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Assessment of monitored energy use and thermal comfort conditions in mosques in hot-humid climates

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ABSTRACT

In harsh climatic regions, buildings require air-conditioning in order to provide an acceptable level of thermal comfort. In many situations buildings are over cooled or the HVAC system is kept running for a much longer time than needed. In some other situations thermal comfort is not achieved due to improper operation practices coupled with poor maintenance and even lack it, and consequently inefficient air-conditioning systems. Mosques represent one type of building that is characterized by their unique intermittent operating schedule determined by prayer times, which vary continuously according to the local solar time. This paper presents the results of a study designed to monitor energy use and thermal comfort conditions of a number of mosques in a hot-humid climate so that both energy efficiency and the quality of thermal comfort conditions especially during occupancy periods in such intermittently operated buildings can be assessed accurately.

1. Introduction

Mosques represent a place of great importance and unique function and operation as worshipers using the mosque need to feel comfortable and calm, and be able to leave with a feeling of tranquility and peace. Consequently, they need to be carefully evaluated in terms of thermal comfort and energy requirements. However, only a limited number of studies have dealt with these requirements of mosques. A study on thermal comfort requirements for *Friday* prayer during the hot season in *Riyadh* [1] indicated that most people are comfortable and few prefer cooler conditions.

Thermal comfort considerations are usually paramount in most buildings involving people occupancy. This requires the addition or extraction of heat from the space depending mainly on the season and type of activities performed indoors. The thermal environment parameters involved are all those affecting body heat gains and losses. Air temperature, air humidity, air velocity, mean radiant temperature as well as human clothing and activity levels are factors that determine the heat balance of a human body in a given thermal environment. Several models are available in the literature to relate the human sensation of comfort to those factors. Prediction of thermal comfort has been of substantial interest to ASHRAE which developed the original comfort index based on effective temperature which is still in use [2]. Later, a new effective temperature was defined at 50% relative humidity, which describes the uniform temperature of a radiantly black enclosure at 50% relative humidity in which the occupant would experience the same comfort, physiological strain and heat exchange as in the actual environment with the same air motion [2].

A more elaborate prediction of thermal comfort at steady state conditions has been carried out by Fanger [3]. Considering the variability of thermal sensation under the same conditions, Fanger devised a means of estimating a predicted mean vote (PMV) of the subjects in a space in which there are deviations from optimal in the thermal sensation. Using the PMV, the percentage of people dissatisfied (PPD) can be predicted.

The impact of air movement and the effect of its flow patterns on thermal comfort have been the subject of many theoretical and experimental studies [4–7]. Results from those studies have emphasized the role of air velocity and air distribution patterns as a determinant factor of thermal comfort. Furthermore, models for predicting comfort at different flow regimes and air distribution patterns have been suggested. Charles [8] reviewed and assessed the validity of Fanger's Predicted Mean Vote (PMV) Model, and Fanger's Draught Model. The review also suggested that the bias in PMV predictions varies by context. The model was a better predictor in air-conditioned buildings than naturally ventilated ones, in part because of the influence of outdoor temperature, and opportunities for adaptation. Ji et al. [9] examined the thermal comfort of people in naturally ventilated environments in a field study in Shanghai, China. The study suggested that people residing

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in such hot area have adapted to its climate and their expectations for comfort allow them to endure heat better than expected.

de Dear and Brager [10] summarized earlier adaptive comfort research, presented some of its findings for naturally ventilated buildings, and discussed the process of getting the adaptive comfort incorporated into Standard 55. Adaptive models include in some way the variations in outdoor climate for determining thermal preferences indoors. Cheng and Ng [11] discussed in a recent study the adaptive model in thermal comfort, which has been included in the new revision of ASHRAE Standard 55-2004. Furthermore, it demonstrated the development of a comfort temperature chart for naturally ventilated buildings in Hong Kong. Van Hoof and Hensen Jan [12] discussed two implementations of the adaptive comfort model in terms of usability and energy use for moderate maritime climate zones by means of literature study, a case study comprising temperature measurements, and building performance simulation. The study concluded that for moderate climate zones the adaptive model is only applicable during summer months, and can reduce energy for naturally conditioned buildings.

The subject of thermal comfort in buildings is intimately related to the energy consumption/conservation issue as most of the time either heating or cooling is needed to maintain the space at a comfortable level. Many studies have been carried out to investigate this relationship and explore means and ways to conserve energy without compromising comfort [13,14]. A multidisciplinary approach for achieving energy saving and thermal comfort simultaneously was developed [15].

The impact of various energy conservation measures and HVAC system and component characteristics on building thermal performance including thermal comfort have been investigated. Results have indicated that adaptation of a higher temperature set point in summer can lead to a significant reduction in cooling energy without loss of thermal comfort [13]. The energy consumption by building heating, ventilating, and air-conditioning (HVAC) systems has evoked increasing attention to promote energy efficient control and operation of HVAC systems [16,17].

Many other measures related to the design and operation of the HVAC system can be considered for conserving energy. However, in no circumstances should the comfort of occupants be compromised. In hot and cold climates, thermal comfort in building is achieved by HVAC systems, resulting in considerable energy costs. In many situations, buildings are over cooled or the HVAC system is kept running for a much longer time than needed. This will allow considerable opportunities to conserve energy while achieving better comfort conditions or at least maintaining the desired comfort conditions at a reduced level of energy consumption. Recently, Budaiwi [18] proposed and implemented a multi-phase approach to investigate and remedy thermal comfort problems in buildings.

