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Investigation of Thermal Comfort for Sedentary Work in Air-Conditioned Bank Office

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Abstract

This study was conducted on the thermal comfort of sedentary work at six air-conditioned bank offices in the hot and humid environment of Malaysia. This study aims to investigate the perceptions of thermal comfort and to determine the comfort temperature of the air for bank office employees. Air temperature, relative humidity and air velocity were measured every 5 minutes. The Predicted Mean Vote (PMV) model based on ASHRAE Standard 55 was used to estimate the requirements for indoor thermal conditions. Two types of building air conditioning systems were studied namely air conditioning and mechanical ventilation system (ACMV) and split unit air conditioning systems. In total, 124 respondents completed the questionnaire to appraise the thermal sensation vote (TSV) of the six bank offices from 8.30 am to 5.00 pm. A comparison between the PMV and TSV shows that TSV values appear to be more sensitive than PMV values. The predicted neutral temperature from PMV is lower than the neutral temperature from TSV.

Discipline: Environmental Engineering, Mechanical Engineering.

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1. Introduction

Malaysia is a tropical country, hot and humid, which is situated between 1° and 7° north and 100° and 120° east. Malaysia has a yearly average temperature of between 26°C to 27°C (Daghigh et al., 2009). It has a high mean outdoor temperature of 27°C to 31°C (Khalid et al., 2019) and relative humidity of 70% to 90% throughout the year. Given the average temperature for the typical Malaysian city, it seems as though air conditioning during office hours is a must if the employees working in a hot and humid climate like Malaysia requires thermal comfort in the building space during the day.

Malaysia's climate is hot and humid; therefore, air-conditioning systems in bank offices have been widely accepted as one of the methods to provide comfort indoors. However, the excessive use of air conditioners can lead to a waste of energy and issues in indoor air quality. Consequently, the behavioural adaptation of the occupants to improve their thermal comfort plays an important role in avoiding the waste of energy in buildings. Air conditioning system used emerged as one of the key drivers of global electricity demand growth and this system is one of the most consumed electricity in an office building (Davis & Gertler, 2015). The use of air conditioners has increased intensely in hot and humid climatic nations as a means of ventilation, particularly in office buildings.

Workspaces are often in an enclosed air-conditioned environment at the bank office building. There are two types of ventilation strategies commonly used in a bank office building which are air-conditioned and mechanical ventilation systems (ACMV) and split unit air conditioning systems (AC) to maintain a comfortable environment for the occupants. A good thermal environment in the bank office environment is essential for the employees because they need to spend most of their daily time in the office. Therefore, human thermal comfort is considered a very important parameter in the design of current and future air-conditioned bank office buildings. The state of mind of thermal comfort results in a thermal environment satisfactory as standardised by ISO (2005) and ASHRAE (2017) which gives the expected average vote (PMV) equation of the thermal environment to determine the mean human response. Furthermore, thermal comfort is closely related to occupants' productivity in a workspace.

ASHRAE (2017) defined human thermal comfort as "the mental state that expresses thermal environment satisfaction". This statement explains the meaning of "condition of mind" or "satisfaction", in which the process of determining comfort is cognitive as it involves various factors like psychological, physical, and physiological (Ribeiro et al., 2015). The human mind will sense temperature and moisture through sensation from the skin, as well as the internal body temperature to decide whether the current environment is comfortable or uncomfortable. The human mind also decides the necessity to regulate body temperature by dissipating heat generated by human metabolism to maintain heat balance with the surrounding environment (Zaki et al., 2017). This shows that the feeling of "cold" or "hot" is not dependent solely upon the air temperature, and comfort is not a state condition, but rather a state of mind.

Based on the PMV-PPD index, the range of temperature for 80% occupant acceptability is based on a 10% dissatisfaction criterion for whole-body thermal comfort, plus an additional 10% dissatisfaction that may occur on average partial body discomfort thermal discomfort (ASHRAE, 2017).

