Study on Indoor Thermal Environment and Thermal Comfort in an Air-Conditioned Mosque during Prayer Times in the Tropical Climate of Malaysia

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https://doi.org/10.5109/7323313

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 10, pp.538-544, 2024-10-17. International Exchange and Innovation Conference on Engineering & Sciences
バージョン：

Study on the indoor thermal environment and thermal comfort in an air-conditioned mosque during prayer times in the tropical climate of Malaysia

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Abstract: *Understanding the environmental dynamics of air-conditioned mosques hosting five daily prayers with fluctuating occupancy is essential for informed design decisions. This study investigates a Malaysian mosque's thermal environment and worshippers' perceptions, including comfort temperatures. Field measurements spanned a week and included various prayer times. A questionnaire-based adaptive thermal comfort was conducted after Friday midday prayer when worshippers fully occupied the mosque's main hall. The mean indoor air temperature (T_a), relative humidity (RH), and air velocity (V_a) for all prayers were recorded at 25.3 °C, 62%, and 0.5 m/s, respectively, aligning with local standards. It was found that the mean operative temperature at the neutral thermal sensation was 26.1 °C. Similarly, the mean operative temperature when respondents preferred no temperature change and comfortable overall comfort was 26.1 °C. Therefore, the temperature set point can be raised while maintaining thermal comfort.*

Keywords: Thermal environment; thermal comfort; comfort temperature; mosque; prayer

1. INTRODUCTION

Mosques, considered holy structures in Islam, mainly function as places of Muslim worship. Nonetheless, their importance extends beyond religious practices, as they act as community centres where various social activities occur.

Mosque buildings are generally large in volume, so the energy use intensity is high [1]. As is known, buildings contribute 35% of final energy consumption and share the same share of greenhouse gas emissions [2]. The most significant proportion is from heating, ventilation, and air-conditioning (HVAC) use, including the behavioral pattern of HVAC use by occupants [3,4]. Although mosques reportedly use high energy intensity for HVAC, worshippers' thermal comfort issues still arise.

Research on mosque thermal comfort is limited [5], with most studies focused on hot-dry climates. Research on this topic is notably sparse in tropical regions with significant Muslim populations and numerous mosques, such as Malaysia and Indonesia [1,6]. Studies on naturally ventilated mosques in these regions reveal common issues: Ibrahim et al. [7] found inadequate thermal comfort due to roof heat in Malaysia, while Kamar et al. [8] and Noman et al. [9] identified poor air circulation and high temperatures away from openings. In Indonesia, Ray et al. [10] simulated ventilation strategies for a mosque under construction, highlighting significant comfort concerns.

Malaysian standard [11] suggests maintaining a dry bulb temperature of 24-26°C for building design to ensure energy efficiency. However, this guideline lacks specific references to local thermal comfort research [12], making it a broad design recommendation. Existing literature on thermal comfort in tropical regions indicates a lack of studies focused on the optimal comfort temperature in mosques. Therefore, this study examines Malaysia's typical air-conditioned mosque's indoor thermal environment and comfort temperature. To this end, field measurements assessed the actual thermal condition, such as temperatures, relative humidity, and air movement. Also, the worshipper's thermal perception and adaptation were investigated using a questionnaire-based thermal comfort survey. Afterwards, the optimum temperature can be determined by linking the field measurements and survey results.