Although mosques are important buildings with a unique function and intermittent operation, evaluation of their thermal performance, problems and, subsequently, possible remedies did not receive adequate attention by researchers. This paper presents the results of a study monitoring energy use and indoor environmental conditions in a number of mosques in order to assess the quality of their thermal comfort conditions especially during occupancy periods in such intermittently operated buildings in hot-humid climates. This study is part of a comprehensive research conducted on mosque thermal performance [19].

In this part of the study, energy use and thermal indoor conditions for three mosques were monitored over a period of one year. These mosques were selected to represent the common types of a single-zone daily prayers mosque, a single-zone Friday (large) mosque, and a two-zone Friday mosque. The criteria of representative mosques selection as well as their physical and operational characteristics have been presented in previous work [20,21].

2. Common characteristics of mosques

Before presenting the energy use and thermal indoor conditions in the investigated mosques, it is essential to briefly describe the basic elements of typical mosque design as well as the activity modes occurring in a mosque.

2.1. Basic design elements of a typical mosque

The mosque is commonly a simple rectangular, walled enclosure with a roofed prayer hall. The long side of the rectangle is oriented toward the direction of the holy mosque in *Makkah* city. This wall is usually described as the *qibla* wall. The wall contains a recess in its center in the form of a wall niche called the *mihrab*. This wall also includes the *minbar* which is commonly an elevated floor, to the right of the *mihrab*, from which the *Imam* preaches or delivers the *Friday* speech, i.e. the *khutba*. These basic elements are the essentials of mosque design. Fig. 1 illustrates the plan and isometric of a simple, typical mosque design in which the basic design elements are emphasized. Though the functions of the mosque have remained unchanged, its architectural form, space, construction system, and building materials have evolved and developed to a significant and variable extent in different parts of the Islamic world, influenced by many factors.

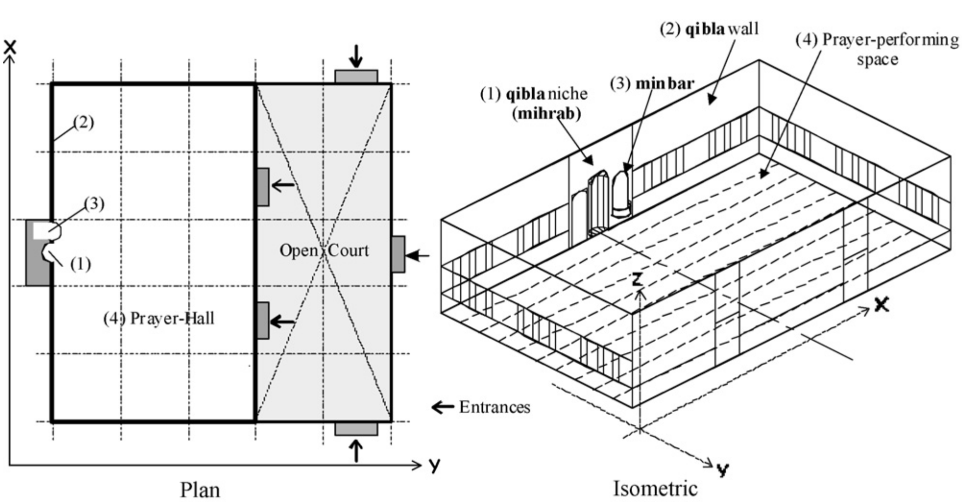

Fig. 1. The basic design elements of a simple mosque (a) plan, and (b) isometric [Reference: [22]].

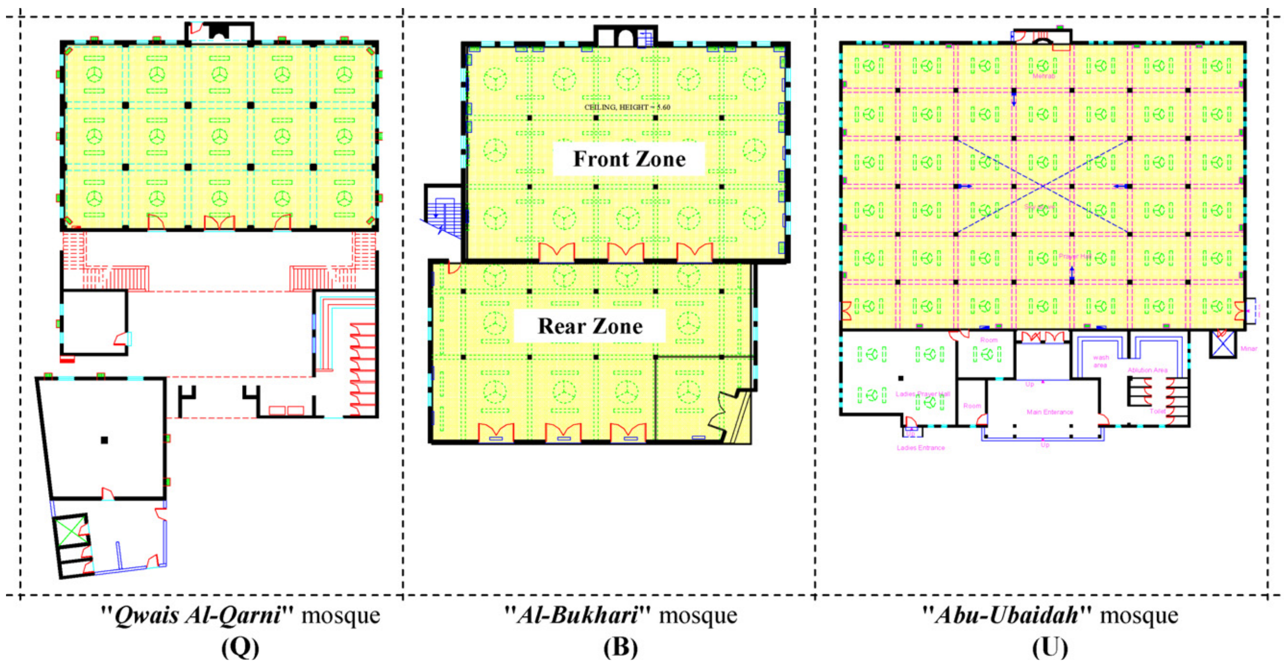

Fig. 2. The geometric configurations (plans) of the investigated mosques.

