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RESEARCH ARTICLE

Improving thermal comfort in mosques of hot-humid climates through passive and low-energy design strategies

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Abstract Mosques have intermittent operational schedules with short-term occupancy during the five daily prayers. The occupancy level of the daily prayers is a fraction compared to the mandatory Friday prayers with full occupancy. Usually, the same thermal control mechanism is operated within the same large prayer hall to maintain the thermal comfort of the occupants. Yet, the comfort requirements are often not met due to the short span of operation during prayer times. Nevertheless, mosques have a very high energy usage as the same energy-intensive system is operated even during minimal occupancy profiles. The current research aims at using a passive approach towards design to achieve the comfort conditions during the low occupancy daily prayer times without employing mechanical intervention. Numerical simulations are carried out on a validated model of the case study building to investigate the impact of the west-facing *Qiblah* wall as the congregation stands in proximity to this wall. The design alternatives are tested in conjunction with ventilation strategies to holistically assess the thermal comfort of the occupants. Results show that as much as 4—6 °C reduction in indoor wall surface temperature can be achieved with a suitable *Qiblah* wall design, which reduces the mean radiant temperature of the occupants by 2—4 °C. Combined with ventilation strategies, thermal comfort can be significantly improved by at least 40% for the prayers during the hottest times of the day, and as much as 80% for night-time prayers. Results suggest that suitable comfort conditions can be achieved without the need for air-conditioning for at least two or three of the five daily prayers.

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1. Introduction

Mosques are establishments where Muslims gather for the five daily congregational prayers that are held at intermittent intervals throughout the day. The prayer times are determined according to the solar position; the congregation occurs at the break of dawn (*Fajr* prayer), after midday (*Dhuhr* prayer), late afternoon (*Asr* prayer), immediately after sunset (*Maghrib* prayer), and beginning part of the night (*Isha* prayer). Additionally, there is a weekly *Jumuah* prayer accompanied by a sermon which is held instead of the *Dhuhr* prayer on Friday. The occupancy level of the mosque is the highest during the *Jumuah* prayers, as it is mandatory to be prayed in congregation, while the daily prayers usually have a much smaller number of congregants (Azmi et al., 2021). The main component of a mosque building is the prayer hall which is designed as a large rectangular or square-shaped hall to accommodate the maximum occupancy during *Jumuah* prayer time. Prayers are held in close ranks facing towards the *Qiblah*, which is the direction towards the *Kaa'bah* in Makkah, Saudi Arabia. Hence, to facilitate even and equal rows, most prayer halls have an orientation that is perpendicular to the *Qiblah* axis (Azmi and Kandar, 2019). Each prayer, along with the accompanying rituals, spans over a 20—30 min period and the mosques remain empty in between the prayer times. Mosques are buildings with user-centric activities and thus, are termed as external-load or skin-load dominated buildings (Azmi and Kandar, 2020). For such buildings, the internal thermal load is mostly dictated by the design features which are influenced by the outside climate, such as the orientation, surroundings, building envelope, etc. (Al-homoud, 2005). Therefore, the optimal thermal performance of the building is of paramount importance in maintaining the thermal comfort of the occupants as well as the energy efficiency of the building (Azmi and Ibrahim, 2020).

The thermal comfort of the congregants is of great importance to maintain a suitable ambience during the prayers. As of 2019, there are over 4 million mosques in the world (Deloitte, 2019), the majority of which are located in hot climates (Azmi and Kandar, 2019). Multiple surveys have found that most mosques in Malaysia (Aziz, 2016), Kuwait (Al-Dabbous et al., 2013), Iraq (Hameed, 2011), Saudi Arabia (Alabdullatief et al., 2016), and UAE (Mushtaha and Helmy, 2017) rely solely on heating, ventilation and air conditioning (HVAC) systems to improve the comfort conditions for the occupants. Most mosques in modern times are designed and built without regard to climatic considerations (Azmi and Ibrahim, 2020) and hence, tend to be very energy-intensive (Hussin et al., 2018). Research regarding the indoor thermal environment in mosques is a relatively new field and not many studies have been conducted. Most of the available studies are focused on optimizing the HVAC system or lowering the thermal load to reduce the overall energy requirements of the building. These studies address various aspects of the HVAC system such as machine efficiency (Al Anzi and Al-Shammeri, 2010), operational strategies (Samiuddin, 2014), thermal zoning (Al-Shaalan et al., 2017; Al-Tamimi et al., 2020), and thermal load optimization (Budaiwi, 2011; Budaiwi et al., 2013). There are very few studies that have been conducted on improving the thermal comfort of occupants. These research have addressed architectural styles (Asfour, 2009), building form (Mushtaha and Helmy, 2017), or individual building elements such as the roof (Ibrahim et al., 2014), walls (Hameed, 2011) etc. to propose design alternatives for better thermal comfort of the occupants. However, all of these research assess thermal comfort in terms of ambient air temperature only. Although air temperature is one of the important factors to gauge comfort conditions, it does not provide a comprehensive evaluation of human thermal comfort in all circumstances, especially in the hot climates (Azmi, 2022). Hence, there remains a research gap in wholistically addressing the thermal comfort of the occupants in the context of mosques.

Typically, the HVAC systems in mosques follow an intermittent operational schedule according to the prayer times (Azmi et al., 2021). For each of the five daily prayers, the HVAC system is generally run for approximately an hour, while the actual prayer time for each instance is about 15—20 min. Research shows that despite a high energy usage for these systems, thermal comfort conditions are not fulfilled for at least three (Budaiwi et al., 2013) to four (Al-Homoud et al., 2009) instances out of the five daily prayers. This is also reflected in multiple surveys carried out in mosques (Hussin et al., 2015; Maarof, 2014; Calis et al., 2015) where occupants have expressed dissatisfaction with the indoor conditions despite HVAC systems being operated. As the HVAC systems are run intermittently throughout the day for a short duration during the prayer times, the indoor air temperature often fails to reach the comfort levels in a large prayer hall. Additionally in hot climates, the solar gain of the building envelope is radiated to the interior which contributes to the thermal discomfort of the occupants (Guo et al., 2020). Furthermore, congregants standing in close proximity during prayer times can be a source of radiant heat, which adds to the discomfort. In the context of hot climates or under summer conditions, the recommended comfort temperature range by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is 23—27 °C (ASHRAE, 2020). This presumption is based on the premise that there is no direct sunlight and the mean radiant temperature (MRT) is below 28 °C, while the relative humidity levels are at 50%. In locations with direct or indirect solar gains, or with high humidity conditions, the ambient temperature would need