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Effect of Mosque Architectural Style on Its Thermal Performance

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Abstract: Mosque acquires its importance from being the main spiritual centre for Muslims. Hundreds of thousands of mosques have been constructed to serve Muslims across the world. This resulted in a wide diversity of design criteria, where different architectural elements and styles could be distinguished. This study aims to discuss the rationale and characteristics of these architectural styles in addition to their effect on mosque thermal performance. Computerised environmental modelling has been implemented using Ecotect program to compare four modelling cases that represent different geometries and geographical locations. Results obtained show the significant effect of mosque architectural style on its thermal performance. The different modelled cases showed different behaviours in terms of building occupants' thermal comfort, where a variation up to 80% has been observed.

Key words: Mosque, architectural style, thermal performance, thermal comfort.

تأثير الطراز المعماري على الأداء الحراري في عمارة المساجد

ملخص: يكتسب المسجد مكانته من كونه مركزاً روحياً للمسلمين، لذا نجد أنه قد تم إنشاء مئات الآلاف من المساجد لخدمة المسلمين في كافة أنحاء العالم، وقد نتج عن ذلك تنوع كبير في معايير التصميم، حيث ظهرت عناصر وطرز معمارية مختلفة في عمارة المساجد، وتهدف هذه الدراسة إلى مناقشة خصائص هذه الطرز المعمارية ومبرراتها، وذلك بالإضافة إلى تأثيرها على الأداء الحراري لمباني المساجد، وقد تم في هذا الإطار تطبيق التمثيل البيئي باستخدام الحاسوب، وذلك بهدف مقارنة أربع حالات افتراضية تعكس أنماطاً معمارية وظروفاً مناخية مختلفة، وقد أظهرت النتائج أن الأداء الحراري للمسجد يتأثر بشكل كبير بطبيعة طرازه المعماري، وانعكس ذلك في الحالات التي تمت دراستها على مستوى الارتياح الحراري لمستعملي المبنى، حيث تم تسجيل تفاوت في الأداء بلغ 80% عند مقارنة تلك الحالات.

1. Introduction

Mosque is the English word used to identify a specific building type called in Arabic *Masjid*. The origin of the latter word is the verb *sajad*, which means to prostrate. Thus, the simplest form of mosque could be a defined enclosure, usually covered, with its floor used for prayer. Historically, mosque function was not limited to worship. This was a response to the concept of the congregational characteristic of this building type, which is concluded from the Islamic traditions related to the Prophet Mohammed (PBUH) Mosque in Medina. Thus, mosque function over history had included three main aspects [1]:

- Worship side (performing of prayers, Friday ceremony, etc).
- Socio-cultural side (educational circles, community problems, etc).
- Political and legislation side (leadership meetings, judgement, etc).

Many designs nowadays, like Islamic centres in the west, started to reclaim a more comprehensive role of the contemporary mosque as a multi-purpose building. This is implemented by the use of many facilities attached to the prayer hall to meet the society needs, mainly for welfare. This highlights the importance of investigating the thermal performance of this building type to ensure that its occupants are thermally comfortable. Therefore, this study aims to highlight this important aspect of mosque design. This is because this type of buildings possesses high importance and respect in urban societies, as well as other religious buildings. For that reason, it is possible to benefit from this symbolism to increase public awareness of the importance of environment conservation and energy saving issues.

Although many studies had focused on mosque architectural design, few of them discussed the environmental aspects of this design. For example, Abideen [2] found that it is possible to significantly reduce cooling load of air-conditioned mosques in Jeddah city by utilizing adequate passive means. Abideen found that the proposed passive cooling strategy secures savings around 82% in air conditioning energy, 50% in money, 28% in CO^2 emission, and 80% in CFCs emission on the city level. Al-Najim and Al-Mofeez [3] investigated the climatic conditions in the eastern region of Saudi Arabia. They found that mosque courtyard can be used as prayer area for a period up to 32% of the overheated period of the year, and recommended further investigation of the courtyard thermal potential in mosque buildings.

2. Mosque Architecture

When Prophet Mohammed (PBUH) established his mosque in Medina in 622 AD, its design was simple and homogeneous with its urban context. It was essentially a large courtyard enclosed by plain walls with three gates and some attached accommodation rooms. Along the *Qiblah* wall, the wall that faces direction of Mecca, a shed was erected from palm trunks carrying a roof of palm leaves plastered with mud to protect people of sun. Another covered area was in the opposite side to accommodate the guests of Islam. The architecture of the Prophet mosque indicates its multi-use as a focal point for Muslims in Medina [4].