2. METHODOLOGY

2.1 Investigated mosque

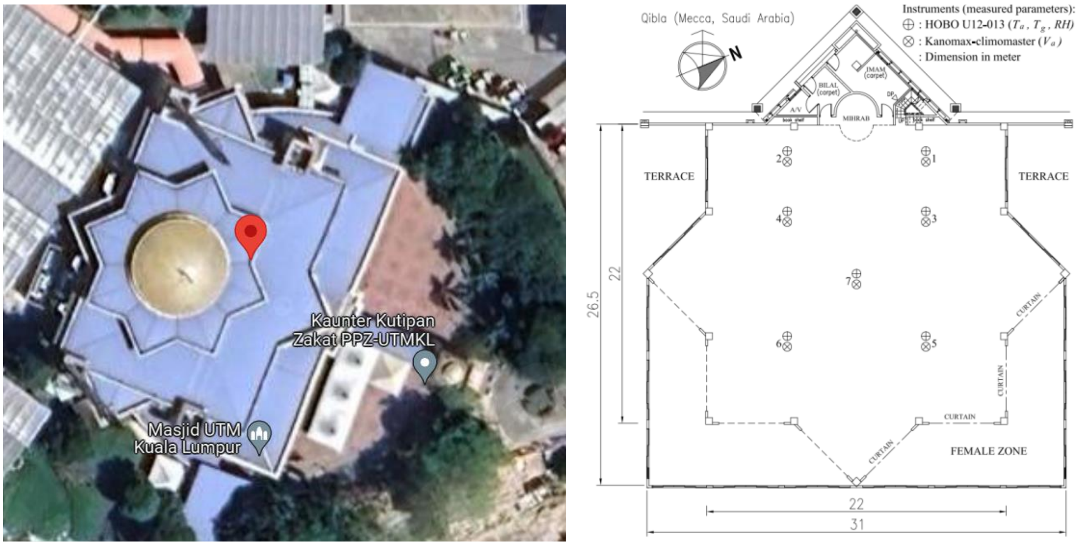
Field measurements were conducted on a typical air-conditioned large mosque located in Malaysia from Thursday, 26th January to Thursday, 2nd February 2023. Fig. 1 (a) shows the Universiti Teknologi Malaysia - Kuala Lumpur (UTMKL) mosque selected as a study case because it holds daily and Friday prayers. The mosque has split air conditioners and fan units (wall-mounted and pedestal fans). Based on the interview with the mosque's administrators, the setpoint temperature was minimum at about 20 °C.

Measuring instruments were located at seven locations in the mosque's main hall, as shown in Fig. 1 (b). The measured parameters were indoor air temperature (T_a), indoor globe temperature (T_g), indoor air velocity (V_a), and indoor relative humidity *(RH)*. The temperatures and *RH* were measured using HOBO-U12-013 datalogger with accuracy of ±0.5 °C and ±5% *RH* (at 25 °C, 50%), respectively. The air velocity was measured using Kanomax-clinometer with an accuracy of ± (2% of reading ± 0.0125) m/s [0.10-30.0 m/s]. The operative temperature (T_{op}) was also chosen for further analysis since it is used in ASHRAE Standards 55 [13] to determine comfort ranges. The T_{op} was calculated using Equation (1) and (2) below.

$$T_{op} = AT_a + (1 - A)T_{mrt} \quad (1)$$

$$T_{mrt} = \left[(T_g + 273)^4 + \frac{1.1 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}}(T_g - T_a)\right]^{1/4} - 273 \quad (2)$$

where T_{op} is the mean radiant temperature, the constant A is assigned, a value based on air velocity: 0.5 when V_a is less than 0.2 m/s, 0.6 when V_a ranges between 0.2 and 0.6 m/s, and 0.7 when V_a is between 0.6 and 1 m/s, emissivity (ε) of the globe is 0.95 for a black globe, and the diameter (D) of the globe is 0.04 m.



(a) (b)

Fig. 1. Selected mosque: a) aerial view of the mosque [14], b) main hall layout plan and instruments position

2.2 Subjective thermal comfort survey

A thermal comfort survey was conducted after Friday prayer on 27th February 2023. The questionnaire was adopted from previous studies [12,15] using bilingual languages. English and Malay. Table 1 provides various scales for assessing thermal sensation in this study, plus questions regarding behavioural adaptation related to room thermal conditions.

A total of 117 worshippers completed the questionnaire. The total capacity of the space is 707 worshipers, representing a confidence level and margin of error of 98% and 8%.

