Envelope Thermal Design Optimization of Buildings with Intermittent Occupancy

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ABSTRACT

Buildings with intermittent occupancy may not perform thermally the same as typical commercial and residential facilities. Thermal comfort requirements require careful envelope design coupled with the appropriate air-conditioning system operation strategies. One of the most promenint examples of such buildings is mosques. Mosques are usually occupied five intermittent times day and night all year round. Like any other building, they have to be mechanically air-conditioned to achieve the required thermal comfort for worshippers especially in harsh climatic regions.

This paper describes the physical and operating characteristics typical for the intermittently occupied mosques as well as the results of the thermal optimization of a medium size mosque in the two hot-dry and hot-humid Saudi Arabian cities of Riyadh and Jeddah. The analysis utilizes a direct search optimization technique that is coupled to an hourly energy simulation program. Based on that, design guidelines are presented for the optimum thermal performance of mosques in these two cities in addition to other design and operating factors that need to be considered for mosques in general.

Key Words: Energy conservation, optimization, thermal design, intermittent operation, mosques, hot, hot-humid climate, Saudi Arabia

INTRODUCTION

Mosques are characterized by having a unique occupancy schedule compared to other types of buildings. They are usually occupied five intermittent times a day all year round. People usually come to the mosque at different times, and therefore the maximum occupancy is expected to occur during the actual performance of prayer which lasts from about 15 to 20 minutes. After prayer they leave gradually as well. Exceptions to this are weekly Friday prayer and Taraweeh prayer during the nights of the month of Ramadan as well as during other special occasions such as lecturing and similar activities where people tend to stay longer in the mosque.

Another unique occupancy characteristic of mosques is that prayer times change following changes in day and night hours over the year. This is different from one locality to another depending on the longitude. Therefore, analysis based on a specific time is not possible. However, this change in prayer times over the year is usually within an hour range especially for peak energy demand periods such as the noon (Duhr) and the afternoon (Asr) prayers. Within a given region of similar time zone, mosques are occupied at the same time. This would have a great impact on the demand for energy particularly at areas with high demand for air-conditioning which frequently coincides with peak energy demand periods.

All of these factors with the importance of thermal comfort for performing prayers in spiritual environment make the design and operation of mosques very important to all Muslims. Because they comprise an important sector of buildings in many parts of the world.

In a recent study, (Abdou, et. al, 2005) the analysis of five-year electric energy billing data for five typical mosques in the hot-humid climate of the eastern region of Saudi Arabia was made. The analyses of the electric energy bills data presented the general trend and the history of energy use for those mosques. Although the billing data can provide a reasonable estimate of the overall annual electric energy use for each mosque, the billing data is not an accurate reference for comparison of different mosques due to differences in data record and reporting periods. In addition, electric energy billing data does not provide the necessary segregated energy end uses by the various energy systems for the purposes of detailed mosque energy analysis. (Abdou, et.al, 2005)

Accordingly, another study was conduted (Al-Homoud, et. al. 2005) where the analysis and results of monitored energy use data for five representative sample mosques in the hot-humid climate of the eastern region of Saudi Arabia was presented. Data acquisition based on 5-minute and 1-hour intervals was used to establish mosque occupancy time periods, energy use patterns and trends. The monitored data was analyzed and compared to a long-term (5-year) average electric energy utility bills data. Analyses of the segregated energy use data of the investigated mosques revealed that, as expected, the air-conditioning is the most single energy intensive system in the mosque with more magnitude than the case in many other types of buildings in hot-humid climates. Lighting system, although requires much less energy than A/C, contributed steady energy use year round. (Al-Homoud, et. al. 2005)

The purpose of this paper is to study the thermal design of mosques with focus on the selection of the envelope parameters for an optimum thermal performance based on the objective function of minimizing Energy Utilization Index (EUI), Btu/sq. ft.yr (kWh/m^2.yr). A medium size mosque occupancy schedule for two hot-dry and hot-humid Saudi Arabian cities is considered. The initial findings were presented in an earlier paper (Al-Homoud, 1999). The subject of air-conditioning operation and the evaluation of various operating strategies for mosques and its impact on energy consumption and demand will be discussed in a near future paper.

TYPICAL CHARACTERISTICS OF MOSQUES

The typically common design and occupancy characteristics of mosques in Saudi Arabia are summarized as follows:

Building	**Characteristic**
Shape	Typically rectangular open space with long axis facing the Holly Kaabah (Qiblah) in the city of Makkah. Typically heigh ceilings, 10-17 ft (3-5 m)
Construction	Usually medium to heavy construction with concrete blocks and reinforced concrete slabs with carpeted floors.
Zoning	Typically one single open space zone for small to medium daily prayer mosques. Two zones for large Friday prayer mosques small