Thermal sensations for different individuals will vary even in the same environment. The opinions on thermal comfort are attributed to a combination of many factors affecting the perception of human beings (Rupp et al., 2015). Although climates, living conditions, and culture differ widely throughout the world, the temperature in which people choose for thermal comfort under similar conditions is found to be very similar after considering the factors influencing thermal sensation (Damiati et al., 2016). According to Standards (2019), the acceptable indoor conditions for the design and maintenance of thermal comfort are as follows:

- Recommended dry bulb temperature = 24 - 26°C
- Minimum dry bulb temperature = 23°C
- Recommended relative humidity = 50 - 70%
- Recommended air movement = 0.15 to 0.5 m/s
- Maximum air movement = 0.70 m/s

The international standards for thermal comfort (ASHRAE, 2017; ISO, 2005) are based on human energy balance obtained by assuming steady-state conditions. However, the steady-state conditions would not reflect the real environmental conditions. The different areas can have different thermal comfort models and a subject's thermal sensation would be different according to individual, race, climate, habits, and customs, etc. Research on thermal comfort studies has been carried out in which thermal comfort standards and comfortable temperatures could vary in different countries or areas as revealed in a lot of previous works (Mishra & Ramgopal, 2013; Rupp & Ghisi, 2017; Rupp et al., 2015). Therefore, the thermal environment in bank offices may be different from other office building settings. The thermal conditions in offices would not reflect the specific design of office buildings such as bank offices, and the operation and activity which may differ from other building designs. An assessment of the thermal comfort level felt by the employees of the bank office must be carried out in real working conditions.

Through the knowledge of the thermal comfort behaviour of humans and the energy utilisation behaviour of buildings, the best strategy can be adopted. A summary of the neutral temperatures and comfort ranges of subjects in Malaysia is shown in Table 1.

Table 1: Thermal comfort study in hot and humid regions.

Ref.	Type of building	RH%	The temperature of comfort (□C)
Yau and Chew (2009)	Hospital	30 – 60	26.4
Razman et al. (2011)	Hostel	55 – 69	27 – 29 (Discomfort)
Shaari et al. (2016)	Classroom		PMV +2□C
Yau et al. (2011)	Green building	55 – 70	23
Ahmad et al. (2015)	A/C Office	40 – 80	24.6
Hussin et al. (2014)	Laboratory	30 – 70	Value 0 to +1

Considerable research has been conducted on thermal comfort in the office, based on the perception of the occupants. Takasu et al. (2017) performed a thermal comfort study in an air-conditioned ventilated office under various operation modes in Japan. The comfort temperature is evaluated with standard effective temperature to incorporate the effect of humidity and air velocity on thermal comfort. They found that the conditions in the ventilated office under various operation modes for optimum comfort temperature is approximately 23.5°C to 26.6°C in mix mode.

There is evidence that thermal comfort could affect occupants' health and productivity within the workplace (Cui et al., 2013; Geng et al., 2017). Thus, thermal comfort standards and guidelines are established to ensure the health and well-being of occupants. These standards and guidelines play a vital role in determining energy consumption and indoor air quality by the ventilation system, which is associated with the building's sustainability (Yau & Chew, 2014). Increased energy use implies that there will be more combustion of fossil fuels, which contributes to carbon dioxide emissions and climate change (Kwok & Rajkovich, 2010).

Due to the lack of research on the thermal environment in a bank office, the purpose of this paper is to study thermal comfort in air-conditioned bank offices and to find the difference between neutral temperature based on PMV and neutral temperature based on thermal sensation vote (TSV). The analysis is based on ASHRAE (2017) and ISO (2005) to predict and calculate PMV accurately. The thermal comfort level and the relationship between TSV and PMV of bank office employees are investigated in this study.

2. Methodology

1. Evaluation of Thermal Comfort

The field research was carried out from September 2018 to January 2019 in six air-conditioned bank offices with different ventilation strategies. The locations of bank offices are Menara Bank Rakyat, Kuala Lumpur; Jalan Tangsi, Kuala Lumpur; Kajang, Selangor; Shah Alam, Selangor; USJ, Selangor; and Putrajaya. Table 2 presents a summary of the main features of the bank offices. Both the objective physical measurements and the subjective assessments were conducted in the bank offices.

For the onsite measurements, indoor air quality parameters such as air temperature, air velocity, and relative humidity were measured. All the measurements were measured at the height of 1 m height from the floor, in accordance with the seat level of the occupants, and with reference to ASHRAE (2017), as shown in Figure 1. These instruments were left for eight hours, and the measurements were taken in 5-second intervals. In the bank office, instruments were placed in the operation division, as shown in Figure 2. Several criteria were considered before placing the instruments, such as the position of the employees. The method applied for the occupants had activity levels that result in metabolic rates between 1.0 and 1.3 and where clothing is worn, it provided between 0.5 to 1.0 clo of thermal insulation. The estimation of metabolic rate for office activities is depicted in Table 3 and the estimation of clothing insulation is presented in Table 4.

