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Enhanced Thermal Performance of Mosques in Qatar

To cite this article: A Al Touma and D Ouahrani 2017 *IOP Conf. Ser.: Earth Environ. Sci.* **104** 012012

Enhanced Thermal Performance of Mosques in Qatar

A Al Touma[1] and D Ouahrani[1,]*

[1]Department of Architecture and Urban Planning, College of Engineering, Qatar University, P.O. Box 2713, Doha, Qatar

*Corresponding Author: djamel@qu.edu.qa

Abstract. Qatar has an abundance of mosques that significantly contribute to the increasing energy consumption in the country. Little attention has been given to providing mitigation methods that limit the energy demands of mosques without violating the worshippers' thermal comfort. Most of these researches dealt with enhancing the mosque envelope through the addition of insulation layers. Since most mosque walls in Qatar are mostly already insulated, this study proposes the installation of shading on the mosque roof that is anticipated to yield similar energy savings in comparison with insulated roofs. An actual mosque in Qatar, which is a combination of six different spaces consisting of men and women's prayer rooms, ablutions and toilets, was simulated and yielded a total annual energy demand of 619.55 kWh/m^2. The mosque, whose walls are already insulated, yielded 9.1% energy savings when an insulation layer was added to its roof whereas it produced 6.2% energy savings when a shading layer was added above this roof. As the reconstruction of the roof envelope is practically unrealistic in existing mosques, the addition of shading to the roof was found to produce comparable energy savings. Lastly, it was found that new mosques with thin-roof insulation and shading tend to be more energy-efficient than those with thick-roof insulation.

1. Introduction

Thorough analysis of the buildings' thermal performances is crucial in mitigating the increasing energy consumption. Among different types of buildings, religious spaces require special function and operation treatments as the indoor environment necessitates thermal and visual comforts, tranquillity and peace.

Qatar, as most states of the Arabian Gulf region, suffers from a hot climate due to the long-lasting summer season where the outdoor temperature reaches a daily mean of 37.7 ℃ [1]-[2]. Air-conditioning (AC) is typically deployed from April through October, leading to tremendous electrical energy demands needed to control indoor spaces [3]. In fact, residential and non-residential buildings in Qatar consume over 60% of the total energy produced in the country [4]. According to the Ministry of Awqaf and Islamic Affairs [5], there are 1,227 mosques in Qatar. Since mosques compose a significant share of these buildings, any reduction in their thermal energy demands will result in significant energy savings that could be used in other more productive sectors.

In religious spaces, AC systems are usually kept on most of the time, which leads to limited indoor environment at considerable energy costs [6]. Since reduction changes in the AC systems are presumed to at least affect the indoor environment and the occupants' thermal comfort, reducing the mosque energy demands by enhancing its thermal envelope is considered as a better alternative solution.

The reduction of the mosque thermal energy demand using enhanced building envelope has been the scope of just a few researchers. For instance, the annual energy consumption of several mosques in the Kingdom of Saudi Arabia (KSA) was measured and an annual average of 182 kWh/m^2 was found [7]. Similarly, Al-Hamoud et al. [8] conducted experimental measurements on the total energy consumed in three different mosques in KSA. They found that air-conditioning cooling needs comprise up to 79% of the total energy of the mosque, where the rest is attributed to lighting and ventilation demands. In addition, it was found that a mosque with roof and wall thermal insulation layers added to the envelope consumed 93.5 kWh/m^2/year, much lower than another mosque with no insulation that consumed 201.5 kWh/m^2/year. Although their measurements were conducted on incomparable buildings, the results reflect the importance of envelope enhancement in yielding energy savings. Moreover, according to Budaiwi et al. [7], more than 20% of the annual cooling energy in mosques could be saved upon the addition of thermal insulation to its envelope.

Generally, mosques' walls in Qatar are thermally insulated as they comprise a considerable portion of the envelope surface area, whereas the roofs are left uninsulated. This study introduces a novel architectural shading design of mosques' roofs that is anticipated to yield similar energy savings in comparison with the conventional addition of insulation layers. In fact, since redesigning the roof construction layers is unpractical and consequently extremely expensive, the proposed model is applicable to both new and existing buildings.