2.2. Activity modes in a mosque

The mosque design is mainly influenced by worship considerations. Worship in a mosque consists of two major modes. The first mode, namely the prayer mode, involves performing prayers either individually or in a group, as religiously prescribed. Group prayer must be performed with worshippers standing, bowing, prostrating, or sitting behind the *Imam*, on the same floor level, aligned in rows parallel to the *qibla* wall with distances around 1.2 m apart. The second mode is the preaching mode, where worshippers are directly seated on the floor in random rows listening to the *Imam* preaching or delivering the *khutba* while he is standing on the elevated *minbar* floor. The *minbar* floor height varies from one mosque to the other but usually is in the range of one to two meters above the mosque floor. The congregational capacity of the mosque is usually determined by the floor area divided by the area required for a worshipper to perform the prayer, i.e. approximately $0.80 \times 1.2 = 0.96\ m^2$.

3. Monitored energy use

In an earlier work, mosque electric energy use data for the full twelve months of the year 2002 have been monitored and presented for different mosques located in the hot-humid climate of the neighboring cities of *Dammam* and *Al-Khobar*, Saudi Arabia [21]. For energy monitoring equipment several *ELITE Pro* data logger were utilized. The logger is a portable poly-phase power meter which measures KW, kWh, Power Factor (PF) and other indicators. It is battery powered with remote downloading capability using an internal modem. The logger has and accuracy of <1% of reading. The three mosques of *"Owais Al-Qarni"*, *"Al-Bukhari"*, and *"Abu-Ubaidah"* will be respectively referred to as Mosque "**Q**", "**B**" and "**U**". The mosques plans are shown in Fig. 2. The mosques' use in terms "*Daily*" and "*Friday*" prayers, and capacity are indicated in Table 1. The monitored energy use data for the mosques are shown in Fig. 3. For the first two mosques, detailed (segregated) monthly energy data are presented while the mosque overall monthly energy use is presented for the "**U**" mosque.

From the analysis of the segregated energy use data for the two mosques "**Q**" and "**B**" as shown in Fig. 3(a and b), it is observed that A/C is clearly the most energy using system representing 79.34% and 70.6% of the yearly total energy use for the two mosques, respectively. While the "**B**" mosque, located in *Al-Khobar*, has energy use by the A/C system of about 70%, the "**Q**" mosque, located in *Dammam*, has a higher share of energy for the A/C system amounting to 79% of the yearly total. The climatic conditions for *Dammam* and *Al-Khobar* are similar and, therefore,

Table 1
List of mosques selected for in-depth energy monitoring and their physical data.

Reference	Type of use (prayer)	Mosque name	Physical data: Dimensions (m) $L \times W \times H$ (Area, m^2)	Capacity (persons)	Air-conditioning and ventilation system(s), number of units, type
Q	Daily	*Owais Al-Garni*	$24.5 \times 14.5 \times 5.4$ (355.0 m^2)	391	4 Floor-mounted Split units 10 Window-type A/C units 15 Ceiling Fans
B	Friday + Daily	*Al-Bukhari*	Front Zone $14.7 \times 22.8 \times 5.6$ (335.0 m^2) Rear Zone $12.4 \times 22.6 \times 5.6$ (280.0 m^2)	384	16 Wall-mounted Split units 17 Window-type A/C units 23 Ceiling Fans
U	Friday + Daily	*Abu-Ubaidah*	$42.8 \times 30.5 \times 5.3$ (1305.0 m^2)	1306	18 Floor-mounted Split units 2 Wall-mounted Split units 42 Ceiling Fans