Predicted mean vote (*PMV*) and predicted percentage of dissatisfied (*PPD*) were calculated using the Center for the Built Environment (CBE) Thermal Comfort Tool [16]. The *PMV* was calculated from T_a, T_{mrt}, V_a, RH, metabolic rate, and clothing insulation. In this study, the metabolic rate and clothing insulation are 1.2 met and 0.5 clo, respectively.

Table 1. Subjective parameter scale

Scale	Thermal sensation vote	Thermal preference	Humidity feeling	Humidity preference	Air movement vote	Air movement acceptance	Overall comfort
-3	Very cold	-	Very dry	-	-	-	-
-2	Cold	Much warmer	Dry	Much drier	-	-	-
-1	Slightly cold	A bit warmer	Slightly dry	A bit drier	-	-	-
0	Neutral	No change	Neutral	No change	-	Not acceptable	-
1	Slightly hot	A bit cooler	Slightly humid	A bit more humid	No air movement	Acceptable	Very uncomfortable
2	Hot	Much cooler	Humid	Much more humid	Low	-	Uncomfortable
3	Very hot	-	Very humid	-	Neither high nor low	-	Slightly uncomfortable
4	-	-	-	-	High	-	Slightly comfortable
5	-	-	-	-	-	-	Comfortable
6	-	-	-	-	-	-	Very comfortable

3. RESULTS AND DISCUSSION

3.1 Indoor thermal environment

Fig. 2 shows indoor air temperature and relative humidity during the measurement campaign. The indoor air temperature fell before the call to prayer (vertical grey dotted line), indicating that air conditioners were switched on. It is noted that it takes time to reach a standard prescribed by Malaysian guidelines of 24 °C. The temperature gradually rose when worshippers arrived. After a short period of prayer, 10-20 minutes, worshippers left the main hall and air conditioners were switched off, causing the temperature to rise significantly. The same manner happened to RH.

The rise in temperature after the air conditioners were turned off was affected by the external air temperature. In agreement with Taufan et al. [1], most of the heat energy the mosque receives comes from external factors due to the large surface area of the envelope. The continuous closure of doors and windows also led to heat accumulation in the main hall. These findings could serve as a basis for enhancing building operation procedures.

Fig. 3 illustrates the airspeed profile during the monitoring period. Airspeed in the first row ($V_{a,1}$ and $V_{a,2}$) was highest due to both wall-mounted and pedestal fans. In contrast, airspeed at position 7 was lowest as it was far from any fan, but its central location under a domed roof allowed air to flow from all directions and rise due to the stack effect. Consequently, its airspeed was not markedly different from other positions.