	one for daily prayers and a large zone for Friday prayer.Third zone is for women which could be a partial second floor or a section in the back end of the main prayer area. An ablution (Whodow) area and storage are usually attached to the mosque (normally unconditioned).
Air-conditioning type	Varies from window type A/C units especially for small size mosques, split DX units to central systems especially for large size (Friday) mosques
Lighting Fluorescent lamps. W/m^2).	Task level is at the floor where people sit and read Quran. type lighting is common often combined with some incandescent Lighting levels vary with a typical value of 1.5 W/sq. ft (16.5 Daylighting can be greatly utilized during daytime prayers.
Internal loads	Mainly from people, then lighting. No equipment load.
Occupancy	8 ft^2/person (0.72 m^2/person, 1.2m by 0.6m).
Operating schedule	Typically five times daily intermittent occupancy with an average of one hour for each occupancy
Inside conditions	75 ^{o}F (24 ^{o}C) and 50% relative humidity.
Ventilation rate short without	Large number of occupants especially during full operation (usually periods). This implies the need for reasonable ventilation rate excessive sizing of the air-conditioning equipment.
Infiltration	The most difficult parameter to measure as usual. Frequent opening of doors and not very tight construction

The specific characteristics of the base case mosque investigated in this study and described below.

THE PRESENT STUDY

The mosque building considered for this study is a typical open space single zone medium size, 3300 sq. ft (300 m^2). It is rectangular in shape with 3:1 aspect ratio with 15 ft (4.5 m) ceiling height and the long axis facing Qiblah. The mosque operates 7 days a week all year round with five intermittent occupancy a day with assumed maximum occupancy of 60% of the 400 people capacity of the mosque (assuming an average occupancy area of 8 ft^2/person, 0.72 m^2/person) according to the occupancy profiles shown in Figures 1 and 2 for the cities of Riyadh and Jeddah, respectively. The mosque is assumed to be used for daily prayers only. The air-conditioning system used is roof-top type with average ventilation rate of 15 cfm/person (7.5 L/s. person). Fluorescent lighting system is used with an average heat gain of 1.5 W/sq. ft (16.5 W/m$^{2)}$.

Occupancy profile

The load profile considered in this analysis is based on a typical intermittent occupancy of the air-conditioning system according to mosque use during the daily five prayers with two hours of operation during each prayer all over the year. A 5% of occupancy is assumed an hour earlier than the actual hour of use by the Muathin (the person who calls for prayer) and some few early comers. The profile of use is similar for both cities analyzed except that

Jeddah prayer time is shifted one hour later than that for Riyadh as shown in Figures 1 and 2 for both cities, respectively. Summer prayer times were used as the basis where peak energy demand is expected and air-conditioning load dominates in many parts of Saudi Arabia. The lighting and ventilation profiles are assumed to coincide with the use profiles where all lights and air-conditioning system are assumed to be turned on with the first comer to the mosque and turned off with the last person leaving as observed in most mosques in Saudi Arabia. Little seasonal variation in indoor conditions is assumed as people using mosques are usually fairly dressed for both seasons. The summer and winter thermostat setting of 75 ^{o}F and 74 ^{o}F (24 and 23 ^{o}C). The assessment of other air-conditioning operating strategies such as continuos versus intermittent operation or combination of the operation between two or more periods during the day as well as other alternatives are not considered in this paper but will be studied in future papers.