2. Methodology

2.1. Description of the Mosque

This study considers an actual mosque in Qatar. The mosque design details, such as its footprint and construction material, were provided by the Ministry of Awqaf and Islamic Affairs [5]. The mosque, whose footprint is shown in figure 1, is composed of six different spaces.

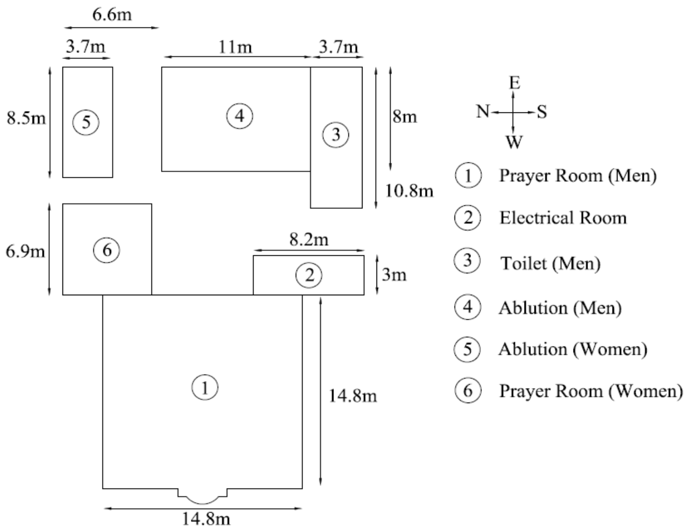

Figure 1. Schematic showing the mosque different rooms/spaces

As seen in figure 1, the selected mosque mimics an actual design of a prayer building in Qatar; it consists of a large prayer room for men, a smaller prayer room for women, separate ablution and toilets for men and women as well as an electrical and storage room. The spaces have different heights ranging from 3.8m to 5.75m, as well as different window and door sizes. The entire building has three entrances in the north, east and south orientations. The mosque design takes into consideration the necessities of any house of prayers in Islam. For this reason, women's privacy is ensured by their own entrance in the north direction that is blocked from the courtyard. In addition, their ablution space has no windows. On the other hand, the mosque considers the men's necessity to attend prayer times, and hence a larger prayer room of 218.3m^2 floor area was built for them. The door to the men's prayer room is on the wall facing east for worshippers coming from the other two entrances towards the courtyard. Both men and women prayer rooms consist of spaces with high ceiling, reaching 5.75m.

Furthermore, the mosque also considers the Mihrab, which is the niche that indicates the direction of the Kaaba in Makkah. The Minbar, which is the place where the leader of the prayer addresses the worshippers, has been built in the men's prayer room on the wall facing the west direction. Note that one meter high parapets have been built on the top of all six spaces, as seen in figure 2. These devices are used to prevent rain from reaching the vertical facades; it is accumulated in one corner and drawn down into sewage systems. Although the parapets are not tall, they are drawn on the spaces so that their minor effects on the buildings thermal performance is accounted for in the simulation. Note that this simplified mosque does not consider several architectural designs that might have little to no effect on its thermal performance.

The mosque envelope construction materials, starting from the outer layers, are as follows:

- Walls: 5mm gypsum plaster – 15mm sand/cement finish – 150mm thick hollow block – 100mm thick solid block – 50mm thick polyurethane insulation – 150mm thick hollow block – 15mm sand/cement finish (U-value = 0.57 W/m^{2}·K).
- Roofs: 15mm sand/cement finish - 300mm lightweight concrete (U-value = 1.85 W/m^{2}·K).
- Floors: 600mm lightweight concrete (U-value = 0.95 W/m^{2}·K).
- Windows: 6mm clear pane – 13mm airgap – 6mm clear pane (U-value = 1.95 W/m^{2}·K).
- Doors: 50mm thick solid wood door (U-value = 2.4 W/m^{2}·K)

2.2. Simulation Model

To be able to simulate the mosque and study its thermal performance, energy simulation software was deemed necessary. OpenStudio 1.13.0 software was selected for this purpose; it uses the EnergyPlus engine for the calculation of the thermal loads using the heat balance method, has a graphical user interface, and may use drawing software such as SketchUp Pro 16, the one picked in this study to build the mosque. A screenshot of the entire mosque as drawn on SketchUp software for simulation purposes is shown in figure 2.