In the subsequent centuries, Islam has spread outside the Arabian Peninsula from Spain to China. Number of mosques in one city increased from one large mosque, which is called *al-Masjid al-Jami'*, the general mosque, to many and may be hundreds of mosques. Mosque design has developed as a response to the regional available resources and needs. Different architectural elements are used in mosque buildings nowadays. These different elements are grouped in different styles of design to accommodate one entity.

2.1 Mosque Constituent Components

This part aims to briefly describe the main elements in mosque buildings, while the following one discusses their architectural styles.

2.1.1 Prayer Hall

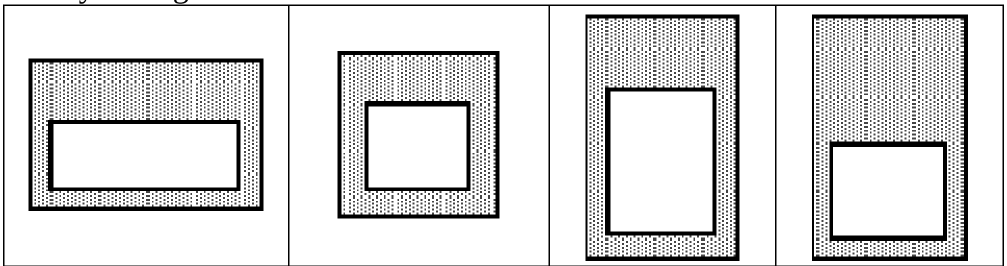
Mosque main volume, or prayer hall, is the place in which prayer is performed. It is known in Arabic as *Bait as-Salah*. It also contains a place for females in the backside of the hall or in the mezzanine floor. The prayer hall is usually rectangular or square in plan. However, it is recommended to be nearer to the rectangular shape to allow more length for the first lines, which has a special virtue in Islamic traditions. It could be covered by flat or pitched roof. Alternatively, roofing system may include a dome or more in different styles.

2.1.2 Dome and Minaret

Dome and minaret have been used in different forms in many historical mosques. It is commonly claimed that dualism of dome and minaret has a symbolic value. Dome represents the vault of heaven, and minaret reflects declaration of faith. This is in addition to their functions. Dome is used as a roofing system that covers the prayer hall with less number of columns. It is also used to provide natural ventilation and lighting the prayer hall central zone. Minaret is the principal vertical feature of mosque architecture that is used to raise the prayer call.

2.1.3 Courtyard

Mosque courtyard is a normal courtyard attached to the covered prayer area. It is usually used to provide an extra-uncovered area for seasonal prayers or for other uses like social activities. Courtyard area varies in relation to prayer hall area as illustrated in Figure (1). Also, ablution facilities could be placed in the courtyard. In many regions, like Andalusia, different plants were used to decorate mosque courtyard. According to Hillenbrand [4], rectangular courtyard in mosques is the most common one, with emphasising on width or depth. Arcades or flat-roofed portico articulates the courtyard edges.



- The Great Mosque of Damascus. - Qarawiyyin Mosque, Fez.	- Prophet Mosque (al-Walid rebuilt). - Ibn Tulun Mosque, Cairo.	- Great Mosque of Samarra. - Great Mosque of Qairawan.	- Great Mosque of Cordoba. - Mansur Mosque.

Figure 1: Different mosque courtyard configurations

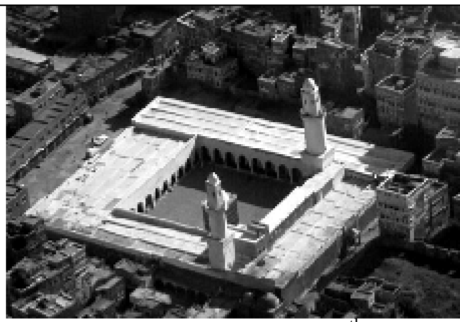
2.2 Mosque Historical Architectural Styles

Hillenbrand [4] presented a summarised classification of mosque architectural styles. He divided mosque architectural styles in the Middle East into three main categories according to their geographical location. These styles are: the Arabic, the Iranian, and the Turkish or Ottoman style. He then attempted to accommodate all other regional variations under one or other of them due to the characteristic similarity between them.