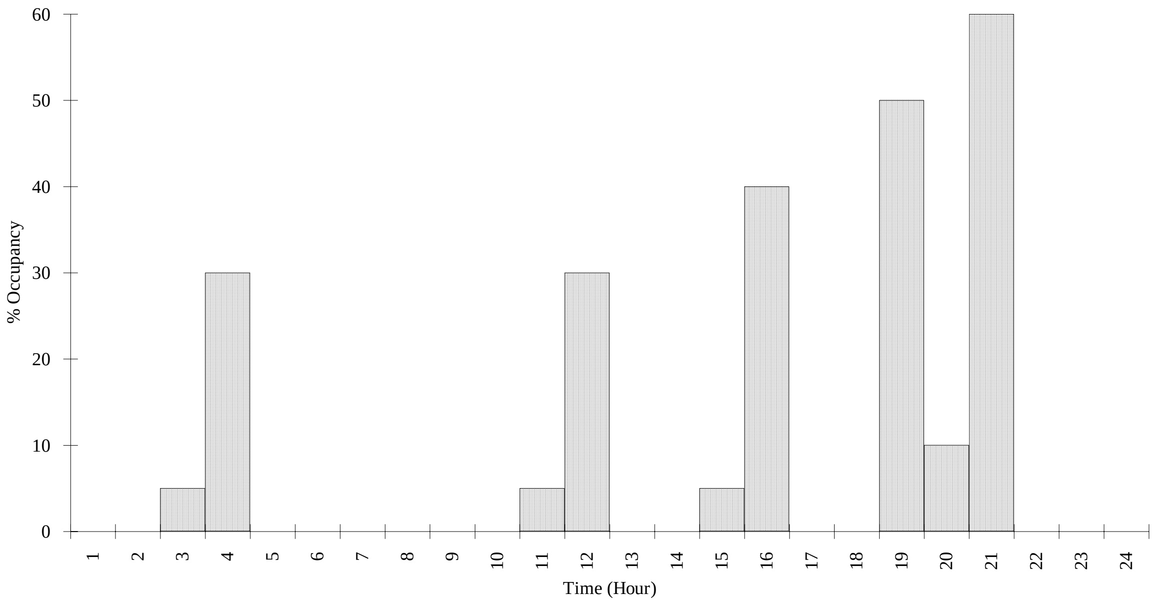

Figure 1. A Typical Occupancy Profile for a Mosque in Riyadh, Saudi Arabia

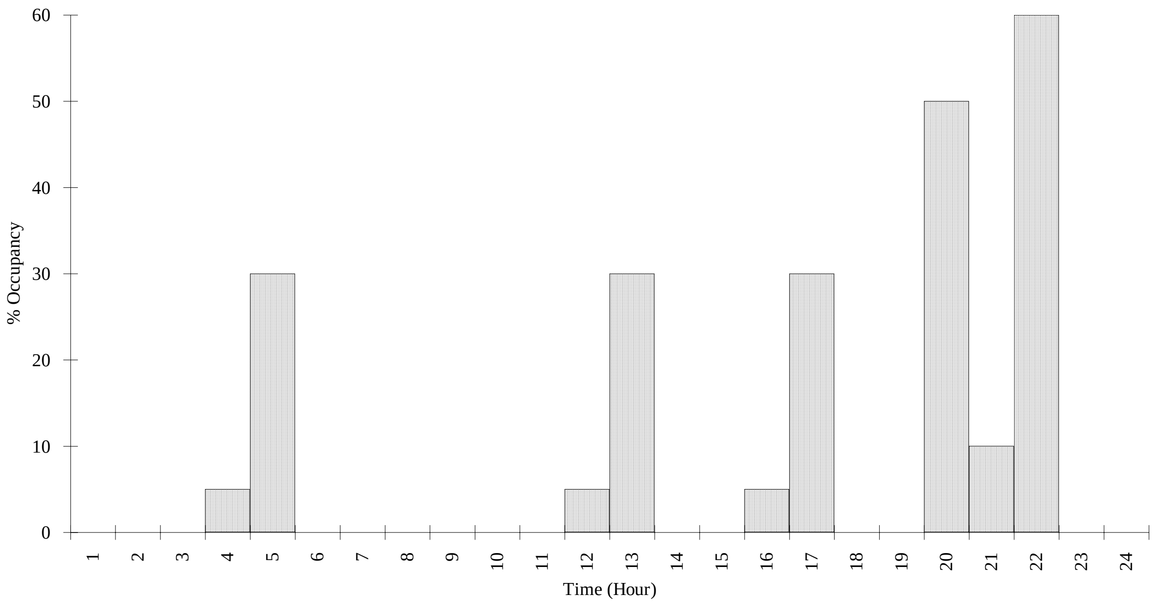

Figure 2. A Typical Occupancy Profile for a Mosque in Jeddah, Saudi Arabia

Climates Analyzed

For the purpose of this research, the weather data for the two Saudi Arabian cities of Riyadh and Jeddah were analyzed representing the two most harsh areas of hot-arid and hot-humid climates of the country, respectively.

Riyadh

Riyadh represents the central regions' hot-dry climate of the Kingdom. It is characterized by extremely hot and dry summers with very large diurnal temperature ranges and moderately cold winters. Skies are clear most of the year and the main concern for a designer is summer overheating. (Al-Homoud, 2004)

Jeddah

Jeddah represents the western coastal hot-humid climate of the Kingdom characterized by long hot and humid summers with very small diurnal temperature ranges. Winters, on the other hand, are short and mild which makes hot and humid summer conditions the main concern for building designers. (Al-Homoud, 2004)

Monthly variable base cooling degree-days and long-term average temperatures for both cities are presented in Table 1 to provide a sense of the severity of weather in those cities (Al-Homoud, 1998). The two cities were selected because they represent the most critical two climatic zones demanding summer air-conditioning in the Kingdom. Also to address building designers and those concerned with thermal design optimization trends at these regions.

Table 1. Monthly variable base cooling degree-days and long-term average temperatures for Riyadh and Jeddah cities (^{0}C-days)* (Al-Homoud, 1998).

City	$T_{Bal.}$ (^{0}C)	Monthly												Yearly
		Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	
Riyadh	**28.0**	0	0	0	0	119	194	231	225	136	1	0	0	**906**
(1971-95)	**25.5**	0	0	0	21	197	269	308	303	211	53	0	0	**1362**
	23.0	0	0	0	95	274	344	386	380	286	131	0	0	**1895**
Lat. 24^o 43$^{'}$	**20.5**	0	0	9	170	352	419	463	458	361	208	11	0	**2450**
Long. 46^o 44$^{'}$	**18.0**	0	0	78	245	429	494	541	535	436	286	80	0	**3124**
Elev. 620 m	$\overline{T}_A$	13.8	16.3	20.5	26.2	31.8	34.5	35.4	35.3	32.5	27.2	20.7	15.3	**25.8**
Jeddah	**28.0**	0	0	0	2	54	77	126	126	93	42	0	0	**520**
(1971-95)	**25.5**	0	0	1	67	131	152	204	203	168	120	48	0	**1095**
	23.0	8	7	63	142	209	227	281	281	243	197	123	44	**1825**
Lat. 21o 41’	**20.5**	81	73	141	217	286	302	359	358	318	275	198	122	**2729**
Long. 39o 09’	**18.0**	158	143	218	292	364	377	436	436	393	352	273	199	**3124**
Elev. 4 m	$\overline{T}_A$	23.1	23.1	25.0	27.7	29.7	30.6	32.1	32.1	31.1	29.4	27.1	24.4	**28**