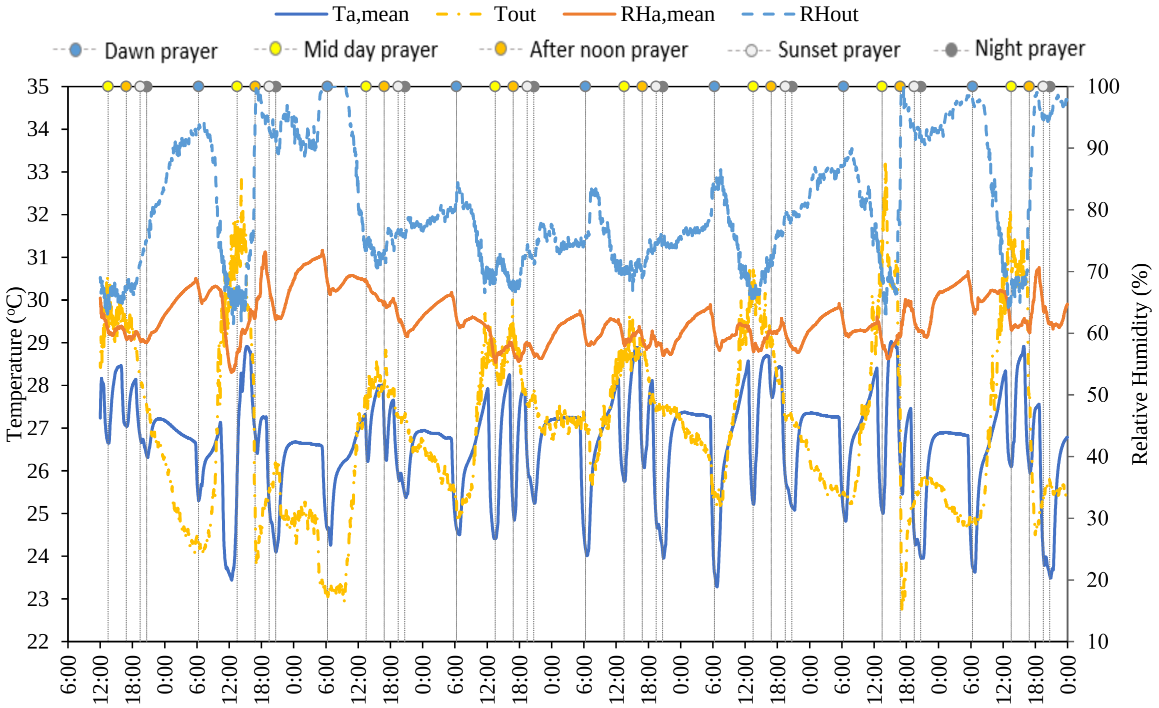


Fig. 2. Indoor air temperature and relative humidity during campaign (from Thursday, 26th January to Thursday, 2nd February 2023)

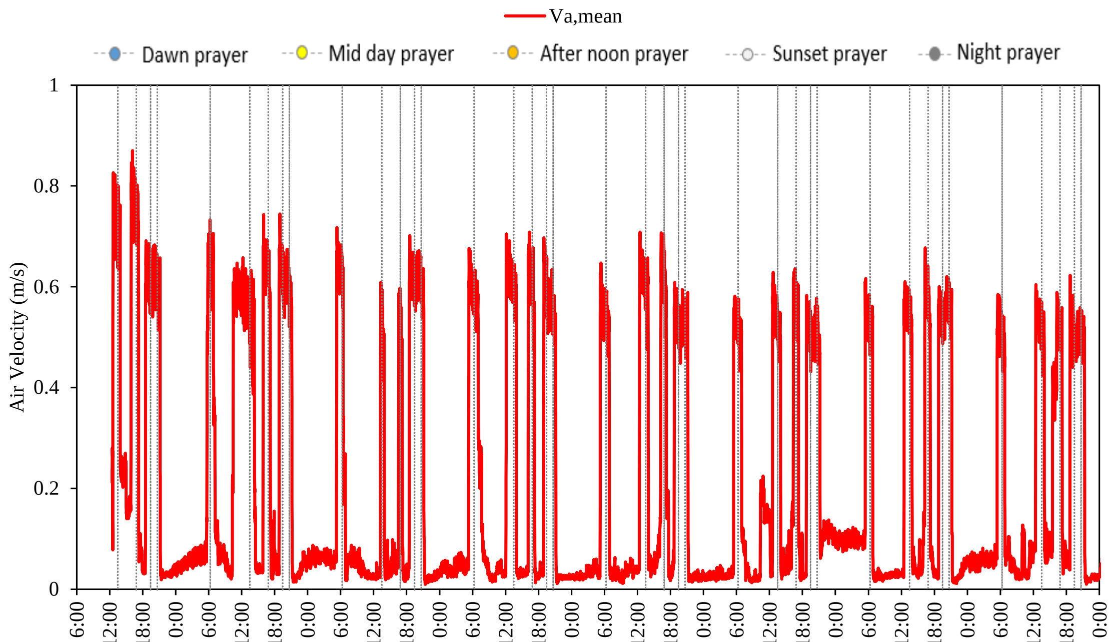


Fig. 3. Air velocity during the campaign (from Thursday, 26th January to Thursday, 2nd February 2023)