After drawing the mosque, the construction envelope of the wall, roof and floor was designed layer by layer and attributed to the corresponding surfaces. Each space was assigned a unique zone of the same building for distinct air-conditioning control. The internal load consisted solely of electric lighting and occupancy as no electrical equipment seemed necessary. According to the Mosque Development Committee [9], the lighting power density in mosques should be in accordance with those outlined in ASHRAE 90.1-2007 Standards [10]. Hence, the lighting power density in the men and women's prayer rooms was set to 2.4 W/ft^2 (25.8 W/m^2) corresponding to religious buildings with worship pulpit, while it was set to 0.69 W/ft^2 (7.4 W/m^2) at the toilets and ablutions consistent with typical restrooms. However, these lighting power densities are not continuous; lights are rather assumed to be turned on and off depending on the occupancy schedule. Regarding the mosque occupancy, its density was set to 0.8 person/m^2. This value was found reasonable in this study, as it falls within the occupancy range of a typical mosque (0.62-1.00 person/m^2) [11]. The worshippers are considered to have a metabolic rate of standing people with light to medium activity, hence dissipating 160 W (2.0 met), according to ASHRAE Standard 55-2010 [12]. As for the occupancy schedule, Muslim traditions indicate five prayers per day, which may differ from one day to another. However, the variations in prayer times are in minutes and can be simplified into five fixed prayers. Note that this simplification will have no implication on the thermal analysis of the building. The appointed prayer times that were selected are 5AM, 12PM, 3PM, 5PM and 7PM. Note that each prayer time was estimated to last for 45 minutes, which is more than the time needed for typical prayers considering the arrival and departure periods of the worshippers. The occupancy schedule has been allocated to lighting demands as lights were turned off outside the prayer time intervals. Similarly, the occupancy schedule was attributed to the infiltration loads due to open doors as worshippers are coming into or out of the spaces. The infiltration rate was set to 1 ACH during occupied times and 0.5 ACH during unoccupied times [13].

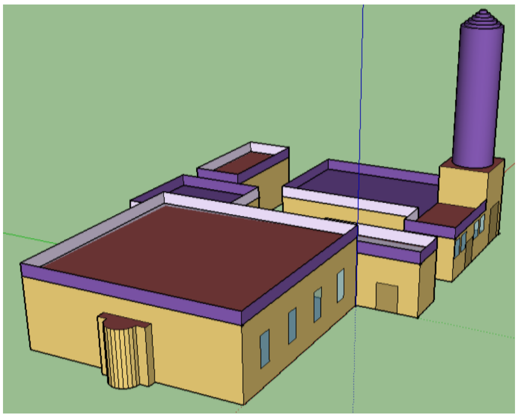

Figure 2. The entire mosque as drawn on SketchUp.

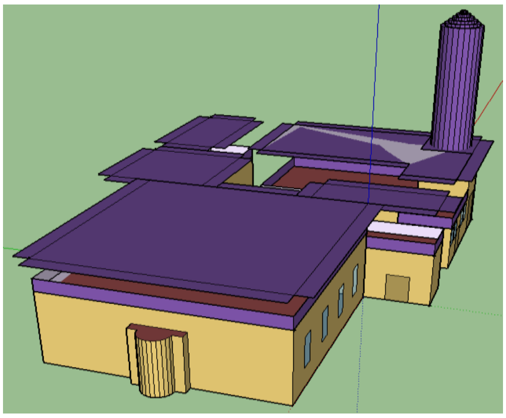

Figure 3. Mosque with shading installed on the roof.

Due to the hot weather conditions in Qatar almost throughout the year, the windows were assumed to be fully-closed. The *Turn On Ideal Air Loads* option was used in order to estimate the site total heating and cooling thermal energy demands without having to define any detailed air-conditioning system [14]. Also, the cooling set-point temperature was set to 24 ℃ all day throughout the year since literature has proven little tendency of turning off the cooling systems in mosques even outside the occupancy intervals. Yet, one of the limitations of this software is that it assumes dual set-point schedule, and hence a heating set-point temperature is required [14]. In other words, a heating schedule should be inputted even into the zones that are expected to require cooling only. Research has shown that this problem is mitigated by selecting a heating schedule that initiates at a practically unachievable low temperature, such as 12 ℃.

