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Unravelling Thermal Comfort: Investigating Tropical Conditions at Bandar Bukit Raja Mosque, Klang

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Abstract

This study investigates thermal comfort conditions at the Bandar Bukit Raja Mosque in Klang, Malaysia, focusing on the impact of air temperature, humidity, and air movement on occupant comfort in a tropical climate. Using the LSI LASTEM HeatShield instrument, physical measurements were conducted, and perception surveys of 86 respondents were analyzed. The reliability of the survey instrument was confirmed with a Cronbach's Alpha value of 0.819, indicating good internal consistency. The survey utilized the Fanger Model to calculate Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). Additionally, the Adaptive Index Equation was used to determine Operative Temperature (T_o), and Temperature Neutral Operative (Tneutop). The study found that environmental measurements and survey results consistently exceeded the thermal comfort limits recommended by ASHRAE Standard 55, indicating significant discomfort among occupants. Specifically, PMV values ranged from 1.4 to 2.6, and PPD values ranged from 48% to 94.7%, demonstrating a substantial level of thermal dissatisfaction. The highest dissatisfaction was observed during midday and afternoon sessions, with air temperatures peaking at 32.4°C and relative humidity levels reaching up to 84.6%. The study underscores the need for improved thermal management strategies, including enhanced ventilation, humidity control, and architectural modifications to mitigate heat gain. These findings contribute to a broader understanding of thermal comfort in naturally ventilated spaces and emphasize the importance of sustainable building practices in tropical climates to enhance indoor environmental quality and occupant well-being.

1. Introduction

Malaysia, a tropical nation near the equator, experiences year-round mild temperatures, leading to high thermal loads and solar radiation on buildings. This is particularly relevant for mosques, where maintaining thermal comfort is crucial due to their frequent use for religious activities [1]. The country's warm and humid climate, influenced by high solar radiation and temperatures, exacerbates this challenge [2]. Poor thermal comfort can lead to health issues such as heart problems and respiratory disorders [3]. Effective ventilation systems, especially natural ventilation, are essential for maintaining acceptable thermal conditions in mosques, as they are more sustainable and cost-effective than mechanical systems [4]. A thorough literature review of thermal comfort is necessary to understand the concepts, factors, and standards involved [5]. Thermal comfort is a state of mind where individuals feel satisfied with their thermal environment, influenced by temperature, humidity, and air movement [6]. Achieving thermal comfort requires balancing heat production and loss, considering factors like air temperature, radiant temperature, humidity, air movement, metabolic rate, and clothing insulation [7]. Understanding these variables is crucial for effective building design and energy efficiency [8].

1.1 Problem Statement

Malaysia is facing significant impacts from climate change, with increasing high temperatures, particularly in areas like Shah Alam, Selangor. This exacerbates the challenge of maintaining thermal comfort in mosques, where worshippers often experience discomfort due to inadequate environmental control measures in the tropical climate [9]. Despite mosques being crucial community spaces, extreme temperatures and high humidity levels pose health risks, making effective cooling and insulation strategies essential, especially during peak prayer times.

The widespread use of HVAC systems has standardized indoor climates, aiming for thermal neutrality. However, studies show that this does not necessarily lead to higher occupant satisfaction [10]. Thermal perception is subjective and influenced by various factors, including cultural, religious, and social aspects [11]. People continuously adjust to their indoor thermal environments, making it challenging to predict behavior under varied conditions.

Poorly designed mosques can lead to discomfort, particularly with the current global warming conditions. While air conditioning systems are commonly used in Malaysian mosques, they contribute to high energy consumption, accounting for 34 percent of a building's yearly electricity usage [12]. To improve energy efficiency, it is crucial to adapt the features of vernacular mosques to be more climate-appropriate and less reliant on mechanical technology.

1.2 Objectives

The objectives of this study are:

i. To measure the parameter influencing thermal comfort levels within Bandar Bukit Raja Mosque, Klang.
ii. To investigate the satisfaction of occupants on comfort level perception within Bandar Bukit Raja Mosque, Klang.

1.3 Scope and Limitation

The study, conducted at Bandar Bukit Raja Mosque in Klang during Ramadan, aimed to assess thermal comfort parameters such as temperature, humidity, air quality, and occupant satisfaction using LSI LASTEM equipment. Data was collected during key prayer times: dawn (Fajr), early afternoon (Dhuhr), late afternoon (Asr), after dusk (Maghrib), and evening (Isha). The study focused on local climate variations but did not cover all seasonal changes, potentially missing specific challenges. Data collection faced logistical and timing challenges related to access to the mosque and the willingness of worshippers to participate.

2. Methodology

The evaluation methodology of this study is to ensure that the work done throughout the evaluation of this study is more structured and organized in order to achieve the objectives that have been set.