Table 2: Thermal comfort study in hot and humid regions.

Ventilation type	Bank Location	Year of Operation	The average number of occupants (per hours)	Volume (m^3)
ACMV	Menara	2014	13	189.7
	Jalan Tangsi	1982	13	860.3
Split unit (AC)	Kajang	2008	26	149.7
	Shah Alam	1996	31	140.5
	USJ	1996	14	134.6
	Putrajaya	2015	14	193.7

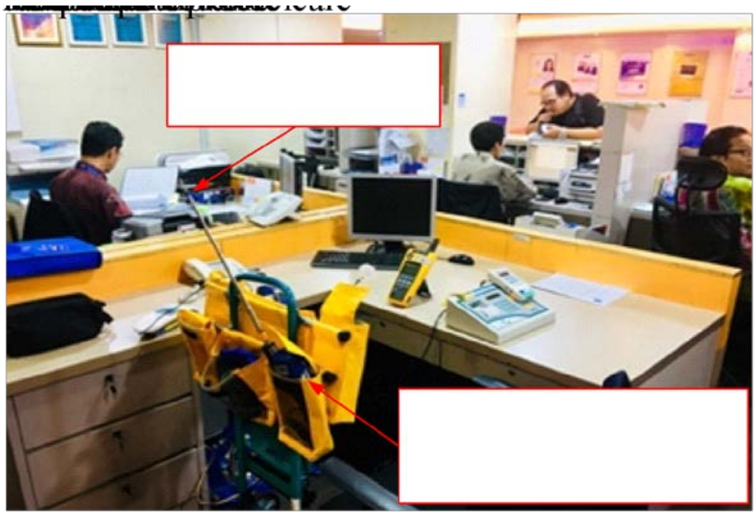

Figure 1: Sampling equipment setup at the operation division

(a) (b)

Figure 2: The floor plan and 3D view of the bank office for (a) Bank office 3 and (b) Bank office 1.

The acceptable range for specific physical parameters (temperature, relative humidity, and air movement) is based on ASHRAE (2017). According to the Industrial Code of Practices on Indoor Air Quality 2010 (DOSH, 2010), the suitable air temperature for indoor air is 23-26°C, the acceptable range for air movement is 40-70%, whereas the relative humidity should be within the range of 40-70%. ISO 7730 uses the Fanger (1970) predicted mean vote (PMV) formula which predicts a numerical value for the mean subjective response to the thermal environment on the ASHRAE 7 points thermal sensation scale (*see* Table 5) from the knowledge of six thermal variables.

Table 3: Metabolic rates for office tasks (ASHRAE, 2017).

Office Activities	Metabolic Rate	
	Met Units	W/m²
Reading, seated	1.0	55
Writing	1.0	60
Typing	1.1	65
Filling, seated	1.1	70
Filling, Standing	1.4	80
Walking about	1.7	100
Lifting/packing	2.1	120

Table 4: Metabolic rates for office tasks (ASHRAE, 2017).

Clothing description	Garments included	I_{cl} (clo)
Trousers	Trouser, short-sleeve shirt	0.57
	Trouser, long-sleeve shirt	0.61
Skirts/Dresses	Knee-length skirt, long-sleeve shirt, full slip	0.67
	Knee-length skirt, long-sleeve shirt, suit jacket	70
	Ankle-length skirt, long-sleeve shirt, suit jacket	80

Table 5: ASHRAE 7 points thermal sensation scale (ASHRAE, 2017).