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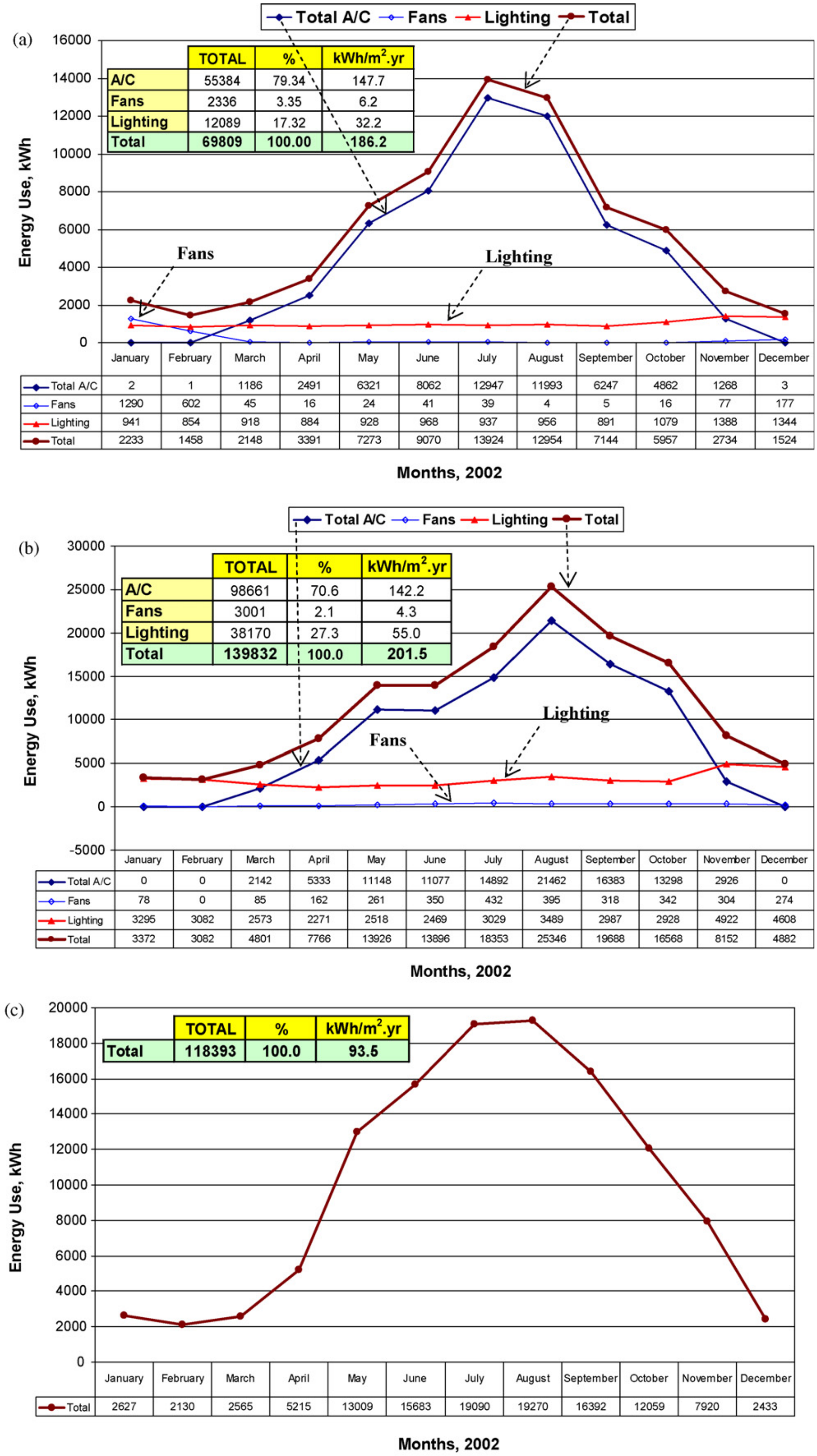

Fig. 3. Monitored energy use of (a) the "**Q**" mosque, (b) the "**B**" mosque and (c) the "**U**" mosque. Monitored annual energy use indices (kWh/m^2 yr) are tabulated.

the difference in the percentage of energy use for A/C, 9% more for the "**Q**" mosque, can be attributed to many factors notable among them being the differences in the physical and operational parameters among those mosques as well as the HVAC system operation and performance.

For the presented mosques, it is observed that the A/C is operating from March to November with its peak use during the summer months. The total energy use, then, follows the profile of the A/C system, the major energy consuming system with relatively small but steady use of lighting, followed by the use of ceiling fans for all months. This confirms the influence of A/C systems on energy use which dominates during summer and then sets the energy use trend for the whole year. The same overall energy use profile applies to the other "**U**" mosque with whole energy monitored data as presented in Fig. 3(c).

The lighting system contributes 17.32% and 27.3%, of the annual total energy use for the first two mosques, respectively. Comparing these percentages to the energy use trends for the same systems as presented in the monthly data of Fig. 3(a–c) shows that while the weather dependent A/C system energy use varies with the season, the lighting system energy use shows a relatively steady profile over the year as expected.

Ceiling fans on the other hand contribute a much smaller amount of energy over the year with 3.35%, and 2.1% of the annual total energy use for the first two mosques. However, the energy use by fans is not consistent for both mosques throughout the year. For example, it shows an increase during the winter months of December, January, and February for the "**Q**" mosque as presented in Fig. 3(a), which can be attributed to the need for air movement to overcome stagnation of air and the latent heat generation during prayer times and, therefore, enhance thermal comfort conditions without the need for using the A/C system during such colder (winter) months. During these same months A/C energy use is negligible (almost zero) where fans are relied upon for achieving air movement in addition to other available natural means such as opening windows and doors for ventilation. This mosque is also noted for not reaching full or even half of its occupancy capacity at any prayer time.

Although energy use by fans in the presented mosques does not show a clear and consistent trend, it is so low that a definite conclusion can not be drawn with the exception that it is needed to induce air movement to supplement A/C during summer months and to replace it during moderate weather conditions. Fans are also relied on during other non-summer months especially when the mosque is fully occupied and/or the A/C system is not as efficient as it should be.

From the analyses of the mosques energy use monitored data, it is clear that the A/C system is the single most energy intensive system in the mosque without which thermal comfort can not be achieved, as is the case in many other buildings in hot-humid climates. Therefore, it requires careful design and operation in order to achieve the required thermal comfort with the least energy requirements. However, means should also be provided in the design of mosques to allow for providing natural ventilation for the worshippers during winter time and in-between season periods.

Comparing the monitored annual energy use indices (kWh/m^2 yr) for the three mosques shows the lowest index for the "**U**" mosque at 93.5 kWh/m^2 yr followed by the "**Q**" mosque with 186.2, with 201.5 for the "**B**" mosque [21].

The low energy use index of the "**U**", can be attributed to a number of different reasons including its new construction and the relatively large area (compared to the other mosques). However, only a small portion (always partially occupied) of that area of the mosque is utilized (air-conditioned) during daily prayers resulting in a smaller energy use per unit area. In addition, it is the only mosque among the investigated group which is known to have wall and roof thermal insulation. This fact indicates the strong dependency of mosques energy use on the outside weather conditions and the importance of envelope design and construction in saving energy needed to air-condition mosques. The "**U**" mosque can be said to represent the type of newly constructed insulated large mosques.