The flow chart of this study has 3 phases that need to be passed to complete the study as in Figure 1. Among the phases involved are:

i. PHASE I: Literature study
ii. PHASE II: Collecting data
iii. PHASE III: Data analysis

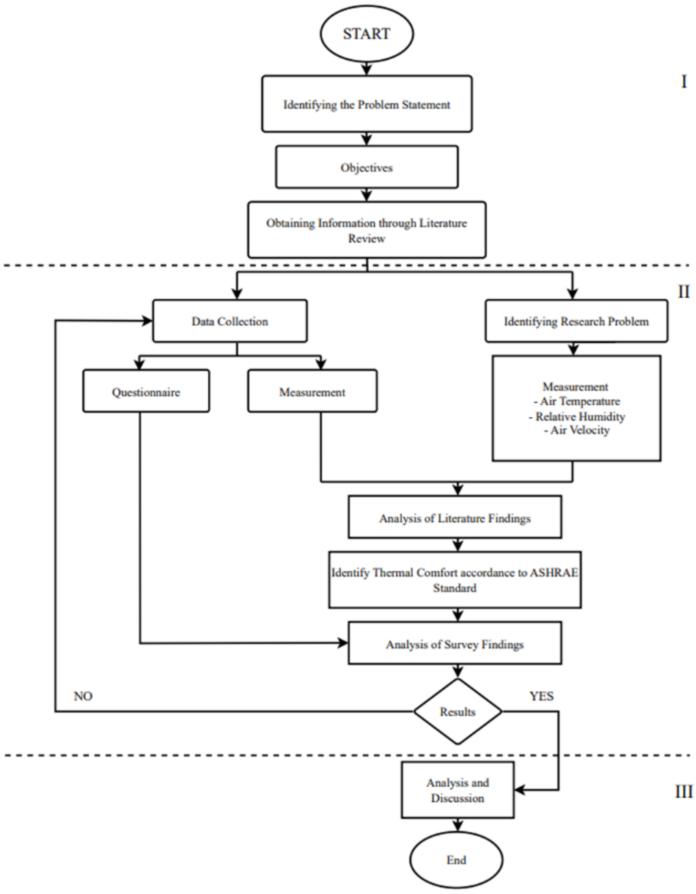


Fig. 1 *Methodology flow chart*

2.1 Quantitative Method (Questionnaire)

The questionnaire method employed in this study involved online data gathering, allowing interaction between respondents and researchers to collect detailed information on thermal comfort at the Bandar Bukit Raja Mosque, Klang [13]. The survey, based on ASHRAE Standard 55 (2017), included clear and concise questions about environmental factors affecting thermal comfort in the prayer room [14]. Distributed via Google Forms, the questionnaire aimed to understand the perceptions of frequent mosque-goers, with a total of 86 respondents participating. The content of the questionnaire is shown in Table 1.

Table 1 *Questionnaire Content*

Part	Measured Constructs
A	This section consists of the respondent's demographic information.
B	3 This section consists of general questions related to the current situation of the thermal environment containing the latest information about the respondent's condition.
C	This section consists of a survey of the satisfaction of the thermal environment that contains the sharing of opinions from the respondents to evaluate the problems present in the Bandar Bukit Raja Mosque

2.2 Reliability Test

The Cronbach's alpha statistic, introduced by Cronbach (1951), measures internal consistency or reliability of items in a survey. According to Churchill (1979), this analysis is suitable for field studies as it requires only one measurement (Nunnally, 1978). A Cronbach's alpha value close to 1.0 indicates high reliability, with values above 0.8 considered good, 0.7 reasonably acceptable, and below 0.6 weak [15]. The pilot study at Universiti Tun Hussein Onn Malaysia involved modifying the questionnaire based on academic staff feedback to ensure comprehension and effectiveness, resulting in 14 well-structured questions in two languages. Figure 2 show the reliability analysis using SPSS showed Cronbach's alpha value of 0.819, indicating good internal consistency and reliability of the questionnaire.

Reliability

Scale: ALL VARIABLES

Case Processing Summary

		N	%
Cases	Valid	86	100.0
	Excluded[a]	0	.0
	Total	86	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.819	14

Fig. 2 *Reliability test*

2.3 Physical Measurements

In this study, physical measurements were taken over the course of a single day covering each prayer time. These measurements were divided into into five sessions: at dawn (Fajr prayer), early in the afternoon (Dhuhr prayer), late in the afternoon (Asr prayer), the (Maghrib prayer) after dusk, and the first portion of the evening (prayer of Isha). Each session measured air temperature, humidity, mean radiation temperature, and air velocity, ensuring comprehensive data collection throughout the day.

Thermal comfort measurements were conducted in the praying areas of Bandar Bukit Raja Mosque using the ASHRAE Standard 55-2017. The LSI LASTEM HeatShield instrument model, equipped with meteorological sensors, was used to measure air temperature (Ta), relative humidity (Rh), mean radiant temperature (Tg) with a 15 cm diameter black globe sensor, and air velocity (Va) with a hot wire anemometer sensor.