* ^{0}F-day = ^{0}C-day x 9/5

THE OPTINMIZATION MODEL

Detailed energy calculations apply hour-by-hour energy simulation. Many programs exist to simulate the energy consumption in a building and its sub-systems for every hour of an average weather year. They offer detailed analysis of a buildings' energy use accounting for all factors such as building schedule, occupancy as well as building mass. They also offer life-cycle cost analysis with different output options depending on the individual program. (Degelman 1998, LBL, 1979, BSO 1997, Al-Homoud 2001)

The drawbacks of simulation, however, are that it requires a prior knowledge of the solution which is not usually available to building designers in the early stages of the design process. Also, evaluating the effect of changing any of the design variables can only be achieved by trial and error, a method that is inconvenient and lacks the interaction between design variables that are of great importance for an integral evaluation of the thermal behavior of buildings. (Al-Homoud 2001)

Objective Function

The objective is to provide occupants with thermally comfortable environment at the least energy cost. Accordingly, it is necessary to formulate a criterion that can be used to compare the process outputs to objectives. Therefore, the building thermal design is with the objective function of minimizing energy requirements to achieve thermal comfort in the air-conditioned space. For this purpose the objective functions was integrated into the ENERCALC (lately changed to EnerWin) (Degelman, 1990 and 1998) hourly energy simulation program as follows (Al-Homoud, 2005):

$$\boldsymbol{Min} \quad Q_s = \sum_{i=1}^{n} (Q_{gas,i} + Q_{elec.,i}) / FA$$

Or:

$$\boldsymbol{Min} \quad Q_s = \sum_{i=1}^{n} \{(Q_{h.w.,i} + Q_{h,i}) + (Q_{c,i} + Q_{fan,i} + Q_{light,i})\} / FA$$

Where:

n = number of hours of simulation over the year

Q_s = annual source energy use level; Btu/sq-ft. /yr (kWh/m^2-yr)

$Q_{elec.}$ = electric energy

$Q_{h.w.}$ = hot water energy; Btu (kWh)
Q_h = space heating energy; Btu (kWh)
Q_c = source line space cooling energy; Btu (kWh)
Q_{fan} = source line fan energy; Btu (kWh)
Q_{light} = source line lighting energy; Btu (kWh)
FA = building gross floor area; ft^2 (m^2)
Source line energy (Btu) = 10,500. (kWh)
1 Btu= 1.055 kJ.

Constraints

The choice and range of variations of design variables is influenced by many factors. For the present case, maximum and minimum values were specified in for each of the follwoing design variables as follows (Al-Homoud, 2005):

$$U_{r\min} \le U_r \le U_{r\max}$$
$$U_{w\min} \le U_w \le U_{w\max}$$
$$\alpha_{w\min} \le \alpha_w \le \alpha_{w\max}$$
$$TL_{w\min} \le TL \le TL_{w\max}$$
$$U_{g\min} \le U_g \le U_{g\max}$$
$$SC_{\min} \le SC \le SC_{\max}$$
$$\varepsilon_{g\min} \le \varepsilon_g \le \varepsilon_{g\max}$$
$$p_{\min_i} \le p_i \le p_{\max_i}$$
$$ach_{\min} \le ach \le ach_{\max}$$
$$psf_{\min} \le psf \le psf_{\max}$$
$$1 \le AR \le AR_{\max}$$

Where

Ur = roof thermal transmittance; Btu/hr-F-ft^2 (W/m^2-C)
Uw = wall thermal transmittance; Btu/hr-F-ft^2 (W/m^2-C)
α_w = wall absorptance
TL = time lag; hrs
Ug = glass thermal transmittance; Btu/hr-F-ft^2 (W/m^2-C)
SC = shading coefficient for glazing system
ε_g = glass emittance
p_i = percentage of glass area to wall area (Ag/Aw); $i=1,..,4$ for all four walls; %
ach = air changes per hour; ac/hr
psf = internal mass; lb/ft^2 (kg/m^2 of floor)
AR = building aspect ratio (length of north wall/east wall).

Optimization Technique

The optimization search technique of Nelder and Mead (Nelder and Mead 1965, Hammilblau 1972) was implemented in the model used in this analysis. Details of the technique and the validation of the model were presented in an earlier paper (Al-Homoud, 2005)

The Thermal Simulation Model

There are many powerful building energy simulation programs available. However, ENERWIN, the window version of ENERCALC program (Degelman 1998 and 1990), developed at Texas A&M University was used. It adequately represents the specified building thermal design parameters with accuracy while maintaining simplicity of simulation. It incorporates an hourly simulation model that permits the simulation of any multiple of seven days each month and still maintains its statistical integrity for energy calculations. (Al-Homoud, 2004)

The Thermal Optimization Model

The main elements required for the implementation of a systems approach into the thermal design of buildings have been defined (Al-Homoud 1994, 2005). Thirteen design variables that basically describe the thermal performance of mosque envelope components have been identified.