2.3. Mitigation Methods for Enhanced Thermal Performance
The first alternative that is considered to mitigate the high total energy demand of the mosque and reduce its cooling loads is the addition of thermal insulation to the roofs. Similar to the ones installed on the walls, a 50mm and 100mm thick polyurethane insulation layer is installed on the roofs between the concrete and the sand/cement finish. In comparison with the old 1.85 W/m^2.K U-value, the new roofs with 50mm and 100mm insulation layers have U-values of 0.56 W/m^2.K and 0.33 W/m^2.K, respectively.

The second alternative considered in this study is the installation of shading device above the roofs of all spaces of the mosque. The purpose of this mitigation method is to come up with a better solution to save energy in comparison with the addition of insulation layer, and is applicable to existing mosques and cheaper in terms of initial capital cost. The new shading device is added at a 1.5m above the parapet level and covers the entire spaces roof surface area. The distance above the parapet height serves as a space for the heated air to be convected away through the passing air currents, hence removing heat accumulated within this area. In addition, these shadings are extended one meter in all directions for installation purposes. A screenshot of the updated mosque as drawn on SketchUp is shown in figure 3. The Casting Real-World Shadows feature on SketchUp was used to check whether the distance of the roof shading is able to shade most of the roof surface area, and the visualization seemed satisfactory. Both updated simulations were run and further analyses were conducted to compare their corresponding energy savings.

2.4. Outdoor Conditions
The hourly weather data for the State of Qatar, which was recorded during 2015 in Doha, was used in this simulation [15]. Since this study deals with the enhancement of the roof envelope, the weather

parameters that mostly affect its thermal performance are the outdoor dry-bulb temperature and the Global Horizontal Irradiance (GHI). According to the weather file, the average temperature per day ranges between 35.7 ℃ in August and 18.3 ℃ in January. On the other hand, the total GHI per day ranges between 7632.6 Wh/m^2 in May and 3258.6 Wh/m^2 in December. This data seems to match with recent results of the work done by Perez-Astudillo and Bachour [1]-[2].

3. Results and Discussion

Upon running the simulations, results were extracted for detailed analysis.

3.1. Site Total Annual Energy Demand

The results that were of interest are the site total annual energy demands composed of the zones' air system cooling energies, lighting energies, infiltration heat gain energies and peoples' total heating energies. Table 1 shows the total energy demands for the base-case mosque, mosque with 50mm roof insulation, mosque with 100mm roof insulation and mosque with roof shading.

Table 1. Site total energy demand for the aforementioned simulation scenarios.

Simulation	Base-case Mosque	Mosque with 50mm Roof Insulation	Mosque with 100mm Roof Insulation	Mosque with Roof Shading
Site Total Energy (kWh/m^2)	619.55	563.43	550.72	581.07
Energy Savings (%)	-	9.1	11.1	6.2

As seen in table 1, the base-case mosque with neither roof insulation nor roof shading has a total site energy demand of 619.55 kWh/m^2. Al-Hamoud et al. [11] found that typical mosque energy demand ranges between 186.2 kWh/m^2 and 201.5 kWh/m^2, based on actual data recordings. However, their mosques consisted of one prayer room only. Considering the fact that this study inspects the energy loads of six thermal zones consisting of two men and women's prayer rooms along with their ablutions and toilets, the total energy demand was found to be reasonably larger.

Upon the installation of the 50mm insulation layer on the spaces roofs, the mosque total energy demand decreased to 563.43 kWh/m^2, thus yielding 9.1% energy savings. Higher energy savings of up to 11.1% were found when the insulation layer thickness was increased to 100mm. On the other hand, by solely installing the shading above the spaces roofs (refer to figure 3) and without any insulation layers, 6.2% energy savings were found with a total energy demand of 581.07 kWh/m^2. This highlights the importance of installing shading on the mosque roof, as it turns out to save comparable energy in comparison with the addition of insulation layers.

3.2. Monthly Total Cooling Demand

The mosque monthly total cooling demands for all four simulated cases are shown in figure 4.