2.4 Analysis Method

This study utilized the Thermal Sensation Vote (TSV) scale from ASHRAE Standard 55, which ranges from -3 to +3, to measure human thermal perception, including levels from cold to hot. The TSV data, combined with measurements from thermal comfort equipment, were used to calculate Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) using the Centre for the Built Environment (CBE) Thermal Comfort Tool. This tool, developed by the University of California, Berkeley, is an online, open-source resource used by over 49,000 professionals annually. It integrates key thermal comfort models, including SolarCal, PMV, and adaptive models, providing dynamic visualizations of thermal comfort zones. Researchers input air temperature, air velocity, and relative humidity to dynamically update charts and indices, ensuring comprehensive analysis consistent with ASHRAE Standard 55-2017, ISO 7730:2005, and EN 16798-1:2019. The study employed both static and adaptive thermal comfort models to evaluate performance, using Microsoft Excel for data analysis [16].

2.5 Sampling Method

his study systematically captured thermal comfort within the Bandar Bukit Raja Mosque, Klang. On the measurement day, 86 respondents completed questionnaires about their thermal comfort perceptions. The LSI LASTEM HeatShield instrument was used to measure essential environmental parameters, including air velocity, globe temperature, air temperature, relative humidity, heat stress index, wet bulb globe temperature, predicted percentage dissatisfied (PPD), and predicted mean vote (PMV). Measurements were taken in the mosque's main prayer areas, where people spend most of their time, with the central point of the room chosen for accuracy.

3. Results and Discussion

This study employed a questionnaire based on ASHRAE Standard 55 (2017) to collect subjective data on thermal comfort from 86 respondents at Bandar Bukit Raja Mosque on April 4, 2024. Respondents completed the survey after spending 30 minutes in the prayer area, providing data on their thermal sensation votes (TSV) and satisfaction levels. Demographic data revealed a majority of male respondents aged 36-45, primarily attending

Isha prayers. Thermal environment data indicated a generally neutral thermal sensation, with most respondents positioned away from windows and walls, and wearing varied attire. The CBE Thermal Comfort Tool was used to calculate PMV and PPD, highlighting areas for improved ventilation and cooling. Satisfaction surveys showed 69.8% of respondents were satisfied with the overall thermal comfort, though 16.3% were dissatisfied with the temperature and 12.8% with ventilation. Overall, the mosque's thermal conditions were found acceptable but had room for improvement, especially in enhancing air circulation and temperature control during specific activities and compared to other mosques.

3.1 Factor Influencing Thermal Comfort

The thermal comfort at the Bandar Bukit Raja Mosque in Klang was influenced by key factors such as air temperature, relative humidity, air velocity, and radiant temperature. These parameters were measured using the LSI LASTEM HeatShield system on April 4, 2024. The data from these measurements are summarized in Table 2, which presents the Excel results from the HeatShield system.

Table 2 *Excel Result Parameter on LSI LASTEM HeatShield*

4/4/2024 5:54:34 AM <-> 4/4/2024 11:14:00 PM

Date Time	tg	tnw	ta	rh	va	WBGT_I	WBGT_O	HI	Hx	PMV	PPD
4/4/2024 6:00:00 AM	28.8	26.6	28.5	84.6	0.7	27.3	27.2	34.4	41.6	1.4	48
4/4/2024 7:00:00 AM	28.8	26.6	28.7	84.5	0.4	27.3	27.3	34.7	41.9	1.6	54.2
4/4/2024 8:00:00 AM	28.8	26.5	28.6	84	0.4	27.2	27.1	34.5	41.7	1.5	53.1
4/4/2024 9:00:00 AM	29.7	27	29.2	82	0.1	27.8	27.7	35.9	42.5	1.9	73.1
4/4/2024 10:00:00 AM	30.5	27.4	30.2	79.6	0.2	28.3	28.3	38.2	44	2.1	81
4/4/2024 11:00:00 AM	31.1	27.2	30.8	75.7	0.4	28.3	28.3	38.7	44.2	2.2	83.7
4/4/2024 12:00:00 PM	30.5	27.3	30.3	79.3	0.4	28.2	28.2	38.2	44	2	77.8
4/4/2024 1:00:00 PM	31.5	26.9	31.3	71.6	0.4	28.3	28.3	39	44.3	2.3	87.2
4/4/2024 2:00:00 PM	32.1	26.7	31.9	66.9	0.4	28.3	28.3	39	44.2	2.4	91.2
4/4/2024 3:00:00 PM	32.5	27.1	32.3	67.5	0.4	28.8	28.7	40.4	45.3	2.6	94.4
4/4/2024 4:00:00 PM	32.6	27.1	32.4	66.6	0.4	28.7	28.7	40.2	45.1	2.6	94.7
4/4/2024 5:00:00 PM	32.2	26.7	31.8	66.8	0.4	28.3	28.3	38.8	44.1	2.4	91.4
4/4/2024 6:00:00 PM	31.4	26.8	31.1	71.8	0.4	28.2	28.2	38.5	43.9	2.2	85.8
4/4/2024 7:00:00 PM	31	26.8	30.8	74	0.4	28.1	28.1	38.1	43.7	2.1	82.6
4/4/2024 8:00:00 PM	30.9	26.9	30.7	74.7	0.4	28.1	28	38.1	43.7	2.1	81.4
4/4/2024 9:00:00 PM	30.5	26.4	30.2	74.5	0.5	27.6	27.6	36.8	42.8	1.9	74.1
4/4/2024 10:00:00 PM	30.1	26.3	29.8	76.1	0.6	27.5	27.4	36.1	42.3	1.8	68.9
4/4/2024 11:00:00 PM	29.3	25.9	29	77.8	0.5	26.9	26.9	34.4	41.1	1.6	57.5
5/4/2024 12:00:00 AM	29.3	25.7	29.1	76.1	0.4	26.8	26.7	34.3	40.9	1.6	58.3