The comfort temperature reflects the influence of fans on warmth perception [17]. Equation (3) shows the relationship between comfort temperature and air speed [17–19]. Given an average air velocity of 0.5 m/s, the comfort temperature will rise by approximately 2.5 °C.

$$7-\frac{50}{4-10V_a^{0.5}}\ {}^\circ C \quad (3)$$

Table 2 shows descriptive statistics of the indoor thermal environment during the field measurements campaign. The mean T_a, T_g, and T_{op} for all prayers were recorded at 25.3 °C, 25.0 °C, and 25.1 °C, respectively, aligning well with local standards. The average airspeed was 0.5 m/s, which contributes positively to thermal comfort. The average relative humidity during prayers was 62%, falling within the CEN CR 1752 standard range of 30-70% [20]. Additionally, due to the mosque's large main hall, there was a temperature variation of 1.7°C between the highest and lowest average temperatures at different measurement points.

Table 2: Mean indoor thermal environment during prayers

	T_a (°C)	T_g (°C)	T_{mrt} (°C)	T_{op} (°C)	*RH (%)*	V_a *(m/s)*
Dawn (06:17-06:40)	24.3	24.0	23.8	24.1	63	0.5
	(0.1)	(0.0)	(0.0)	(0.0)	(1)	(0.0)
Midday (13:28-14:00)	26.0	25.8	25.7	25.8	60	0.5
	(0.2)	(0.2)	(0.2)	(0.2)	(0)	(0.1)
Afternoon (16:50-17:10)	26.2	25.9	25.7	26.0	62	0.6
	(0.1)	(0.1)	(0.0)	(0.1)	(0)	(0.0)
Sunset-Night (19:26-21:05)	25.0	24.6	24.5	24.7	61	0.6
	(0.2)	(0.2)	(0.2)	(0.2)	(1)	(0.0)

T_a: air temperature, T_g: globe temperature, T_{mrt}: mean radiant temperature, T_{op}: operative temperature, RH: relative humidity, V_a: air velocity. Values in brackets denote standard deviation.

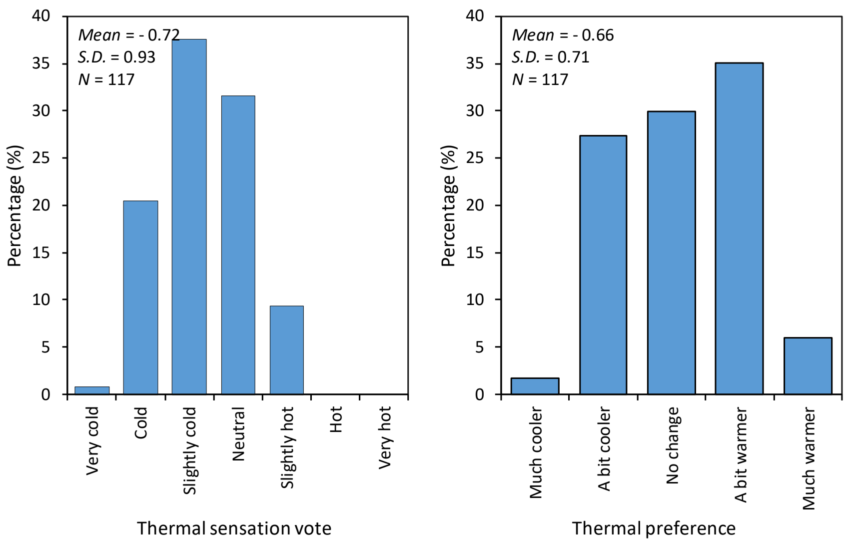
3.2 Subjective assessment

Results show that most respondent's thermal sensation votes were within -1 ≤ *TSV* ≤ 1, as in Fig. 4 (a). Among 79% of comfort responses, 32% of respondents had neutral sensations. Also, this result indicates that most worshippers felt slightly cold inside the main hall, with a mean *TSV* of -0.72. of calculating the predicted value produces a predicted mean vote (*PMV*) of -0.38 and a predicted percentage of dissatisfaction (*PPD*) of 11%.