4. Monitored thermal comfort conditions

Air temperature and humidity are the two most important parameters in determining the level of indoor thermal comfort. Accordingly, a total of 15 temperature/humidity data loggers were obtained, tested and installed in the selected mosques. The *Dickson D-200* data logger was found to be the most suitable for unattended measurement of the temperature and humidity necessary for evaluating the thermal environment and consequently the comfort conditions in mosques. It has a temperature accuracy of 0.28 °C at 25 °C. The loggers were placed in the walls and/or columns in each mosque at a height of 1.00 m from the floor level. This height is thought to be reasonable for standing as well as seated persons performing prayers and/or reciting the holy "*Qu'ran*". For practical reasons and cost considerations, each mosque was divided into zones with each zone served by one logger ranging from two to four loggers per mosque according to its size.

Important parameters for determining thermal comfort of the worshippers such as air velocity and MRT were not measured. It should be noted that the study was not intended to conduct a comprehensive thermal comfort assessment in existing mosques, but rather to have a fair, good idea about comfort conditions as related to the existing A/C operation strategies. Considering the relative importance of the air temperature in determining comfort, while recognizing the importance of other parameters particularly air velocity, the quality and condition of thermal comfort can be fairly judged based on air temperature and humidity assuming that normal air movement and air humidity are maintained within the space. Air movement patterns within an existing mosque are influenced by many factors determined by type and location of the A/C outlets, ceiling fans type, and installation and operation scheme. This would result in a complicated pattern that cannot be quantified based on few measurements.

In order to assess the thermal comfort conditions inside each mosque especially during prayer times, temperature and humidity measuring instruments were set to record readings every 5 min. However, due to the massive data recorded, the analyses were made for one day (the 15th day) in the middle of each of the four months of January, April, July, and October representing the four seasons of winter, spring, summer, and autumn, respectively for the year 2002 as presented in the parts of Fig. 4(a–d) for the investigated "**Q**" mosque. The figures show hourly mosque indoor temperature and relative humidity for the full day of each of the representative months with the acceptable thermal comfort zone limits superimposed. The indicated comfort temperature range is considered from 20 to 24 °C during the winter season while is determined from 23 to 26.5 °C during the summer, autumn and spring seasons. This comfort range is determined according to ASHRAE thermal comfort standard considering occupants with light activities and light summer clothing. Additionally, occupants are assumed to stay in the mosque for sufficient periods of time so as steady state model can be applicable. The comfort range is bounded by a relative humidity limit of 30–60% for the four seasons of winter, spring, summer, and autumn.

A close look at the presented data shows that thermal comfort is hardly achieved in the mosque during winter as represented by the month of January where the temperature records are below or just at the lower limit of comfort for the whole day and just