Description	Numerical value
Hot	3
Warm	2
Slightly warm	1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

PMV is usually calculated from Equations (1)–(4) (ASHRAE, 2015), which are deducted from thermal investigations on European young persons:

$$\begin{aligned} PMV = & \left(0.303e^{-0.036M} + 0.028\right)\Big\{(M-W) - 3.05\times10^{-3}\times\left[5733-6.99(M-W)-P_a\right] \\ & -0.42\left[(M-W)-59.15\right] - 1.7\times10^{-5}M\left(5867-P_a\right) - 0.0014M\left(34-t_a\right) - 3.96\times10^{-8}f_d \\ & \times\left[\left(t_{cl}+273\right)^4 - \left(t_r+273\right)^4 - f_{cl}h_c\left(t_{cl}-t_a\right)\right]\Big\} \end{aligned} \quad (1)$$

The f_{cl}, t_{cl} and h_c are determined by the following equations:

$$t_{cl} = 35.7 - 0.028(M-W) - l_{cl}\left\{3.96\times10^{-8}f_{cl}\times\left(t_{cl}+273\right)^4 + f_{cl}h_c\left(t_{cl}-t_a\right)\right\} \quad (2),$$

$$f_{cl} = 1.05 + 0.645 l_{cl} \qquad \text{for } l_{cl} \geq 0.078 \quad (3),$$

$$f_{cl} = 1.00 + 1.290 l_{cl} \qquad \text{for } l_{cl} < 0.078 \quad (4).$$

Where, M is the metabolism rate, depending on activity level in W/m²; W, is the external work in W/m²; P_a is the partial vapor pressure in Pa; t_a is the air temperature in °C; f_{cl} is the ratio of a person's surface area while clothed to the surface area while naked; t_{cl} is the surface temperature of clothing in °C; t_r is the mean radiant temperature in °C; h_c is the convective heat transfer coefficient in W/m$^2\cdot$°C ; and I_{cl} is clothing insulation in m$^2\cdot$°C/W.

2. Survey Evaluation

To evaluate the occupants' votes on the thermal condition of the bank office, a questionnaire survey was given out. The sample size of the valid questionnaire was 124 for the employees of bank offices. The employees worked from 8.30 am to 5.00 pm. Male employees accounted for 57.3% and female employees, 42.7%. The age distribution of bank office employees is depicted in Figure 3. The age was between 24 to 53 years and the average age was 37. This study focused on employees of the bank votes, where all employees were asked to fill in the questionnaire and rated their thermal comfort level.

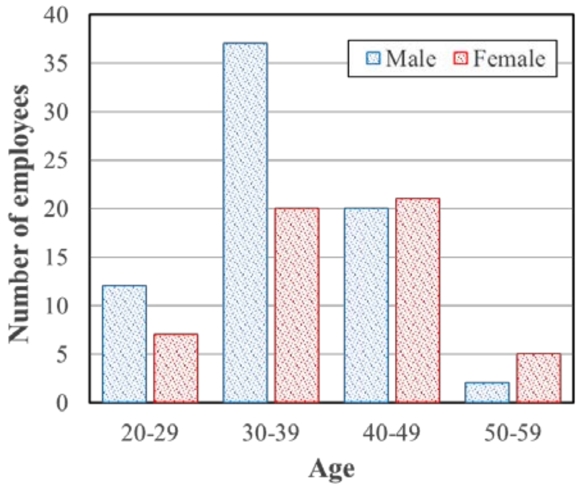

Figure 3: Age distribution of employees of bank offices.

The factors affecting the rating of thermal comfort can be classified into two categories; four objective environmental factors (air temperature, humidity, air velocity and mean radiant temperature) and two subjective individual parameters (metabolism rate and clothing insulation). So, both objective and subjective measurements were carried out simultaneously in the field survey.

1.1 Measurement Instrument

Metabolic rate and clothing insulation were estimated based on workplace observation. The objective measurement was aimed to collect data on environmental parameters which were necessary for further thermal comfort analysis and PMV calculation. The accuracy of the instruments used met the requirements of ASHRAE (2017) and ISO (2005). The details of the instruments are shown in Table 6. All equipment was calibrated and had a valid calibration certificate to give reliable results.

The mean radiant temperature was calculated based on ASHRAE (2017) analytical comfort zone method, which is a method for determining an acceptable thermal environment in occupied spaces that uses the mean radiant temperature of 2.8 °C, higher than the average air temperature.

Table 6: ASHRAE 7 points thermal sensation scale.

Measurement item	Instrument	Range	Accuracy
Air Temperature	Anemometer VelociCalc Plus Multi-Parameter Ventilation	-10 to 60 °C	±0.3°C
Air velocity		0 to 50 m/s	±3%
Relative humidity		0 to 95%	±3%

1.2 Determination of PMV and PPD

ASHRAE (2017) stipulates, based on the satisfaction of an occupant of 80 per cent or more, that heat comfort can be achieved. The remainder of individuals will experience 10% dissatisfaction based on whole-body discomfort (all specified PMV influencing factors) and 10% dissatisfaction based on local discomfort/part of their body discomfort (includes fewer than whole-body factors).