The building thermal design optimization model, termed ENEROPT (ENERgy OPTimization), that integrates the optimization technique of Nelder and Mead with the described hourly energy simulation program was used as descibed in more details by Al-Homoud, 2005.

DISCUSSION OF THE RESULTS

Analysis of the optimization results for the described mosque in the two selected climates shows that building thermal design optimization trends provide useful information on the selection of building components. The optimization results revealed significant reductions in the mosque's EUI for both climates. Significant energy savings were achieved for such buildings with optimization. The magnitude of reduction in the mosque's energy use for the optimum design from the starting base case reached 21% and 18.8% for Riyadh and Jeddah, respectively as shown in Figure 3 and illustrated in the optimization results of Table 2.

In addition to the potential energy savings, design optimization produced buildings with smaller peak heating and cooling loads as illustrated in Figure 4 (positive values represent cooling load while negative values represent heating load in the figure). The optimization results revealed as much as 12 % reduction in peak cooling loads for Riyadh and 15.4 % for Jeddah. This corresponds to reduction in the required capacity of the air-conditioning system from 40.3 ton to 35.5 ton for Riyadh and from 35.1 to 29.7 ton for Jeddah as shown in Figure 5.

BENCHMARKING THE RESULTS WITH MONITORED DATA

In order to verify the optimization results with real data, it is important to have measured energy use data for similar mosque. In another study (Al-Homoud, et. al. 2005), monitoring of sample mosques’ energy was undertaken to determine the characteristics of the actual energy end uses in mosques and their trends over time. Five mosques were monitored on an hourly basis for a two-year period. The monitored mosques were selected to represent diffirent types charactarized by different sizes, construction, and operation. They were all located at the hot-humid climate of Dhahran, Saudi Arabia.

For the purpose of benchmarking the results of this study, available monitored energy use data for other mosques are used. Eventhough the compared data are for mosques located at different cities, furtunately the weather for Dhahran where energy monitoring was made is similar to a certain extent to that of the city of Jeddah reported in this study. Therefore, only the results of optimization for Jeddah are benchmarked with monitored data for Dhahran, both of which are charactarized by hot-humid climates and are located in Saudi Arbia.

Comparasion are made for a mosque that is comparable to the mosque under invistigation in size, zoning (zingle zone), operation, construction and type of air-conditioning system. The actual monitored annual EUT for the Dhahran mosque is 186.2 kWh/m^2.yr (587 MBtu/sq. ft. yr.). This is a higher value than the optimized results of 108.5 kWh/m^2.yr (342 MBtu/sq. ft. yr.) for the Jeddah mosque as used in this study with a difference in the mosque EUI of 41.7% as a result of envelope optimization. Considering the actual design and operation of the monitored mosque which is not insulated and lacks proper operation of its air-conditioning system in addition to the slight climatic differences due to the different mosque locations, the ruslt is an indication of the great improvement that can be achieved through optimization of the mosque envelope.

When the optimized EUI is compared to another monitored mosque located in Dhahran also (Al-Homoud, et. al. 2005), which is newly constructed, well insulated, with efficient air-conditioning system, the latter showed a EUI of 93.3 kWh/m^2.yr (294 MBtu/sq. ft. yr.) which is 16% less than the optimized mosque of 108.5 kWh/m^2.yr (342 MBtu/sq. ft. yr.). However, this difference is not surprizing considering the difference in mosques sizes where the monitored mosque air-conditioned area in this case is almost four times that of the optimized mosque (1266 m^2 compared to 300 m^2), in addition to the possible difference due to the difference in mosques locations as indicated earlier. Had the air-conditioned area of the monitored mosque in this case been close to the optimized one, the results would have been very close especially that large percentage of the monitored mosque area is not occupied and would normally be sufficiently air-conditioned with less energy requirements due to the less occupants' load in that un-occupied part of the mosque.