On April 4, 2024, the thermal comfort at Bandar Bukit Raja Mosque in Klang was influenced by several factors. The air temperature ranged from 28.5°C in the early morning to a peak of 32.4°C in the late afternoon, typical for the region and significantly impacting comfort during midday. Relative humidity fluctuated between 66.6% and 84.6%, with higher levels above 70% making the air feel warmer by impeding sweat evaporation. Heat Index values ranged from 34.4°C to 40.4°C, indicating perceived temperatures higher than the actual air temperature. Air velocity was low, from 0.1 m/s to 0.7 m/s, reducing the cooling effect. Globe Temperature and Natural Wet-Bulb Temperature showed radiant heat effects, particularly at midday. The Wet Bulb Globe Temperature for indoor and outdoor conditions peaked at 28.8°C, indicating significant heat stress. The Heat Stress Index ranged from 40.9°C to 45.3°C, posing challenges during high physical activity. Predicted Mean Vote (PMV) values ranged from 1.4 to 2.6, and Predicted Percentage of Dissatisfied (PPD) ranged from 48% to 94.7%, suggesting that many occupants felt thermally uncomfortable, especially during the hottest parts of the day.

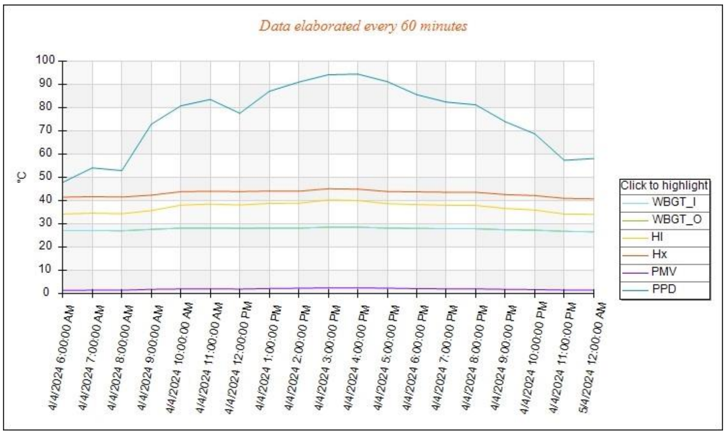


Fig. 3 *Reliability Data elaborated from LSI LASTEM HeatShield every 60 minutes*

The thermal comfort at Bandar Bukit Raja Mosque in Klang was evaluated using the LSI LASTEM HeatShield system, revealing key environmental parameters as shown in Figure 3. The air temperature ranged from 28.5°C in the early morning to a peak of 32.4°C in the late afternoon, reflecting the typical daily solar heating cycle. Relative humidity varied from 66.6% to 84.6%, with higher levels in the morning and evening, impacting perceived warmth. The Heat Index indicated that perceived temperatures were higher during midday. Air velocity remained low (0.1 m/s to 0.7 m/s), suggesting minimal natural ventilation. The Globe Temperature and Natural Wet-Bulb Temperature followed similar trends to air temperature, indicating radiant heat effects. Wet Bulb Globe Temperature and Heat Stress Index values peaked in the afternoon, showing significant heat stress. Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) were highest during midday, with many occupants feeling thermally uncomfortable. This data highlights the need for improved ventilation and cooling strategies to enhance thermal comfort within the mosque [14].