The suggested thermal limit for the PMV 7-point scale is from -0.5 to 0.5 in accordance with ASHRAE (2017). The PPD can range from 5% to 100%, depending on the calculated PMV. These comfort values will vary depending on the location of the occupant in the building. For comfort ranges to comply with standards, no occupied point in space should be above 20% PPD.

3. Result and Discussion

1.3 Thermal Comfort Evaluation

PMV and PPD are based on Fanger's model of thermal comfort (Fanger, 1970). To find the correlation between thermal sensation vote (TSV) and predicted mean vote (PMV), a questionnaire survey and thermal comfort parameter measurements were performed simultaneously. The bank temperature was measured for 8 hours as shown in Figure 4. The indoor air temperature varied over time from morning to noon, especially in bank offices 2, 3 and 4. Based on the number of occupants, Bank 3 and 4 received a higher number of occupants which Bank 3 had 26 people and Bank 4 had 31 people as shown in Figure 5. This expresses a major thermal transfer between internal and external climates, especially when the door opens at the main entrance of the bank.

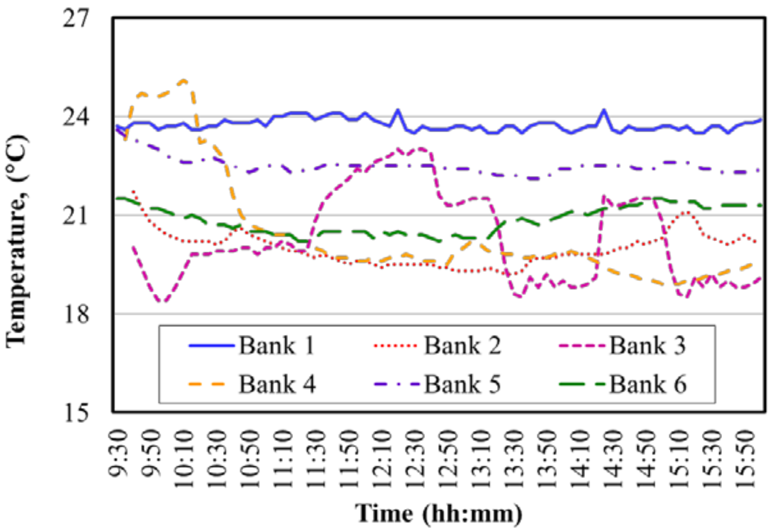

Figure 4: Indoor temperature measurement in operation division.

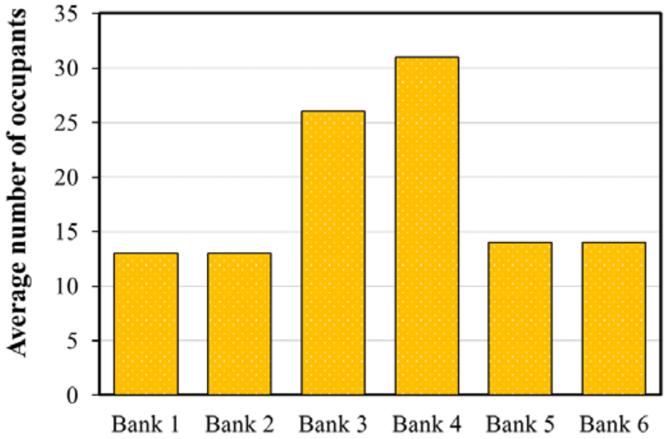

Figure 5: Average number of bank occupants.

The indoor climatic condition varied on bank offices and type of air-conditioner systems. Table 7 shows the maximum, mean, and minimum standard deviation of the measured temperature, relative humidity, and air movement. The data shows that there was no significantly different indoor air temperature at the area operation of the bank office even though the ventilation system was different. The higher mean value of air temperature was 23.2°C at bank office 1 and the lower mean value of air temperature was 20°C at bank office 2. Both banks used the same ventilation system.

Table 7: Maximum (Max), minimum (Min), mean and standard deviation (SD) of temperature, relative humidity and air movement for six bank offices..