2.2.1 Arabic Style

This style appeared in Medina in the Prophet Mosque, which has been discussed in section (1) of this study. It is also named ‘hypostyle mosque’ because of its structural system, where many regularly spaced pillars or arcades support the roof. The Arabic mosque style consists of a large courtyard and a covered prayer hall with flat or pitched roof. Domes and minarets have been integrated with this style in different shapes in a later stage. The use of *riwaq*, a covered walk on courtyard edges, is common in this style as extra prayer area. This style includes many historic periods like Umayyad and Abbasid dynasties, Moroccan mosques, and Egyptian mosques [5].

(a): Dome of the Rock, 6^{th} century, Jerusalem [Photo by the author].



(b) Great Mosque of Sana'a, 8^{th} century, Sana'a, Yemen: Aerial view [6]

Figure 2: Some historical examples on Arabic style mosque

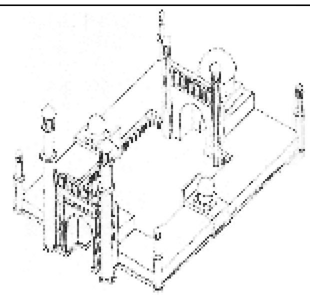
2.2.2 Persian Style

The Iranian style was common in some parts of the eastern Islamic world. The early mosques in Iran were similar to Arab mosques. It includes many historic periods like *Saljuq* and *Safavid* mosques. Iranian architects enriched the hypostyle mosque by two elements [4]:

- The dome chamber: one configuration here is to use dome near the *mihrab* or above it to emphasize the direction of *Qiblah*.
- The *iwan*, which is a vaulted open hall with rectangular arched facade used as a monumental entrance.

Many ideas have been applied to combine between these two elements. Some of them are the use of many *iwans* in different sides of the courtyard, or to use of twin minaret at the corners of the dome chamber, as illustrated in Figure (3). The bulbous dome, or the onion shaped dome, is a favoured shape in this style. This style is also well known by the extensive use of colour and ornaments, which is used also to cover domes.

(a) Abdullokhon Mosque, 16^{th} century, Tajikistan: the entrance [6].

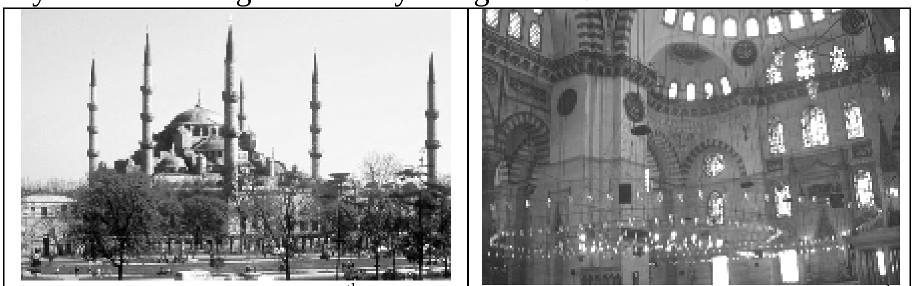


(b) Bibi Khanum mosque, 14th, 15^{th} century, Uzbekistan [4].

Figure 3: Some historical examples on Persian style mosque

2.2.3 Ottoman Style

The Turkish or Ottoman style was common in Anatolia and other parts of the Ottoman Empire. It is well known by the emphasized use of domes and pencil-like minarets. In contrast with Iranian style, the Turkish style focuses on the integration of domes with spaces around it. Size and design of dome in the Ottoman style had been apparently increased and developed. Dome in this style may cover the entire plan with lateral and smaller numerous domes. This increased height of the roof and resulted in a massive appearance of the mosque. It is possible to say that the Ottoman style changed the concept of mosque buildings from semi-opened enclosure to a totally closed building crowned by a large dome.



(a): Sultan Ahmed mosque, 17th century, Istanbul: the multiple domes and cylindrical minarets [6].

(b): Süleymaniye Mosque, 16th century, Istanbul: interior massive height [6].