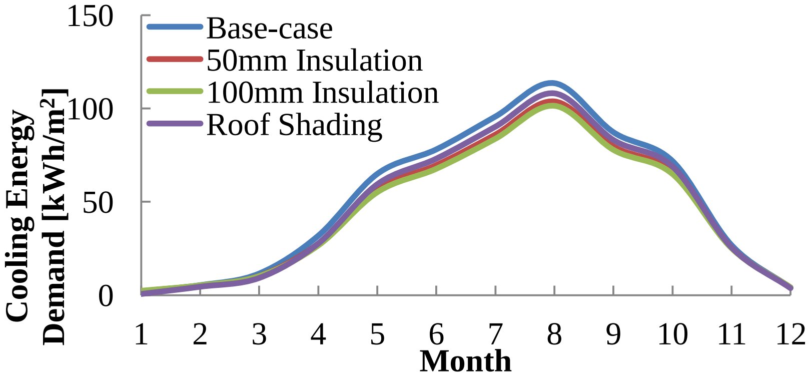

Figure 4. Mosque total monthly cooling demand.

As shown in figure 4, the total cooling energy demand was at maximum during the summer season between July and September and minimum during the winter season between December and February. For the base-case mosque with no roof insulation or shading, the mosque cooling demand ranged between 2.19 kWh/m^2 in January and 113.59 kWh/m^2 in August. For the mosque with 50mm and 100mm roof insulation, the cooling demand followed a comparable trend but with peak values of 103.75 kWh/m^2 and 101.44 kWh/m^2, respectively. The mosque with roof shading had a less intense reduction in the peak load, which reached 108.07 kWh/m^2, along with attenuation of the monthly demands for the rest of the year.

The reasons behind the results of table 1 and figure 4 could be explained as follows. The addition of polyurethane insulation layer that has a very low conductivity (0.02-0.04 W/m.K) leads to significant rejection and resistance to thermal heat passage through the roofs. However, the walls of all spaces are already insulated, which limits the effect of insulation addition on the roofs and leads to moderate energy savings compared to other studies [7]-[8]. In addition, all mosque spaces tend to have larger floor-to-ceiling heights in comparison with other office or residential spaces. For instance, the space heights of this mosque range between 3.80m and 5.75m, whereas it is only 2.8m in typical office spaces [16]. This fact also decreases the effect of enhancing the roof envelope due to its low ratio of surface area with respect to the entire envelope surface area. On the other hand, the addition of the shading reflects all direct solar radiation before it reaches the roof surface. Yet, it still allows diffuse and reflected radiation rays to hit different surfaces. In addition, it contains a 1.5m distance from the roof, which allows air currents to remove any heat accumulated within this region. Nonetheless, it is not made of insulative material, which means that it slows down heat passage due to its thermal mass more than it rejects it off its surface. For this reason, the installation of the shading had a moderate effect on the thermal envelope and led to 6.7% and 6.2% energy savings in the site cooling and total energy demands, respectively. Hence, these results reflect the ability to save energy easily in existing mosques with the simple installation of roof shading.

3.3. Men's Prayer Room

Going deeper into thermal zones, the men's prayer room was picked as it represents the major contributor towards the mosque total site energy demand. Hence, the percentage breakdown of energy demands for the base-case simulation for the men's prayer rooms is calculated. As anticipated, more than half (54%) of the space energy demands are attributed to cooling. Since Qatar is a country with hot weather conditions throughout the year, cooling is anticipated to have a substantial share of the total load. The rest of the total load is internal and divided between people, lighting and infiltration. As mentioned before, worshippers visit the mosques five times per day throughout the year. With an occupancy density of 0.8 person/m^2, the internal load caused by occupants reached around 30% of the total loads for men's prayer room directly followed by infiltration load (9%) that is subject to the same occupancy schedule. Lastly, lighting internal load had the lowest contribution, accounting for only 7%. To study the thermal demands of the men's prayer room only, their total annual energy end uses were extracted and presented in table 2.

Table 2. Total annual energy end uses of the men's prayer rooms for the studied cases.