Area	Ventilation type	Parameter	Temp (°C)	RH (%)	Air movement (m/s)
Bank 1	ACMV	Max	23.8	50.9	0.170
		Mean	23.2	50.6	0.124
		Min	22.9	50.2	0.110
		SD	0.2	0.2	0.013
Bank 2	ACMV	Max	21.7	61.7	0.110
		Mean	20.0	60.5	0.079
		Min	19.2	59.9	0.050
		SD	0.5	0.5	0.013
Bank 3	AC	Max	23.0	49.7	0.310
		Mean	20.3	52.3	0.152
		Min	18.4	44.4	0.090
		SD	1.4	1.7	0.055
Bank 4	AC	Max	25.1	58.6	0.120
		Mean	20.4	55.8	0.060
		Min	18.9	52.6	0.000
		SD	1.8	1.3	0.030
Bank 5	AC	Max	23.6	59.6	0.090
		Mean	22.5	52.9	0.057
		Min	22.1	50.5	0.050
		SD	0.3	1.7	0.007
Bank 6	AC	Max	21.5	53.7	0.030
		Mean	20.9	51.5	0.015
		Min	20.1	49.8	0.000
		SD	0.4	1.0	0.007

1.4 Indoor Thermal Environment During the Voting

A total of 124 occupants as respondents participated in this survey which was distributed throughout the six bank offices. The respondents were asked about their thermal perception and thermal preference in the working area. The answer to the thermal perception question was organised based on the seven-point ASHRAE scale which included cold, cool, slightly cool, neutral, slightly warm, warm, and hot. Table 8 illustrates the results of the TSV in different bank offices. The table shows PMV, mean TSV and PPD in the mentioned bank office area. According to the site measurement and theoretical calculation, there was a deviation between PMV and TSV as shown in Table 8. The values of TSV were smaller than those of PMV. This deviation may be due to PMV calculation obtained from the determination of the metabolic rate and average air velocity. Thus, calculated PMV cannot accurately present the practical thermal sensation of occupants in bank offices.

Figure 6 depicts the percentage of dissatisfaction in banks for a single measurement session. As shown in Figure 6(a), four bank offices were on the slightly cool side of the seven-point ASHRAE scale with nearly 20% predicted dissatisfaction. Based on the Fanger's formula, two bank offices were in a comfortable condition with a minimum percentage of dissatisfied people.

Table 8: Thermal sensation vote in six bank offices area.

Area	Air temp. (°C)	TSV on the ASHRAE scale							Mean TSV	Mean PMV	PPD (%)
		Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot			
Bank 1	23.72	0	1	4	16	0	0	0	-0.29	0.02	5
Bank 2	19.98	1	6	14	7	0	0	0	-1.04	-1.03	27
Bank 3	20.30	0	6	7	5	0	0	0	-1.06	-1.17	34
Bank 4	20.44	0	2	11	6	0	0	0	-0.79	-0.91	22
Bank 5	22.49	0	3	4	12	0	0	0	-0.53	-0.26	6
Bank 6	20.86	0	6	5	8	0	0	0	-0.89	-0.80	18