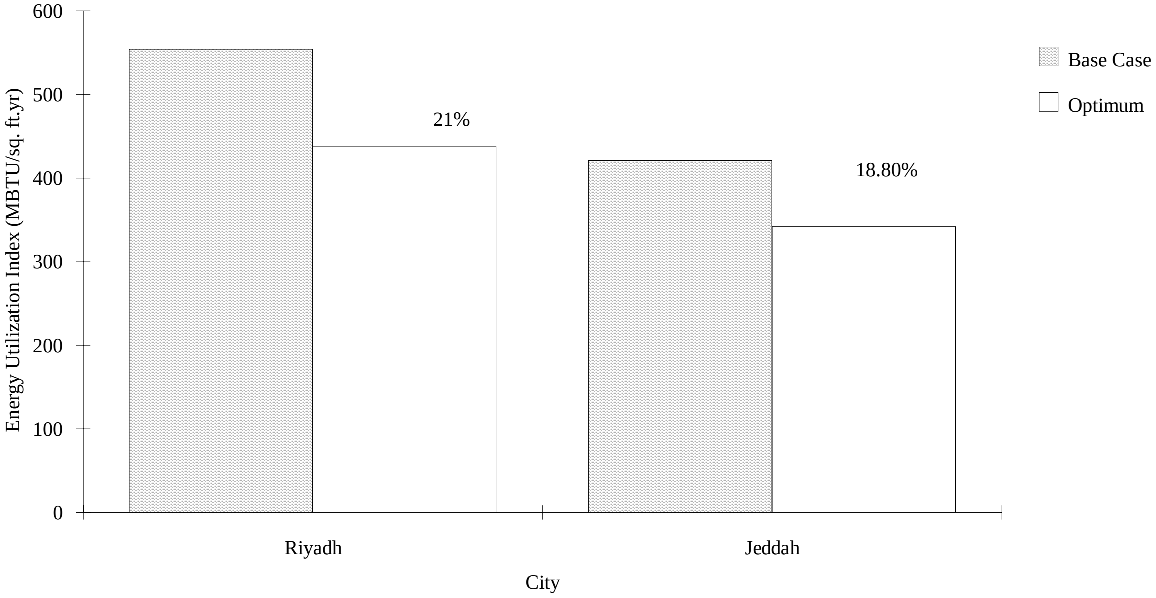

Figure 3. Mosque's optimum versus base case annual source energy utilization index for Riyadh and Jeddah, Saudi Arabia.

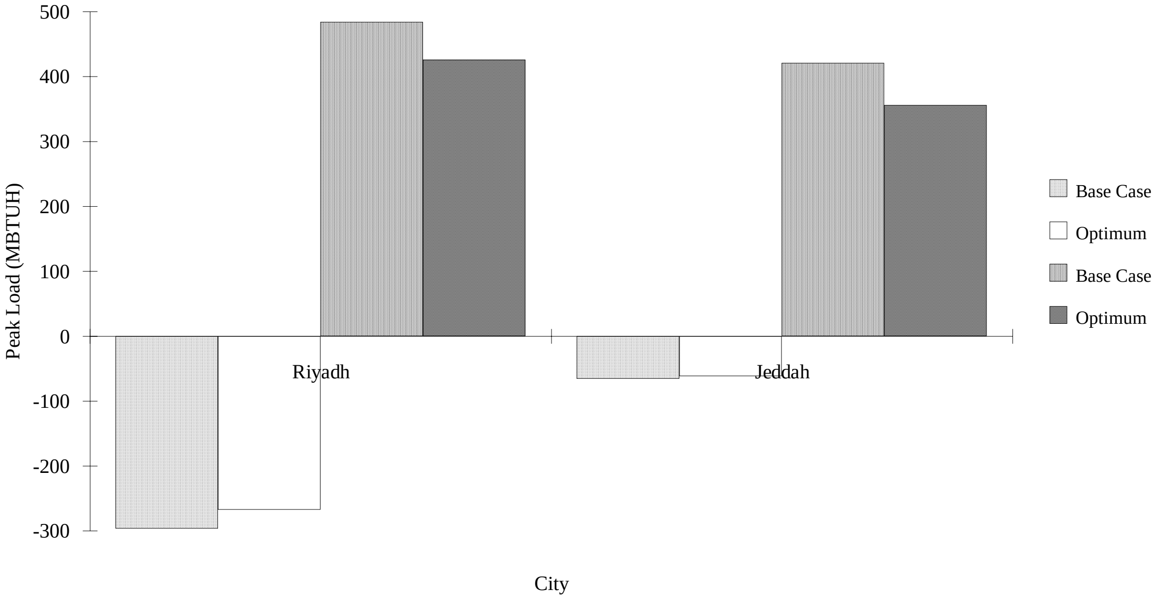

Figure 4. Mosque's heating and cooling peak loads evaluation.