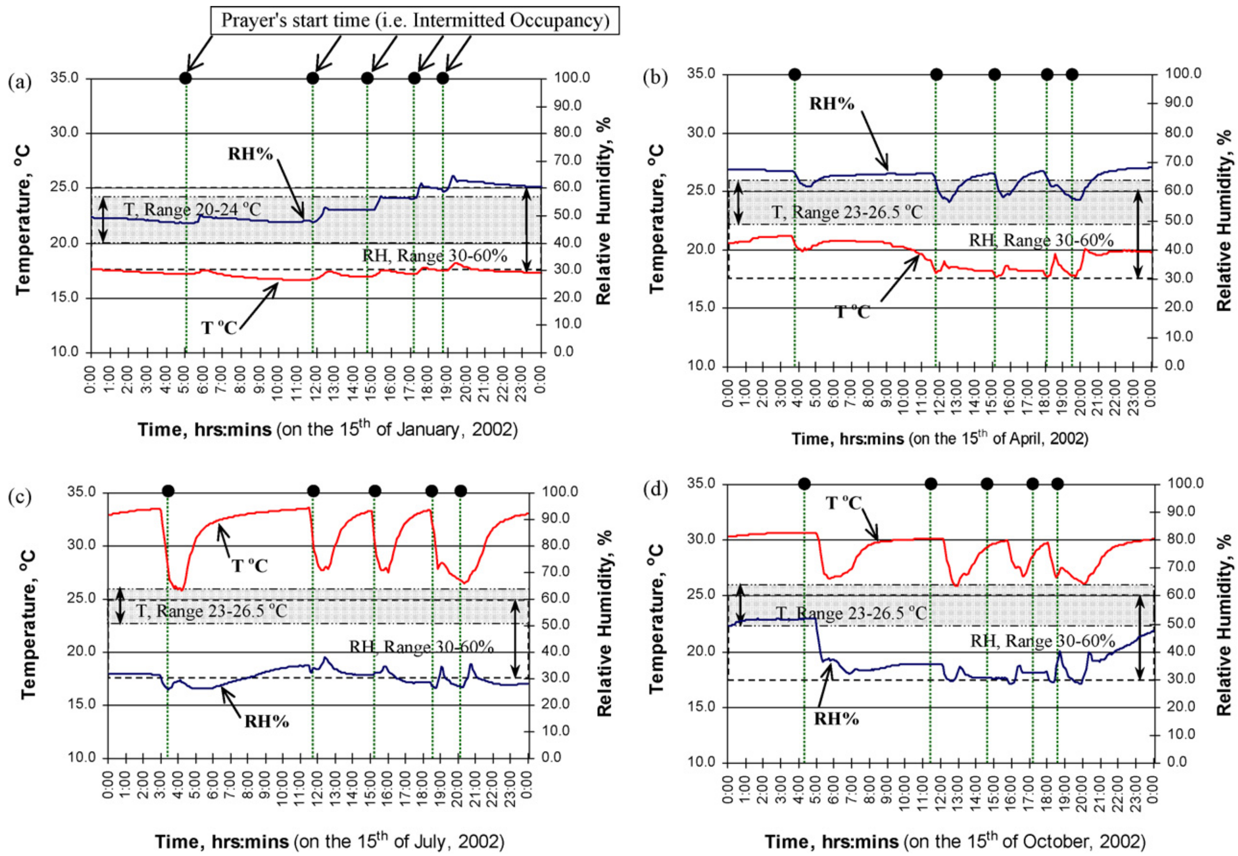

Fig. 4. The measured daily temperature-RH profile of the "**Q**" mosque during the 15th of (a) January, winter season, (b) April, spring season, (c) July, summer season, and (d) October, autumn season (2002). *Note*: The **start time** of each of the **five occupancy period** is indicated by **vertical dashed line**. The occupancy period varies from 25 to 45 min.

approaching the limit during some prayer times as a result of heat generated by users. Moreover, this is directly influenced by the outside weather conditions in the absence of heating provided during this period as observed in the monitored energy use data for the same mosque discussed earlier and shown in Fig. 3(a). However, the same figure also shows that fans are used during this month more than any other time period of the year. Relative humidity, on the other hand, is observed to be within acceptable comfort limits for most of the day with a slight increase beyond the upper limits towards the end of the day.

For the spring season as represented by the month of April, temperature and humidity measurements shown in Fig. 4(b) indicate that while temperature records fall within the acceptable comfort range, humidity is beyond the upper limits except during prayer times where it tends to be just below the upper limits. This month is expected to have mild conditions. However, thermal comfort is not achieved without the use of air-conditioning. With the negligible use of fans at this period, the air-conditioning system is providing the necessary comfort conditions with insignificant energy use as shown earlier in Fig. 3(a).

For the months of July and October, thermal comfort is observed not to be achieved, especially with regard to dry-bulb temperature where it falls outside the upper limit of the comfort zone for most prayer times while the relative humidity is to the lower limit of the comfort zone as shown in Fig. 4(c and d) for each month, respectively. Conditions reach their extreme of about 34 °C during off-use periods and just approaching the upper acceptable limits during prayer times after the A/C is turned on. The same applies for the month of October but with a lower extreme of about 30 °C.

Relative humidity, on the other hand, is always at its lower limit for the whole day during all months reaching its highest values around the middle of the comfort zone during night times in the months of April and October. These results indicate the ineffectiveness of the air-conditioning system to cool the space to the desired conditions during its short and intermittent operation during prayer times. However, there might be sufficient air movement to alleviate the accumulation of humidity as observed.

Similar trends are observed for other mosques. For the second two-zone mosque "**B**", it is observed from the winter temperature and humidity profiles similar trend is present in both zones with temperatures towards the lower limits while relative humidity readings are within/to the upper limits of the comfort zone. However, in the absence of the use of any heating or cooling as discussed earlier, the occupancy of the rear zone is observed to result in a higher temperature and humidity levels especially at night times. For the warmer spring season, Fig. 5(b) shows temperatures beyond the upper limits of the comfort range continuously for the unoccupied front zone with reasonable relative humidity values. However, the use of the A/C has brought both temperature and humidity to within the acceptable limits during all prayer times for the same month.

For the summer season represented by the month of July as shown in Fig. 5(a) the front zone is observed to be continuously considerably beyond the upper comfort conditions reaching 40 °C while relative humidity is very low reaching as low as 25%. The temperature of the rear zone (Fig. 5(b)) on the other hand reaches as high as 35 °C during unoccupied periods while being within an acceptable range during all prayer times with low relative humidity values especially at night. Had the whole mosque (both zones) being operated, it is expected that comfort conditions would not be achieved easily or a lot of energy would be required to achieve the desired conditions. Fig. 5(c and d) shows similar trends for the autumn season represented by the month of October for both zones but with less severity in temperature profiles and

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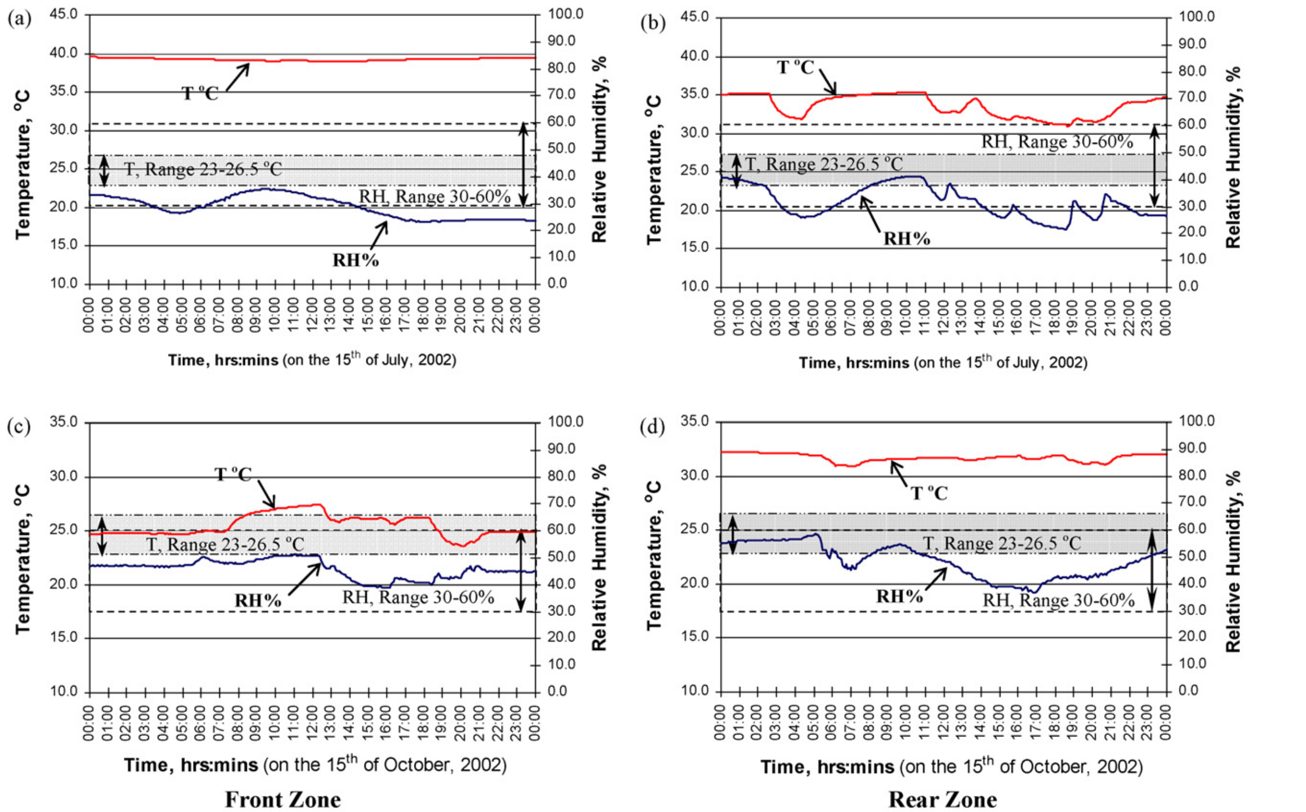

