 manually stored data points 1 year against defects in materials and workmanship

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