Fig. 4 (b) shows that most worshippers prefer warmer temperatures, with a mean thermal preference of -0.66. About 20% of respondents voted for "no change" thermal preference, whereas they did not feel neutral. This result might show a contradiction; however, as indicated in a previous study [21], the thermal sensation may not match one's preferences.

Worshippers tended to feel neutral humidity, with a mean vote of humidity feeling of -0.17 (Fig. 4 (c)). This result explains why their preference in Fig. 4 (d) mainly was "no change" humidity preference. Most worshippers accepted the air movement (Fig. 4 (e)), although about 30% voted for the low air movement (Fig. 4 (f)). This indicates that their acceptability is more related to their thermal sensation.

Fig. 4 (g) shows that, in general, the worshippers felt comfortable in the main hall with a mean of overall comfort of 5. This value was obtained mainly from those who voted -1 ≤ *TSV* ≤ +1, namely 88%.



(a) (b)

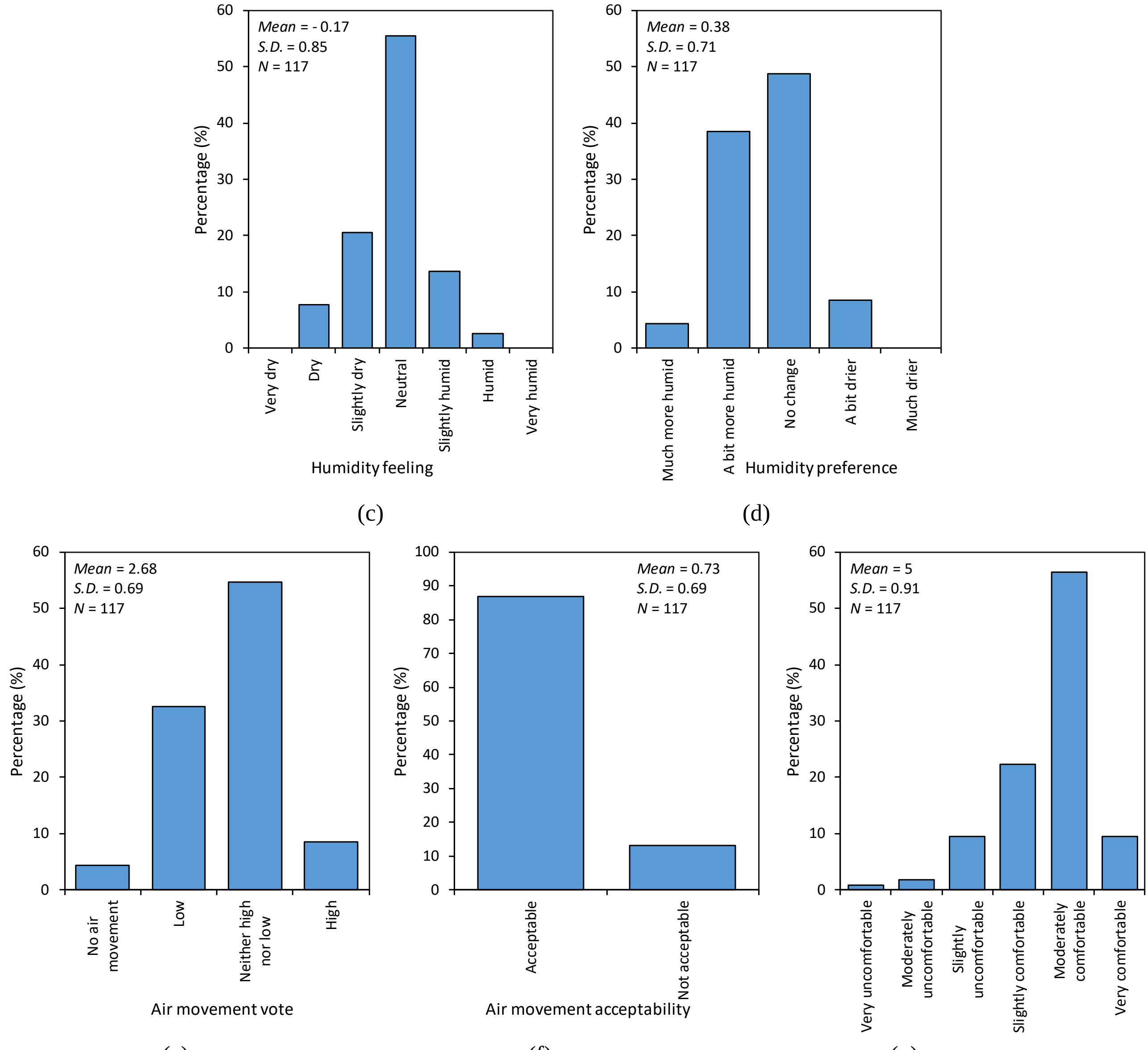


Fig. 4. Subjective results: (a) thermal sensation vote, (b) thermal preference, (c) humidity feeling, (d) humidity preference, (e) air movement vote, (F) air movement acceptability, and (g) overall comfort

Indoor neutral temperature for further analysis was calculated by calculating the data based on the position of the worshipers towards the measurement points they stated on the questionnaire sheet. The data were then plotted in Fig. 5. The linear regression for *TSV* and *PMV* is therefore found as follows:

$$TSV = 0.2587\, T_{op} - 12.172\ (R^2 = 0.7191) \qquad (4)$$

and

$$PMV = 0.4568\, T_{op} - 7.439\ (R^2 = 0.2374) \qquad (5)$$

Furthermore, Equations (4) and (5) predict the indoor neutral operative temperature for *TSV* and *PMV* to be 28.8 °C and 26.6 °C, respectively. This result aligns with previous studies [22,23] that indicate *PMV* underestimates the neutral temperature obtained with *TSV*. In the *PMV* model, occupants are considered passive recipients of thermal conditions without considering occupancy adaptation, especially in hot climate areas.

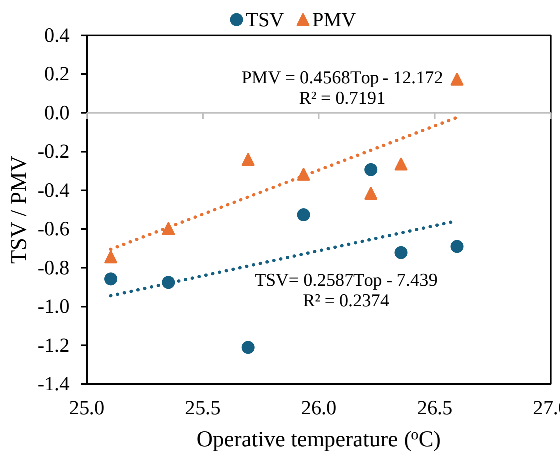


Fig. 5. Linear regression between T*SV*/*PMV* and T_{op}

It should be noted that the above method averages all respondent's answers. Therefore, comfort temperatures were estimated from three circumstances of votes. They are the "neutral" vote of thermal sensation vote (*TSV* = 0), the "no change" vote of thermal preference (*TP*= 0), and both "moderately comfortable" and "very comfortable" votes of overall comfort (*OC* = 5 or 6). As shown in Table 3, the mean operative temperatures for selected *TSV*, *TP*, and *OC* were 26.1 °C. The results are within the range of previous studies that only used linear regression methods, namely 26.1 °C to 31.4 °C [22–24].