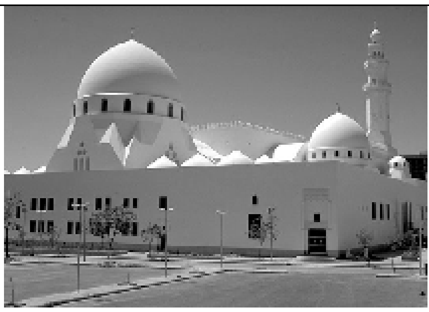
Figure 4: Some historical examples on Ottoman style mosque

3. Style Dilemma and the Contemporary Mosque

In the recent decades, the development of architectural design theory and structural systems has obviously affected mosque design. Although, many necessary design requirements still to be considered, like orienting towards Mecca, the argument regarding the necessity of other elements, like dome and minaret, could not be ignored. In spite of this argument, it is crucial to preserve mosque historical typology in order to keep this building type linked to the Islamic history, and to express the Islamic identity of the Muslim societies across the world. One way of achieving this target is to highlight the environmental potential of mosque architectural elements.

This means that even when mosque design is intended to be modern; it should reflect the historical architectural identity. As an example [7], Turkey is a large Islamic country with a rich Islamic heritage of Ottoman mosques. Under the rule of a secular state, many architectural designs there are intended to express the trend of modernism. However, this did not result in mosque models that are isolated from the context of that heritage. As shown in Figure (5), contemporary mosques can be designed in a way that represents a mix between traditional elements and contemporary materials and construction methods.

Corniche Mosque, Jeddah [6].



King Saud Mosque, Jeddah [6].

Figure 5: Some contemporary mosques that reflect a good combination between past and present

4. Effect of Mosque Architectural Style on its Thermal Performance

In order to highlight the environmental potential of mosque architectural elements, as argued in section (3), an exploratory thermal modelling study will be carried out n this section. This will be done by implementing computerized thermal performance modelling using Ecotect 5.5 program. This software is a widely-used building design and environmental analysis tool that offers several analysis functions to demonstrate how buildings operate thermally. It allows for three-dimensional modeling of buildings considering many variables like geographical location, building design and materials, ventilation and lighting systems, etc.

In order to understand the relationship between mosque architectural style and environmental performance, it is essential to analyse these buildings to their constituent components. This has been reviewed in Section (2) of this study. It is possible to conclude that many parameters of mosque architecture can affect its environmental performance. However, two geometrical parameters in the reviewed mosque architectural styles will be tested here in order to cope with the limitation of this study:

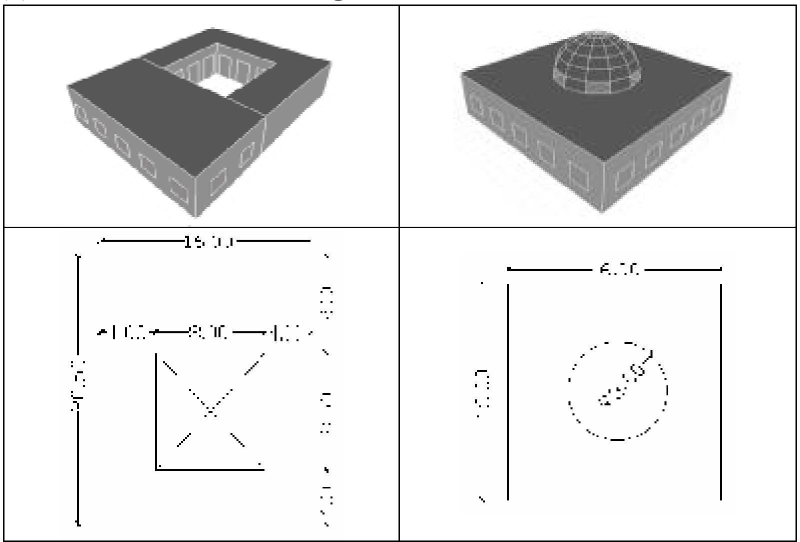
- Mosque space enclosure, where the building could be closed or semi-opened to the external environment.
- Mosque roof shape, where the building could be covered by flat or domed roofing system.

It is important also to consider the effect of the climatic conditions. Ecotect doesn't offer a wide range of building locations in the Middle East. Thus, two cities that represent two common climatic conditions in the Middle East will be tested. These are the cities of Riyadh and Rome to respectively represent hot-dry and temperate climatic conditions.