3.2 Thermal Sensation Votes (TSV)

The Thermal Sensation Votes conducted using LSI LASTEM HeatShield on April 4th, 2024, provides a comprehensive overview of thermal conditions. The data reveals fluctuations in air temperature, relative humidity, and WBGT index throughout the day, impacting perceived thermal comfort. Morning hours experienced warm and humid conditions, while midday saw peak temperatures and decreased humidity. WBGT values indicated increased thermal stress in the afternoon, potentially leading to discomfort. Overall, the survey underscores the dynamic nature of thermal conditions and the need for appropriate measures to enhance comfort.

3.3 Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)

Data collected at Bandar Bukit Raja Mosque in Klang using PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indices revealed significant variations in thermal comfort throughout the day. Early morning PMV values ranged from 1.4 to 1.9, indicating a slightly warm sensation, with PPD values increasing from 48% to 73.1%, reflecting growing discomfort. By midday, PMV peaked at 2.4, with PPD values soaring to 91.2%, indicating high dissatisfaction. In the afternoon, PMV values remained high at 2.6, with PPD at 94.7%, suggesting nearly universal discomfort. By evening, PMV values declined to 1.6, and PPD decreased to 58.3%, indicating improved but still noticeable discomfort. These findings highlight the significant thermal discomfort experienced, particularly during midday and afternoon hours, and suggest a need for better thermal management [14]. Table 3 shows the environmental parameters value during the measurement at Bandar Bukit Raja, Klang on April 4, 2024 from the result Table 2.

Table 3 *Environmental Parameters Value*

Session	Air Temperature (°C)	Mean Radiant Temperature (°C)	Air Velocity (m/s)	Relative Humidity (%)
Morning	Min: 28.5 Max: 29.7 Average: 28.75	Min: 26.5 Max: 27.0 Average: 26.68	Min: 0.1 Max: 0.7 Average: 0.4	Min: 82.0 Max: 84.6 Average: 83.78
Midday	Min: 30.2 Max: 31.9 Average: 30.9	Min: 26.7 Max: 27.4 Average: 27.1	Min: 0.2 Max: 0.4 Average: 0.36	Min: 66.9 Max: 79.6 Average: 74.62
Afternoon	Min: 31.8 Max: 32.5 Average: 32.17	Min: 27.1 Max: 27.1 Average: 26.97	Min: 0.4 Max: 0.4 Average: 0.4	Min: 66.6 Max: 67.5 Average: 66.97
Night	Min: 29.0 Max: 31.4 Average: 30.27	Min: 25.9 Max: 26.9 Average: 26.52	Min: 0.4 Max: 0.6 Average: 0.47	Min: 66.8 Max: 77.8 Average: 74.82

Based on measurements of air temperature, mean radiant temperature, relative humidity, air velocity, and personal parameters such as clothing insulation (0.5 clo) and metabolic rate (1.2 met), the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) for each respondent at Bandar Bukit Raja Mosque were calculated using the CBE Thermal Comfort Tool. The results showed a PMV of 2.02 and a PPD of 75.71%. According to ASHRAE Standard 55-2017, the acceptable PMV range for general comfort is -0.5 to +0.5, with a PPD of less than 20%, indicating that the mosque's thermal environment does not meet these standards for thermal comfort. Table 4 shows the data input for PMV and PPD value [14].

Table 4 *Data Input for PMV and PPD Value*

Parameter	Average Data
Air Temperature (°C)	30.43
Mean Radiant Temperature (°C)	26.76
Relative Humidity (%)	75.4
Air Velocity (m/s)	0.42
Metabolic Rate (met)	1.2
Clothing Insulation (clo)	0.5
PMV	2.02
PPD (%)	75.71%

From the survey analysis, thermal sensation voting is essential in environmental cases to determine PMV and PPD. Table 5 illustrates the relationship between PMV, PPD, and thermal sensation. The population's thermal sensation is a critical measure in assessing comfort conditions and is useful in predicting satisfaction levels. For international standardization, individuals who vote hot, warm, cool, or cold on the thermal sensation scale are considered thermally dissatisfied (ISO 8996, 2004).

Table 5 *The relationship between PMV, PPD and thermal sensation*

PMV	Thermal Sensation	PPD
+3	Hot	100
+2	Warm	75
+1	Slightly warm	25
0	Neutral	5
-1	Slightly cool	25
-2	Cool	75
-3	Cold	100

Table 6 shows the thermal sensation votes from the survey analysis. The majority of respondents chose neutral, indicating satisfaction, while warm was the second most common vote, indicating dissatisfaction. Fewer respondents selected cold, cool, or hot, also interpreted as dissatisfaction. Overall, 52 people were satisfied with the thermal sensation level, and 34 were dissatisfied.