Table 3: Mean T_{op} from selected votes

Description	*TSV* = 0	*TP* = 0	*OC* = 5 or 6
N	37	35	77
Mean T_{op} (°C)	26.1	26.1	26.1
S.D. (°C)	0.5	0.4	0.5

Fig. 6 shows a venn diagram of respondent's adaptive choices related to their perceived conditions. Some chose "did nothing", namely 64 respondents. About 17% of those who chose "did nothing" basically felt an uncomfortable thermal sensation (*TSV*=-2). Those who decide to do something sometimes have more than one adaptive choice. These results seem to relate to the Friday prayer procession, which emphasizes silence and calm throughout the procession.

Related to the previous discussion, a person's thermal history may play an important role in responding to thermal conditions. Previous studies [22,25–27] indicate that thermal history influences physiological, psychological, and behavioral adaptation. Therefore, most may have already adapted to their new location's thermal environment.

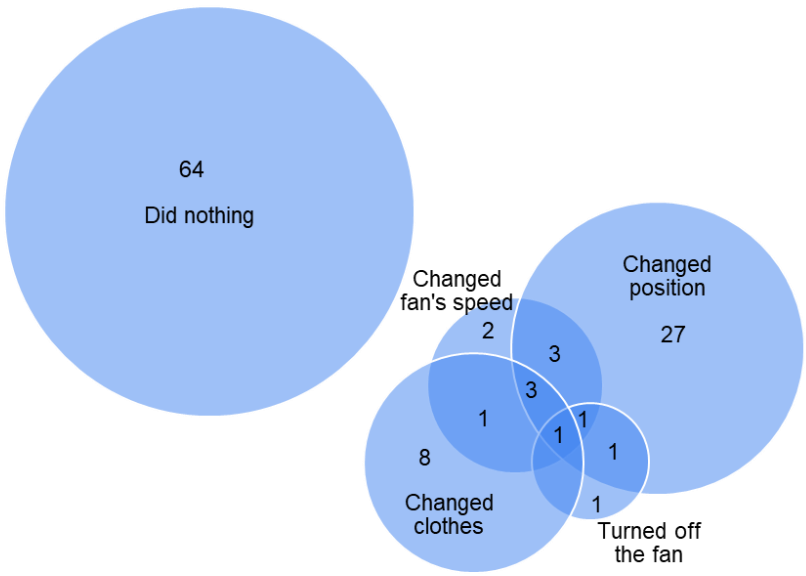


Fig. 6. Venn diagram of respondent's adaptive vote

4. CONCLUSIONS

Thermal environment examinations were carried out for one week and a questionnaire survey at the full occupancy rate. The results show that the objective parameters, including the mean value of T_a, T_g, T_{op}, RH, and V_a, were 25.3 °C, 25.0 °C, 25.1 °C, 62%, and 0.5 m/s, respectively. The temperature features during the prayers indicate that the thermal conditions aligned with local standards.

The survey's results indicate that worshippers tend to feel slightly cold, with an average *TSV* of -0.72. However, since the results were still in the standard range of $-1 \leq TSV \leq 1$, more than half of the respondents did nothing to adapt to the thermal condition. In general, the worshippers accept all the subjective parameters with the mean overall comfort of moderately comfortable.

Deriving comfort temperature from the selected votes, namely *TSV* = 0 (neutral), *TP* = 0 (no change of temperature), and *OC* = 5 or 6 (moderately comfortable or very comfortable), resulted in a mean T_{op} of 26.1 °C. The findings reveal that maintaining the air conditioning's set point temperature of approximately 20°C (as observed) did not enhance thermal comfort during prayer times. Consequently, it is recommended that the temperature be raised to a more acceptable level.

5. ACKNOWLEDGEMENTS

This research was financially supported by the Ministry of Higher Education Malaysia under the Fundamental Research Grant Scheme [FRGS/1/2023/TK08/UTM/02/2] and Universiti Teknologi Malaysia Fundamental Research Grant [Vot 22H26].

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