Fig. 5. The measured daily temperature-RH profile in the "**B**" mosque during the 15th of (a and b) July, summer season, and (c and d) October, autumn season (2002).

more acceptable relative humidity values than those observed for summer. It is worth mentioning here that operational zoning of this two-zone mosque was changed and the front zone was used for daily prayers instead of the rear zone during this month as can be observed from the readings of the indoor conditions in Fig. 5(c and d).

It can be concluded that the latter two mosques "**B**" and "**U**" have better thermal performance and, therefore, more acceptable thermal comfort conditions than in the "**Q**" mosque. This can be attributed to the use of operational zoning in the "**B**" mosque and the use of envelope thermal insulation as well as the new and more uniform A/C system for the "**U**" mosque as opposed to the "**Q**" mosque which is a single zone characterized by inefficient envelope thermal design and an old and inefficient A/C system.

However, for the third "**U**" mosque, temperature is observed to be within or just exceeding the upper limits of the comfort zone especially during night time prayers of *Maghrib* and *Isha* during winter (Fig. 6(a)) while relative humidity is close to the lower limit of the comfort range during the day time and close to the upper limit during night prayers. For the spring season, temperature is found just at the upper limit of the comfort zone during prayer times with little use of A/C while relative humidity is observed to be well within the acceptable range. However, the use of A/C clearly brings the mosque indoor conditions within the acceptable comfort range during all prayer times for the "**U**" mosque, especially, for the summer and autumn seasons represented by the two months of July as shown in Fig. 6(b) and October. Relative humidity is found well within the comfort zone for October and close to the lower limit during July (Fig. 6(b)). The capability of the A/C to bring the indoor conditions within acceptable higher levels during prayer times especially during summer and autumn seasons with much less energy use as discussed earlier for "**U**" mosque compared to that for the "**Q**" mosque is apparent. This can be attributed to the fact that the latter mosque is well insulated and has a relatively new and more uniform A/C system.

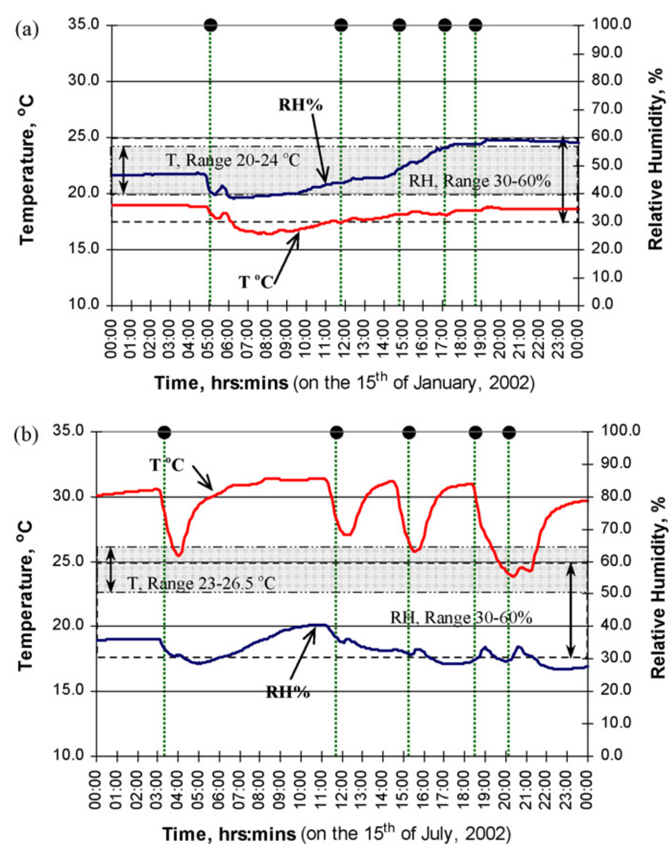

Fig. 6. The measured daily temperature-RH profile of the "**U**" mosque during the 15th of (a) January, winter season, (b) July, summer season (2002). *Note*: The **start time** of each of the **five occupancy period** is indicated by **vertical dashed line**. The occupancy period varies from 25 to 45 min.