Thus, this study will assume four cases:

- Case A-h: is a semi-opened enclosure with flat roof as an example on the Arabic styles. Building is exposed to hot climatic conditions.
- Case A-t: is a semi-opened enclosure with flat roof as an example on the Arabic styles. Building is exposed to temperate climatic conditions.
- Case B-h: is a totally closed building with domed roof as an example on the Ottoman style. Building is exposed to hot climatic conditions.
- Case B-t: is a totally closed building with domed roof as an example on the Ottoman style. Building is exposed to temperate climatic conditions.

Figure (6) illustrates the two configurations that will be tested in this study:



Configuration A	Configuration B

Figure 6: Illustration of the modeling configurations

To allow for a fare comparison, all modeling parameters will be assumed fixed apart from building geometry and location. These parameters are as follows:

- Building covered area is assumed 225 m^2, and building height (H) is 4 m. In Configuration A, this area is evenly divided between the main prayer hall and the porticos (*riwaqs*) that surround a courtyard. In Configuration B, this area is represented by a square plan that is covered by a hemispherical dome.
- Building materials: concrete slab with water insulation for roofs, concrete blocks for walls, and single glazing with aluminium frame for windows.
- Building occupancy: 200 persons in low activity. Using the 'Operation Schedule' facility in Ecotect software, 80% of this number will be

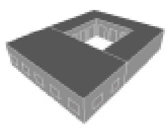
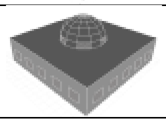
assumed to use the mosque five times a day for five hours, while 20% will be assumed to use the mosque at the rest of times.

- Internal heat gains: these gains mainly occur due to lighting in mosque buildings. In residential buildings, lighting heat gains can be assumed $11 W/m^2$ using high frequency luminaries [8]. Thus, heat gains due to lighting and other equipments will be assumed 15 W/m^2.
- HVAC system: natural ventilation. Building porosity (opening area) is assumed 20% of the floor area. In Configuration A, this area is evenly divided between the main prayer hall and the *riwaqs*. In Configuration B, this area is represented by regularly distributed wall openings (90% of the opening area) and dome openings (10% of the opening area).

It is possible to assess the resulting thermal performance of these cases depending on the level of occupants' thermal comfort. This parameter measures periods over which those occupants feel too hot, when temperature exceeds 26^{o}C, or too cold, when temperature drops below 18^{o}C. Ecotect specifies these periods depending on percentage of discomfort time, total hours of discomfort, or discomfort degree hours. The last method has the advantage of not only specifying the time of discomfort but also specifying to which extent occupants feel uncomfortable. One degree hour of discomfort means that the zone spent 1 hour at 1 degree below or above the comfort limits.

Table (1) shows the resulting discomfort degree hours in the different tested cases. These values have been averaged for summer months (June, July, and August), and for winter months (December, January, and February). It is important to notice that data obtained here are not intended for design purpose. Rather, they will be used to give a general assessment of the effect of mosque architectural style on its thermal performance.

Table 1: Occupants' thermal comfort assessment using discomfort degree hours for the different tested cases

Illustration	Cases	Summer	Winter
	Case A-h	9986	650
	Case A-t	1451	4516
	Case B-h	7208	1274
	Case B-t	248	7070
*** 'h' refers to the hot climate, while 't' refers to the temperate climate**.			

It is possible to notice from Table (1) that Configuration A (cases A-h and A-t) performs better during winter when compared to Configuration B. This is regardless the climate being hot or temperate. Discomfort degree hours recorded in winter for Case A-h are less by about 50% when compared to Case B-h. Also, discomfort degree hours recorded in winter for Case A-t are less by about 35% when compared to Case B-t.

On the other hand, building Configuration B (cases B-h and B-t) performs better during summer when compared to Configuration A. Similarly to the previous observation, this is true in both hot and temperate climates. Discomfort degree hours recorded in summer for Case B-h are less by about 30% when compared to Case A-h. Also, discomfort degree hours recorded in summer for Case B-t are less by about 80% when compared to Case A-t.

The better performance of Configuration A in winter can be referred to many factors. Considering that the focus of this study is the building geometry, the main reason could be the courtyard. This is because buildings with courtyards offer substantial potential for creating improved indoor microclimate. This means that this architectural element offers a buffer zone that helps isolating the building from the unfavorable outdoor climatic conditions. This can be noticed by comparing air temperature profiles inside and outside the porticos (*riwaqs*) that surround the courtyard, as shown in Figure (7). Temperature profiles have been estimated on the 31st of December. According to Ecotect software, this is the average coldest day in Rome, which represents the temperate climate in this study.