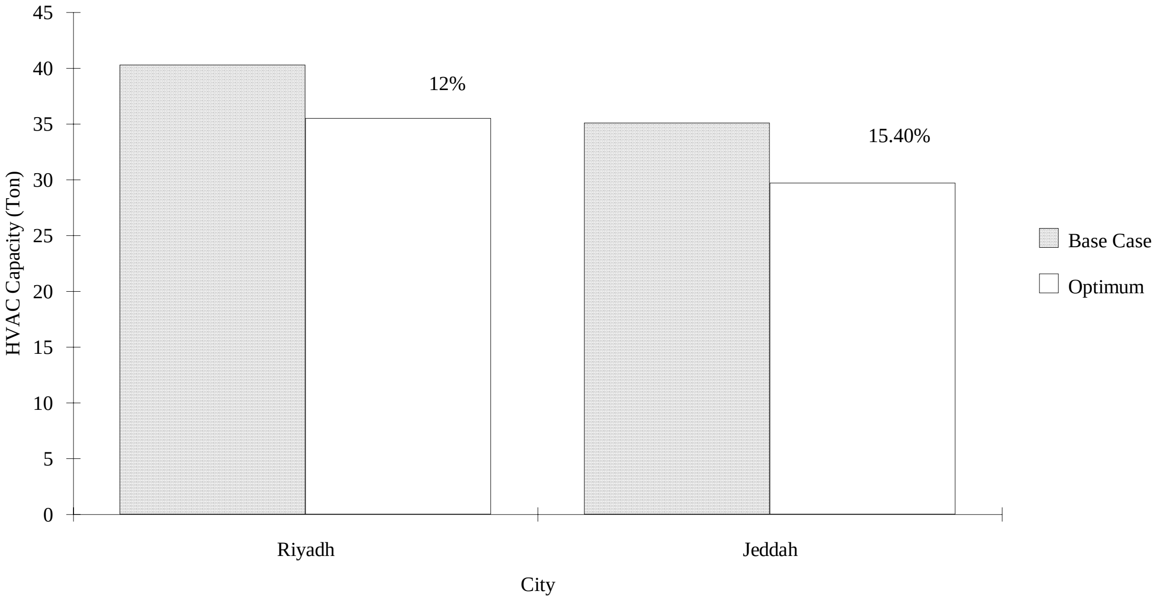

Figure 5. Optimum versus base case reduction in mosque's air-conditioning capacity.

Table 2. Optimum thermal design summary for a typical mosque in the two Saudi Arabian cities of Riyadh and Jeddah

Variable	**Base Case Initial**	**Constraints**	**Optimum Values**	
			Riyadh	**Jeddah**
Wall U-value (Btu/hr. F. ft.^{2})	0.33	0.06 - 1.10	0.06	0.06
Absorptance	0.26	0.10 - 0.98	0.18	0.18
Time Lag (hr)	5.00	1.00 - 10.00	1.51	1.01
Roof U-value (Btu/hr. F. ft.^{2})	0.34	0.04 - 1.10	0.10	0.04
Glass U-value (Btu/hr. F. ft.^{2})	0.55	0.25 - 1.10	0.25	0.25
Shading Coeff	0.35	0.20 - 1.00	0.21	0.23
Emittance	0.20	0.20 - 0.98	0.25	0.23
% glass area: N	20.00	15.0 - 99.0	30.85	17.84
E	20.00	15.0 - 99.0	21.72	17.64
S	20.00	15.0 - 99.0	21.15	24.96
W	20.00	15.0 - 99.0	26.88	15.01
Infiltration rate (ach)	0.70	0.50 - 3.0	0.50	0.50
Internal mass (lb/ft.^{2})	75.00	50.0 - 150.0	88.20	93.1
Opt. SEUI (MBtu/sq.ft.yr.)	**--**	**--**	**438**	**342**
Base SEUI (MBtu/sq.ft. yr.)	--	--	554	421
% Reduction in SEUI	**--**	**--**	**21**	**18.8**
% Reduc. in air-conditioning	**--**	**--**	**12**	**15.4**

1 Btu/hr. F. ft.^{2} = 5.679 W/m^2. C.;
1 lb/ft.^{2} = 4.883 kg/m^2.
1 MBtu/sq.ft. = 3.153 W/m^2

Design Parameters

One of the most important advantages of optimization is the interaction between the design variables. Therefore, it is important to have an overall look at all values of the optimum solution (not only at individual variables) as change in the value of one variable might affect the optimum values of other variables. (Al-Homoud, 1997)

A summary of the optimum thermal design solutions for the analyzed mosque in the two selected climates is illustrated in Table 1 along with the design values for the base case as well as the limiting constraints used in the analysis. Optimum thermal design trends are discuused below for each parametr.

Building Orientation and Form

The orientation of mosques is determined by the Qiblah (direction with respect to the Holy Kaabah in the city of Makkah) where all mosques are oriented to that direction. Therefore, the orientation is fixed with respect to Makkah rather than being a design variable. Mosques are usually formed elongated with the long axis facing Qiblah with a typical aspect ratio ranging from 2:1 to 3:1 for the purpose of having the largest number of people performing prayer in the first rows of a mosque. This orientation is different from one area to another depending on its location with respect to Makkah. Therefore, mosques in the regions east of Makkah are oriented towards west, and those to the west are oriented east and so on. However, variations occur in Makkah itself and around Kaabah where people pray toward Kaabah from all directions in a circular form.

In the present study, the mosque in Jeddah is oriented with the long axis facing 21º south-east toward Makkah while oriented 25º due south of west for Riyadh.

Glazing

Glazing was expressed as a percentage of the gross wall area for each of the four exposures of the building. Without considerations for daylighting, a minimum glass area of 15% and a maximum of 99% of the wall area on each exposure were specified. The optimization trend was generally toward the specified minimum glass area some with flexibility to benefit from winter heat gains.

Other otimized glazing variables were shading coefficient, U-value and emittance of the glazing system. In both climates, the optimization trend was generally to the lower boundary of the constraint for each variable. The shading coefficient is referred to in the optimization model as a single property of the glass and represents the value for the window system as a whole. Lower values for the glass emittance were called for in both climates. However, the impact of these properties increased proportional to the increase in glass area.