Table 5 *Thermal Sensation Votes (TVS) via survey analysis (Khalid et.al., 2019)*

Thermal Sensation	Cold	Cool	Cool/ chilled	Neutral	Warm	Hot	Very Hot
Satisfied	-	-	2	50	-	-	-
Dissatisfied	0	2	-	-	20	10	2

According to Pourshaghagy and Omidvari (2012), the PPD index based on the survey in any part of the building can be calculated using the following expression with Equation 1 as shown below:

$$PPD = \left(\frac{Number\ of\ surverys\ indicating\ dissatisfaction}{Total\ number\ of\ surverys\ in\ any\ part\ of\ the\ building}\right) \times 100 \quad (1)$$

$$PPD = \left(\frac{2+20+10+2}{86}\right) \times 100$$

$$PPD = 40\%$$

Based on the survey analysis, 40% of the occupants at Bandar Bukit Raja Mosque in Klang are dissatisfied with the thermal conditions. According to Guan et al. (2003), a PPD of less than 20% is considered a good condition, indicating that the mosque's thermal conditions do not meet this standard and are not satisfactory to the occupants. Figure 4 illustrates the gap between PPD and PMV, showing that 40% of occupants are dissatisfied. The PMV result, determined by the mean vote of respondents, is 1.36, falling between slightly warm (+1) and warm (+2) conditions, which exceeds the upper limit of +0.5 recommended by ASHRAE Standard 55.

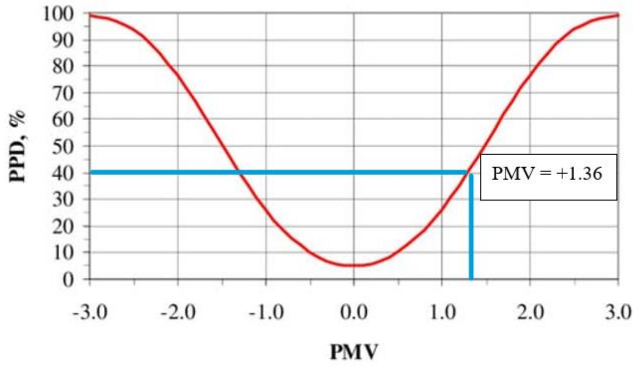


Fig. 4 *Graph of PPD versus PMV*

The PMV and PPD values from physical measurements are 2.02 and 75.71%, respectively, while the values from thermal sensation voting are 1.36 and 43%. This indicates that the PMV model tends to classify the thermal environment as warmer than the actual sensation experienced by the occupants. This discrepancy arises due to significant individual variations in physiology and psychology, a pattern also observed by Cardoso et al. (2017).

3.4 Operative Temperature (To) and Neutral Operative Temperature (Tneutop)

The operative temperature index (To) is used to compute and analyze mean radiant temperature (Tr) readings, acquired from globe temperature (Tg) measurements with a 50 mm diameter black globe thermometer probe, as per ASHRAE Standard 55. Various formulas exist for calculating To, with this study employing Equation 2 from the ASHRAE Standard 55 procedures. Indoor and outdoor measurement data were utilized to predict the operative temperature and neutral operative temperature. Linear regression using Equation 2 was applied, setting the value of A at 0.5 due to an average air velocity (Va) of less than 0.2 m/s. This resulted in an operative temperature (To) of 28.595°C.

$$T_o = AT_a + (1 - A)T_r \quad (2)$$

$$T_o = 0.5 \times 30.43 + (1 - 0.5) \times 26.76$$

$$T_o = 0.5 \times 30.43 + 0.5 \times 26.76$$

$$T_o = 15.215 + 13.38$$

$$T_o = 28.595°C$$

$T_o = Operative\ temperature$

$T_a = Average\ temperature$

$T_r = Mean\ radiant\ temperature$

The value of A is selected based on the average air velocity (Va), being 0.5 for Va < 0.2 m/s. For analyzing the Neutral Operative Temperature (Tneutop), an adaptive equation by Toe & Kubota (2013) was used, suitable for naturally ventilated buildings in hot, humid climates like Malaysia. This equation considers relative humidity, indoor air velocity, and typical outdoor air temperatures. Using Equation 3, with a daily minimum outdoor air temperature (Toutdm) of 28.5°C, the Tneutop was calculated as 30.045°C. Additionally, the prevailing mean outdoor temperature for April 4, 2024, was averaged from recorded temperatures, resulting in approximately 29.62°C. These calculations ensure accurate thermal comfort predictions based on widely accepted standards (ASHRAE Standard 55).

$$T_{neutop} = 0.57T_{outdm} + 13.8 \quad (3)$$

$$T_{neutop} = 0.57 \times 28.5 + 13.8$$

$$T_{neutop} = 16.245 + 13.8$$

$$T_{neutop} = 30.045°C$$

$$T_{out} = \frac{\sum T_a}{n}$$

$$T_{out} = \frac{562.7}{19} \approx 29.62°C$$

T_{neutop} = *Operative indoor temperature*

T_{outdm} = *Daily minimum outdoor air temperature*

$\sum T_a$ = Sum of the recorded air temperature

n = Number of recorded temperatures

Figure 5 shows the operative temperature for one session on April 4, 2024 ranges from 27.71°C to 29.5°C.