5. Conclusions and recommendations

Based on the findings from the measurements of the mosque indoor environmental parameters, the following recommendations can be stated:

- The relatively high energy use for some mosques is not necessarily translated into better thermal comfort conditions. Thermal comfort is observed not to be achieved in most of the investigated mosques especially the un-insulated ones during times of peak thermal loads.
- Acceptable thermal comfort conditions can be greatly enhanced by using mosque envelope thermal insulation due to their skin-load dominated load, especially during the long un-occupied periods, as well as their intermittent operation.
- Mosque operational zoning can lead to maintaining acceptable thermal comfort conditions when carefully considered in the design stage and subsequently appropriately implemented. The level of thermal comfort improvement as well as energy savings as a result of mosque operational zoning can be more pronounced in Friday and large mosques with partial daily occupancy compared to medium and small size mosques.
- Most mosques, especially large ones, have high ceilings that will create an upper warm zone due to air stagnation warm periods. In order to ensure achieving thermal comfort at reduced energy requirements, the height of the air supply outlets should be located as low as possible (i.e. around 2.0 m above the floor level) and close to the occupied zone.
- When A/C intermittent operation is combined with an appropriate operational zoning strategy, acceptable thermal comfort can be achieved with less energy use.

Although the study was conducted for mosques designed and operated in the hot-humid climates of the eastern region of Saudi Arabia, the above recommendations can be applicable to mosques in general. However, the relative effectiveness of the findings may vary according to the mosque type, size, operation, and location.

Acknowledgments

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References

[1] S.A.R. Saeed, Thermal comfort requirements in hot dry regions with special reference to Riyadh part 2: for Friday prayer, International Journal of Ambient Energy 17 (1) (1996) 17–21.
[2] ASHRAE, ASHRAE Handbook-Fundamental, American Society of Heating Refrigeration and Air-Conditioning Engineers Inc., Atlanta, GA, 2005.
[3] P.O. Fanger, Thermal Comfort Analysis and Applications in Environmental Engineering, McGraw-Hill Book Company, 1970.
[4] Z. Jiang, F. Haghighat, J. Wang, Thermal comfort and indoor air quality in a partitioned enclosure under mixed convection, Building and Environment 27 (1) (1992) 77–84.
[5] A.A. Fissore, G.A. Liebecq, A simple empirical model for predicting velocity distribution and comfort in a large slot-ventilated space, ASHRAE Transitions, Part 2 (1991) 1087–1095.
[6] M.E. Fountain, Laboratory studies of the effect of air movement on thermal comfort, a comparison and discussion of methods, ASHRAE Transactions, Part 1 (1991) 863–873.
[7] W.K. Chow, L.T. Wong, Experimental studies on air diffusion of a linear diffuser and associated thermal comfort indices in an air-conditioned space, Building and Environment 29 (1994) 523–530.
[8] Kate E. Charles, Fanger's Thermal Comfort and Draught Models, IRC Research Report RR-162, 2003.
[9] X.L. Ji, et al., Predicting thermal comfort in Shanghai's non-air-conditioned buildings, Building Research and Information 34 (5) (2006) 507–514.
[10] Richard J. de Dear, Gail S. Brager, Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55, Energy and Buildings 34 (6) (2002) 549–561.
[11] V. Cheng, E. Ng, Comfort temperatures for naturally ventilated buildings in Hong Kong, Architectural Science Review 49 (2) (2006) 179–182.
[12] Joost Van Hoof, L.M. Hensen Jan, Quantifying the relevance of adaptive thermal comfort models in moderate thermal climate zones, Building and Environment 42 (1) (2007) 156–170.
[13] K.W. Tham, M. Bullah, Building energy performance and thermal comfort in Singapore, ASHRAE Transactions, Part 1 (1993) 308–321.
[14] R. Zmeureanu, A. Doramajian, Thermally acceptable temperature drifts can reduce the energy consumption for cooling in office buildings, Building and Environment 27 (4) (1992) 469–481.
[15] K.W. Tham, Energy conservation without sacrificing thermal comfort, Building and Environment 28 (3) (1993) 287–299.
[16] E.H. Mathews, D.C. Arndt, C.B. Piani1, E. van Heerden, Developing cost efficient control strategies to ensure optimal energy use and sufficient indoor comfort, Applied Energy 66 (2000) 135–139.
[17] E.H. Mathews, C.P. Botha, D.C. Arndt, A. Malan, HVAC operation strategies to enhance comfort and minimize energy use, Energy and Building 33 (2002) 853–863.
[18] I.M. Budaiwi, An approach to investigate and remedy thermal-comfort problems in buildings, Building and Environment 42 (2007) 2124–2131.
[19] M.S. Al-Homoud, I.M. Budaiwi, A.A. Abdou, Thermal Design and Air-Conditioning Operation Strategies of Mosques in Hot-Humid Climates of the Kingdom, KACST Funded Research Project No. AT-18-13, Final Report, 2005.
[20] A.A. Abdou, M.S. Al-Homoud, I.M. Budaiwi, Mosque energy performance, part I: energy audit and use trends based on the analysis of utility billing data, Journal of King Abdul-Aziz University for Engineering and Sciences 16 (1) (2005) 165–184.
[21] M.S. Al-Homoud, A.A. Abdou, I.M. Budaiwi, Mosque energy performance, part II: monitoring of end energy use in a hot-humid climate, Journal of King Abdul-Aziz University for Engineering and Sciences 16 (1) (2005) 185–202.
[22] A. Abdou, Measurement of acoustical characteristics of mosques in Saudi Arabia, Journal of Acoustical Society of America 113 (3) (2003) 1505–1517.

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