Wall and Roof Construction

Optimization trends were toward specifying lower U-values of both components, walls and roof, for the selected climates. Roof absorptance was kept constant at 0.75, while wall absorptance was optimized toward the specified minimum value. For most wall and roof thermal properties, the otimization trends were towards minimum values. However, relatively higher time lag values (even though not as high as expected) are called for in the dry climate of Riyadh than that for the humid climate of Jeddah. On the other hand relatively lower wall U-values for Jeddah was called for copared to that for Riyadh. It is worth mentioning that the more focus is made on the optimization trends for the investigated variables as a whole rather than the absolute values that result from the optimization.

Infiltration

Optimum infiltration rates were to the lower end of the specified constraint boundary for both climates. This indicates the importance of sealing all leaks in the building to minimize infiltration loads. This is more important in mosques in particular whre frequent outside doors opening as a function of people entry into the moaque is expected.

Other Parameters

Lighting contributes to both annual electrical consumption as well as to the generation of heat within the space resulting in more cooling load on the air-conditioning system. However, a fixed lighting load of 1.5 Watts/sq. ft. with no equipment load was assumed in the optimization of the mosque. In addition, benefits from daylighting were not considered in the optimization.

Although building operation and the type of air-conditioning system used have an impact on the annual energy use, they were kept fixed as the objective was to investigate the improvements that result in the mosque annual Energy Utilization Index with respect to the climate as a function of envelope parameters optimization. Accordingly, a single typical profile of occupancy and a roof top unit air-conditioning system were used in the optimization.

In general, the mosques' occupancies vary with location and time over the year as prayer times vary with the dominating load from occupants followed by lighting during the short occupied periods which are operational parameters.

Design Guidelines

Based on mosque optimization results, a number of recommended design guidelines for optimum thermal performance of mosque envelope in the climates of Riyadh and Jeddah are summarized as follows:

- The significance of glazing treatment is a function of its amount and exposure. Therefore, attention should be given to the size and location of glazing over the different exposures of the mosque to achieve the desired balance between summer and winter thermal tradeoffs.
- For hot climates such as those of Riyadh and Jeddah where summer gains are the major concern, the treatment of glass shading that will result in the lowest possible shading coefficient is important for reduscing heat gains. External shading is preferrable as it intercepts the intense sun rays before they are transmitted through the glass while allowing daylight and view.

- Use thermal insulation to achieve the lowest U-values for both roof and walls in both climates of Riyadh and Jeddah. However, being exposed more to the direct solar radiation, the impact of roof U-value is generally more significant and is worthy of more consideration.

- Due to frequent opening of doors in mosques during prayer times as people move in and out of the mosque randomly, consideration for infiltration control should be given enough attention. Therefore, minimum infiltration rate should be allowed through double (curtain) doors as well as careful treatment of cracks and leaks around window and door frames. Especial attention should be given to sealing leaks around window type a/c units openings which are common in mosques.

- At times where outdoor air could be utilized for natuaral ventilation especially at cool summer nights in hot-dry climates such as that of Riyadh, means should be provided for proper utilizatin of controlled ventilation through operable windows.

- Use light colored surfaces to minimize heat absorbed into the building surfaces especially during the summer period for both hot climates of Riyadh and Jeddah.

Other Design Considerations

There are other design and operating strategies that could be suitable to mosques which were not investigated in the present study but worthy of consideration as summarized below:

- Mosque users are normally fairly well dressed during both summer and winter seasons. Therefore, middle range of the design temperature is favorable with little summer/winter variations.

- Thermal zoning is important for comfort control and energy savings especially for large mosques with Friday, daily and women prayer areas. Each zone should be designed to be operated/controlled independently for use as needed. This will ensure achieveing the desired thermal comfort with least energy avoiding air-conditioning large volume of space with no occupancy.

- Given the intermittent occupancy of mosques, precooling of building mass several degrees below comfort level at least one hour before occupancy will help to absorb portion of the peak heat load which would result in less demand and smaller equipment size. This is particularly important in hot climates.

- High ceilings of mosques may cause stratification of heat above the occupied zone. Stratification is good for cooling and can be achieved by low elevation supply and return air where it does not mix with upper air. However, stratification is not good for heating and its effect can be reduced by using ceiling fans or low air distribution (ASHRAE 2005). However, side wall supplies, when used, should have enough throw to satisfy the air distribution requirements while watching for noise.

CONCLUSIONS AND RECOMMENDATIONS

The envelope optimization results indicate that mosques design in the climates of Riyadh and Jeddah should be air tight, well insulated, with light colored surfaces and minimum area of shaded glass to avoid the dominant summer overheating. This revealed both lower energy use as well as lower peak heating and cooling loads where as much as 21% and 18.8% annual energy savings were obtained for the moque in Riyadh and Jeddah, respectively, as a result of the mosque envelope optimization. This also corresponds to a reduction in the required capacity of the air conditioning system of 12% and 15.4% for both climates, respectively. Therefore, operating as well as initial air-conditioning equipment costs can be reduced due to smaller system capacity required to provide comfort for the optimized mosque.

The unique short and frequent intermittent occupancy of mosques makes the operating strategy of the air-conditioning system very important to achieve the desired thermal comfort with minimum energy requirements. Therefore, different operating strategies as well as other design considerations as suggested above would provide further optimization of operatiing this type of buildings.

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