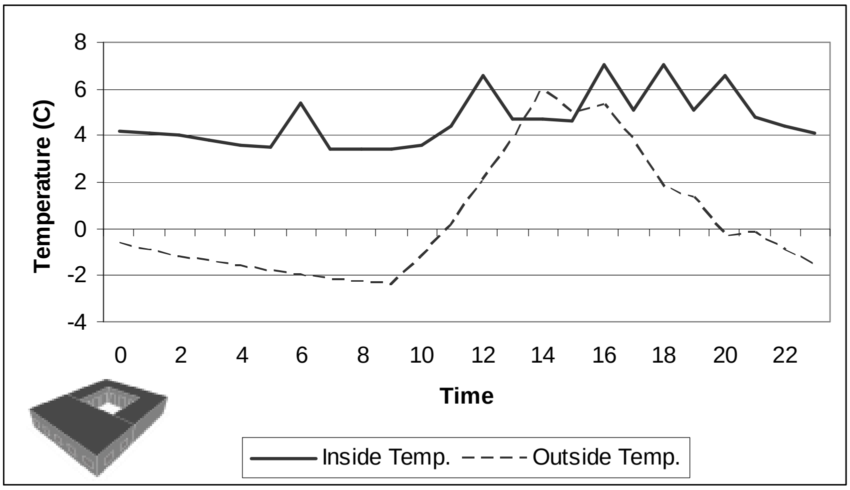


Figure 7: Air temperature profiles inside and outside Case A-t on the average coldest day of the year

It can be noticed in Figure (7) that the internal air temperature (inside the *riwaqs*) is higher than the outdoor air temperature for most of the day, which reflects the passive heating effect of the courtyard. This is not the case in Case B-t as can be noticed in Figure (8), where no courtyard has been used. Additionally, the pattern of building occupancy is clearly reflected in the internal temperature profile. Air temperature value fluctuates five times a day, which reflects times assumed for the daily five prayers.

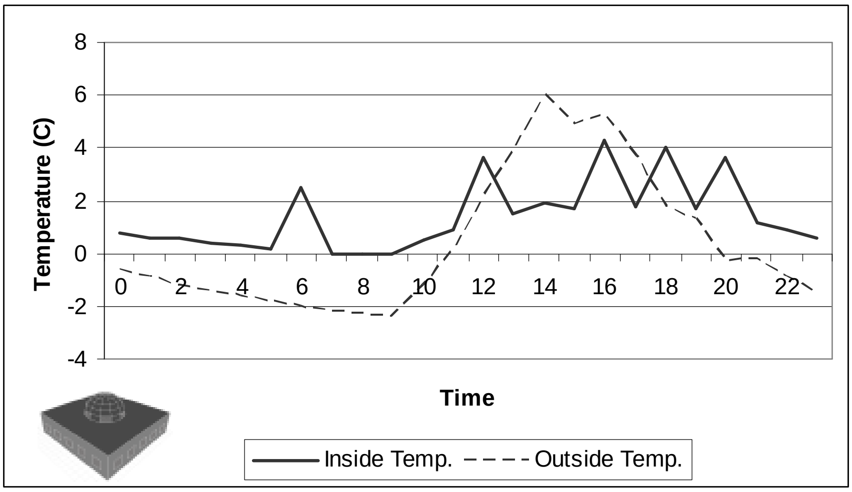
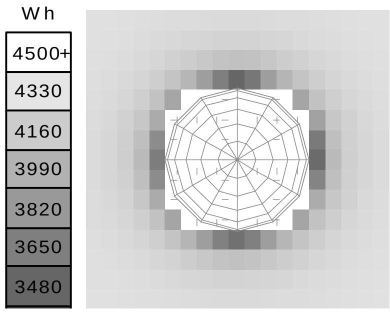
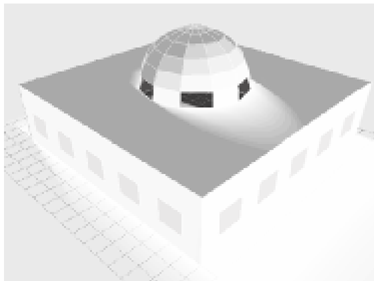


Figure 8: Air temperature profiles inside and outside Case B-t on the average coldest day of the year

In summer, building Configuration B performed better than building Configuration A, as indicated in Table (1). This can be linked to many factors including dome existence. Shade and shadow of the domed roof reduces its exposure to the incident solar radiation (insolation). This can be noticed by comparing insolation values for Case A-h and Case B-h. Insolation values at roof level have been estimated on the average hottest day in Riyadh, which represents the hot climate in this study. A uniform insolation value of 4500 Wh has been recorded at the flat roof level in Case A-h, while insolation value recorded at the flat roof level in Case B-h ranges between 3500 and 4500 Wh, as shown in Figure (9).