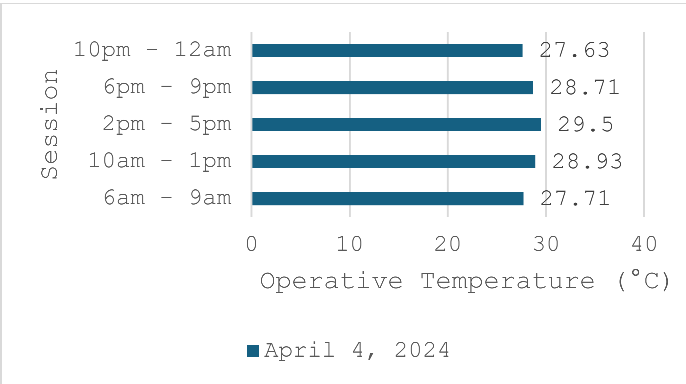
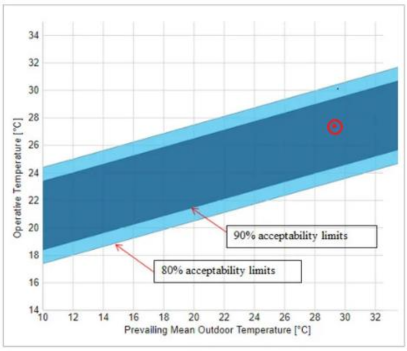


Fig. 5 *Operative temperature in mosque*

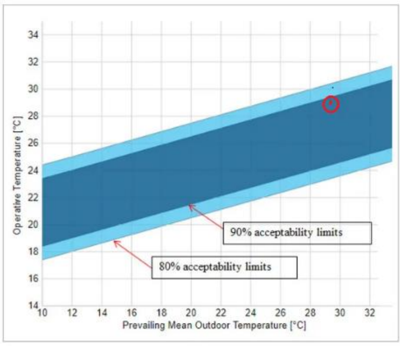
Equation 3 calculates the neutral operative temperature (Tneutop) and requires the average daily outdoor air temperature (Toutdm) to be between 19.4°C and 30.5°C, with indoor air velocity below 0.65 m/s at or below the neutral operative temperature, and ≥0.65 m/s above it. There is no set limit for indoor humidity in this equation. This approach, suitable for naturally ventilated buildings in hot, humid climates like Malaysia, ensures accurate thermal comfort predictions in line with ASHRAE Standard 55.

3.5 Adaptation Chart

The chosen location, Bandar Bukit Raja Mosque in Klang, meets the criteria for this study, utilizing natural ventilation supplemented by ceiling and standing fans. Occupants' metabolic rate is estimated at 1.2 MET, and average clothing insulation is 0.5 clo. Using the adaptive method from the CBE Thermal Comfort Tool, adaptive charts were constructed in Figure 6 to show the recommended operative temperature range for naturally ventilated spaces based on ASHRAE Standard 55. These charts include the 80% and 90% acceptability ranges. The morning session's operative temperature, ranging from 22.9°C to 29.9°C (80% acceptability) and 23.9°C to 28.9°C (90% acceptability), indicates comfort. However, during midday, afternoon, and evening sessions, the operative temperature exceeds these ranges, indicating overly warm conditions.



(a)



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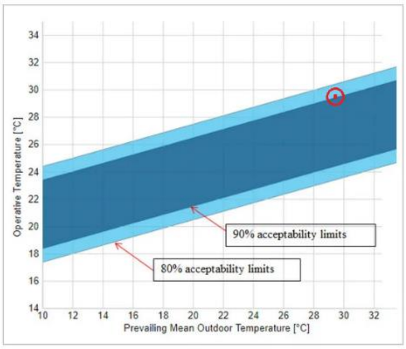

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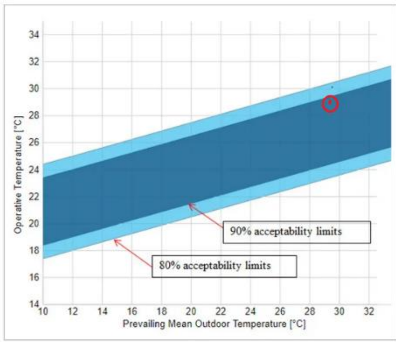

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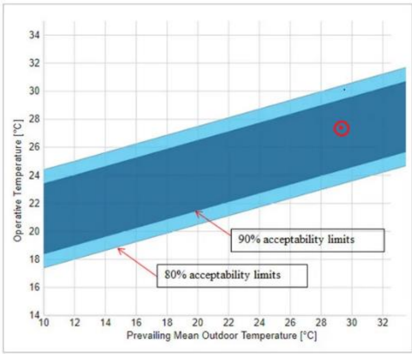

(e)