Simulation	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Occupants (kWh/m^2)	Infiltration (kWh/m^2)	Total (kWh/m^2)
Base-case Mosque	288.17	41.77	158.18	44.91	533.03
Mosque with 50mm Roof Insulation	239.14	41.77	158.18	42.14	481.23
Mosque with 100mm Roof Insulation	227.42	41.77	158.18	41.33	468.70
Mosque with Roof Shading	243.58	41.77	158.18	42.66	486.19

As seen in table 2, the men's prayer room total annual energy demand is 533.03 kWh/m^2, 288.17 kWh/m^2 of which are attributed to cooling needs whereas the rest is internal loads. The addition of the 50mm and 100mm insulation layers decreased the annual energy demands to 481.23 kWh/m^2 and 468.70 kWh/m^2 respectively due to the decrease in the cooling and infiltration loads. For the case when shading is added on the top of the mosque, the men's total energy demand decreased to 486.19 kWh/m^2. Since the lighting and occupants' internal loads are inputs to the simulated model, they are not affected by any changes in the envelope and consequently have a fixed annual thermal load of 41.77 kWh/m^2 and 158.18 kWh/m^2, respectively.

As shown in table 2, it could be noticed that the performance of the mosque different spaces, and more specifically the men's prayer rooms, is fairly similar when the roof is insulated with 50mm polyurethane and when it is shaded. These results re-highlight the benefits of installing the shadings on the thermal energy demands of different spaces.

4. Roof Insulation and Shading of New Mosques

In this section, the mosque has been reconstructed with enhanced roof envelope through the addition of 50mm roof insulation as well as roof shading. The model was re-simulated and results were as follows.

The site total energy demand turned out to be 539.62 kWh/m^2, yielding 12.9% energy savings in comparison with the base-case mosque with neither roof insulation nor roof shading. The results seem interesting as this mosque produced more energy savings in comparison with a mosque with 100mm roof insulation (refer to table 1). As for the mosque total cooling demand, the mosque had a more intense reduction where the peak decreased from 113.59 kWh/m^2 (refer to figure 4) to 99.87 kWh/m^2 along with reduced loads for the rest of the year. Hence, 13.5% of the annual cooling demand was saved. Similarly, the results for the men's prayer rooms were extracted for analysis.

Table 3. Total annual energy end uses of the men's prayer rooms with insulated and shaded roofs.

	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Occupants (kWh/m^2)	Infiltration (kWh/m^2)	Total (kWh/m^2)
Men's Prayer Room	216.39	41.77	158.18	40.97	457.32

As seen in table 3, the annual cooling energy demands of the men's prayer room decreased significantly from 288.17 kWh/m^2 to 216.39 kWh/m^2 when the roofs construction was insulated and shaded. Similarly, the infiltration loads decreased as the envelope was more tightened. This construction envelope led to 14.2% energy savings in the total annual energy demands of the men's prayer room. Consequently, large amounts of energy could be saved if such conservation strategies are adopted in new mosques.

5. Conclusion

Mosques are plentiful in the Arabian Gulf, and their increasing consumption of energy is something that contradicts with the countries' future energy-conservation visions. In Qatar, most mosques' walls are already insulated, thus limiting the capability of building envelope enhancement in reducing energy demands. In this study, a novel design consisting of roof shading is compared to the conventional addition of insulation layer to the roof, and results were compared to a base-case mosque with neither roof insulation nor roof shading.

An actual mosque consisting of six spaces built according to the design and building envelope characteristics provided by the Ministry of Awqaf and Islamic Affairs in Qatar was simulated on Openstudio and estimated to demand 619.55 kWh/m^2/year. As the space walls are already insulated, the addition of thin and thick insulation layers to the mosque roofs was found to yield 9.1% and 11.1% energy savings. On the other hand, the addition of shading to the mosque roof singlehandedly produced 6.2% energy savings. As the roof reconstruction is practically unrealistic, these results highlight the importance of roof shading as a mitigation measure for saving comparable energy in existing mosques. As for new mosques, it was found that roofs built with 50mm insulation and shading outperforms those built with 100mm insulation and tend to produce 12.9% energy savings.

This study provides practical mitigation methods against the increasing energy consumption in existing and new mosques as the addition of the insulation layers in the roof is cumbersome and expensive. Future work includes further studies on the optimization of the parameters related to the installation of the shading device on the roof of the mosque combined with life-cycle cost analysis.

6. Acknowledgment

The authors would like to acknowledge Qatar University for their support in providing the necessary tools for the completion of this study.

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