The incident solar radiation at roof level.



Shade and Shadow of the dome

Figure 9: The advantage of using the dome in Case B-h as observed on the average hottest day of the year

The previous presentation investigated the effect of mosque geometry on its thermal performance. However, other factors can not be ignored in the real design process. For example, thermal performance of Configuration A in summer can be improved, despite that Configuration B has been found to offer better thermal performance. It is possible to protect the building from the undesired outdoor climatic conditions during summer by increasing building insulation.

Assuming that U-Value of walls is reduced from 1.8 to 0.9, it is possible to reduce the total heat gain through building fabric by 20%. Figure (10) shows a comparison between heat gains through building fabric in the prayer hall in Case A-h before and after improving building thermal insulation. It is true also that performance of Configuration B in winter can be improved using the same strategy. Additionally, it is possible to study the effect of using night-time ventilation strategy along with the use of high thermal mass building materials. This strategy cools down the building envelop overnight so that it can effectively absorb heat gains during daytime, which in turn improves occupants' thermal comfort in the overheated periods.

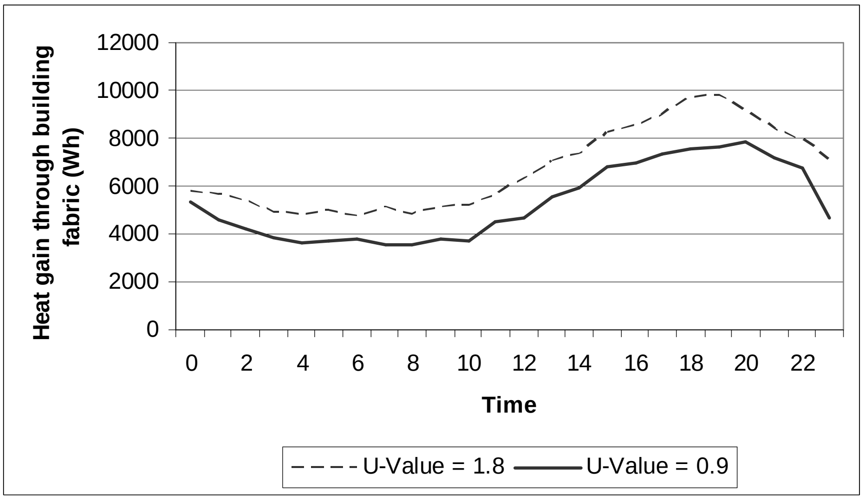


Figure 10: Heat gains through building fabric in Case A-h before and after increasing building insulation level

4. Conclusion

Mosque architectural elements and historical styles have been reviewed in this study. The conflict between the historical preference and contemporary architectural trends in mosque architecture was discussed and resolved from an environmental point of view. Since this building type has a great symbolic value in Muslim societies, it has been suggested that it is crucial to preserve mosque traditional topology and to cast more value on this topology utilising the contemporary technology. One way of achieving that is to expose and improve its environmental potential using advanced research techniques.

Thus, some mosque configurations have been tested using computerised thermal performance modelling. The effect of building geometry (Arbic and Ottoman mosque architectural styles) in different geographical locations has been considered as an example. It has been noticed that mosque architectural style is sensitive to its local environment, which necessitates that its thermal potential should be considered in the design process. For example, this study founds that the tested Arabic mosque configuration has been found to offer better thermal performance compared to the Ottoman one during winter season. This is because building users feel less discomfort by about 50% in the case of hot climate and by about 35% in the case of temperate climate. On contrary, the tested Ottoman mosque configuration has been found to offer better thermal performance compared to the Arabic one during summer season. This is because building users feel less

discomfort by about 30% in the case of hot climate and by about 80% in the case of temperate climate.
However, it is recommended that further researches have to be conducted to investigate the environmental potential of mosque architecture in details and recommend some design guidelines for the different climatic conditions.

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