Fig. 6 *Adaptive chart for the acceptable operative temperature range for natural ventilation (a) morning, (b) midday, (c) afternoon, (d) evening, € night*

3.6 Overall Thermal Comfort Condition

Table 6 provides a comprehensive comparison of parameter values, operative temperature, PMV, and PPD throughout the day for morning, midday, afternoon, evening, and night sessions. The analysis includes air temperature, mean radiant temperature, air velocity, and relative humidity. PMV and PPD values are also included for all sessions. The data shows average relative humidity values exceeding recommended limits due to unsettled weather during data collection. While mechanical fans should theoretically control humidity, high levels can negate their cooling effects (Nicol et al., 2002). This comprehensive analysis highlights the variability in thermal comfort parameters throughout the day, emphasizing the challenges of maintaining comfort in naturally ventilated spaces.

Table 5 *Overall comparison results of parameter value, operative temperature, PMV and PPD*

Session	Air Temperature (°C)	Min Radiant Temperature (°C)	Air Velocity (m/s)	Relative Humidity (%)	Operative Temperature (°C)	PMV	PPD (%)

	Morning	28.50	26.6	0.7	84.6	27.71	1.4	48
	Midday	31.30	26.9	0.4	71.6	28.93	2.3	87.2
	Afternoon	32.40	27.1	0.4	66.6	29.50	2.6	94.7
	Evening	30.80	26.8	0.4	74.7	28.71	2.1	81.4
	Night	29.50	25.9	0.5	77.8	27.63	1.6	57.5
Min		28.50	25.9	0.1	66.6	27.63	1.4	48
Max		32.40	27.4	0.7	84.6	29.50	2.6	94.7
Average		30.43	26.76	0.42	75.4	28.60	2.02	75.71

The analysis of environmental parameters and thermal comfort indices at the mosque indicates predominantly warm to hot conditions throughout the day. Air temperature ranged from 28.5°C to 32.4°C, averaging 30.43°C, while the mean radiant temperature varied between 25.9°C and 27.4°C, averaging 26.76°C. Air velocity was low, averaging 0.42 m/s, which diminished cooling effects. High relative humidity averaged 75.4%, intensifying the heat sensation. The operative temperature ranged from 27.63°C to 29.5°C, averaging 28.595°C. PMV values exceeded the ASHRAE recommended range of -0.5 to +0.5, indicating a warm to hot thermal sensation, with PPD values between 48% and 94.7%, far above the acceptable 20% limit, suggesting widespread discomfort. According to Table 4.10, the mosque did not meet ASHRAE Standard 55-2017 for acceptable thermal conditions. Improvements such as enhanced ventilation, dehumidification systems, cooling systems, and architectural modifications like shading devices and reflective surfaces are necessary to mitigate heat gain and improve thermal comfort, particularly during midday and afternoon periods when conditions were most uncomfortable. Addressing these issues is crucial for ensuring a thermally comfortable environment that meets ASHRAE standards and enhances occupant well-being.

4. Conclusion and Discussion

This study on thermal comfort models, crucial for predicting and assessing human comfort in buildings, fulfills its objectives by evaluating thermal comfort in the Bandar Bukit Raja Mosque, Klang, through subjective and physical assessments. A survey involving 86 respondents revealed high thermal sensations, with most residents experiencing neutral to warm conditions and expressing slight dissatisfaction. The physical measurements indicated that air temperature, mean radiant temperature, air velocity, and relative humidity did not meet ASHRAE Standard 55 guidelines, with air temperatures peaking at 32.4°C, significantly exceeding the recommended range of 22.5°C to 26°C. This resulted in high PMV values (1.4 to 2.6) and PPD values (48% to 94.7%), reflecting substantial thermal discomfort. High humidity levels (66.6% to 84.6%) exacerbated the discomfort, although air velocity was within acceptable limits. The findings underscore the need for enhanced ventilation, cooling mechanisms, and architectural modifications to meet ASHRAE standards and improve thermal comfort (ASHRAE Standard 55; Nicol et al., 2002).

4.1 Recommendations

The study on thermal comfort at Bandar Bukit Raja Mosque, Klang, revealed that current conditions do not meet ASHRAE Standard 55-2017, particularly during midday and afternoon. To improve thermal comfort, recommendations include enhancing ventilation by upgrading mechanical systems and optimizing natural ventilation through strategic window and door placement. Controlling humidity with dehumidification systems and installing cooling systems such as air conditioning or evaporative coolers are also advised. Architectural modifications like shading devices, reflective roofing, and green building practices can reduce heat gain. Future research should explore green technologies and smart building systems for sustainable thermal comfort improvements, investigate different architectural designs, and consider personal factors affecting thermal comfort perceptions. Addressing equipment failures, as noted with the LSI LASTEM HeatShield malfunction, is crucial for reliable data collection (ASHRAE Standard 55-2017; Nicol et al., 2002).

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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