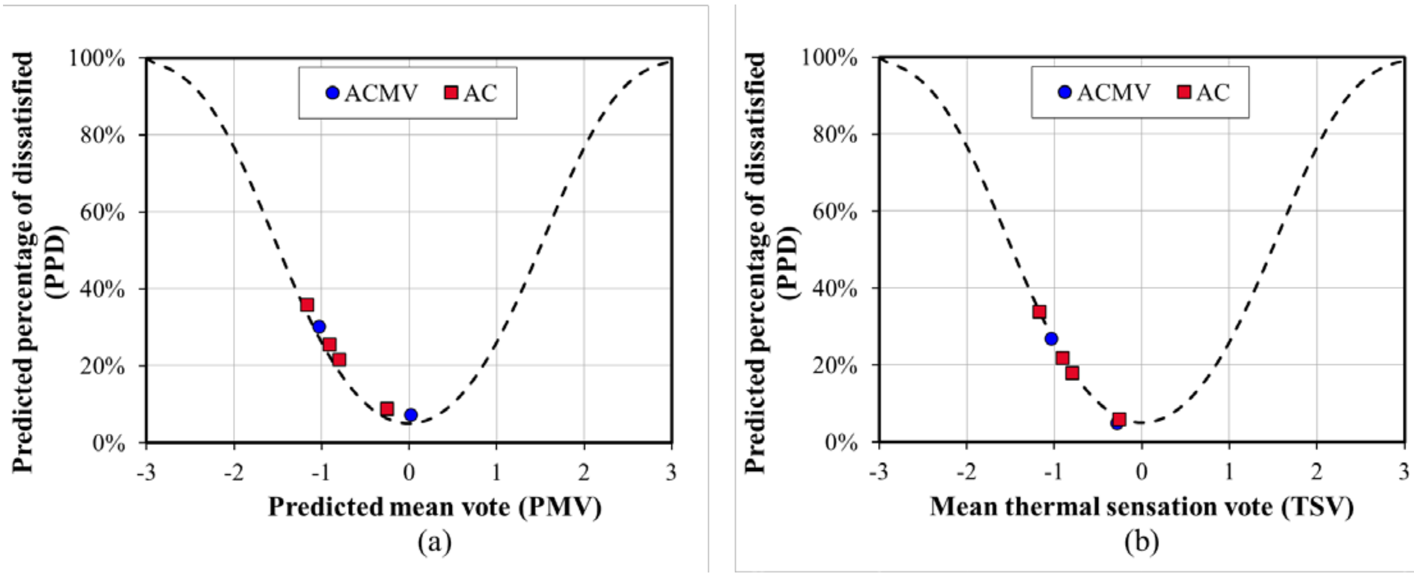

Figure 6: Percentage of dissatisfied in Banks with AC and ACMV systems. (a) Predicted mean vote and (b) Thermal sensation vote.

1.5 Correlation Between PMV and TSV Results

A comparison between PMV and TSV was conducted to explain the correlation between PMV and TSV. Table 8 provides a comparison of the TSV, PMV and PPD values. As presented in Table 8, in all bank office areas, the calculated PMV value was higher than the mean TSV. It can be concluded that bank employees are well-conditioned and used to hot and humid weather and this suggests that neutral temperatures are not necessarily desired. This finding is consistent with several studies that have been conducted which emphasize the role of respondents responding to the temperature of thermal comfort evaluation (Mustapa et al., 2017).

Linear regression was conducted on the PMV and TSV data. The results show a relationship between the TSV and PMV data for R^2 = 0.9526. Figure 8 depicts the fitted regression model with the following equation: PMV = 1.5066TSV +0.4634. Moreover, based on this model, the neutrality points shifted to -0.3 instead of 0 on the seven-point ASHRAE scale.

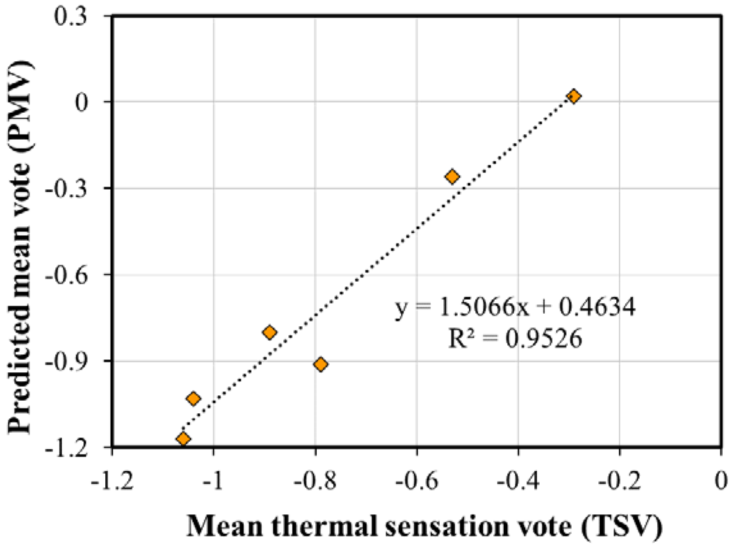

Figure 7: Correlation between PMV and TSV.

1.6 Correlation Between TSV and PMV with Air Temperature

Figure 8 depicts the correlation between the mean TSV with air temperature in each investigated bank office area within the operative 18.5°C – 25°C temperature range. The neutral temperature estimated by the regression line for TSV equal to 0 was 24.6°C, and the strong relationship was indicated by R^2=0.9209. The regression line slope in Figure 8 was equal to 0.2232/°C, which means more than a 5°C variation in temperature can cause the result to be equal to the variation of TSV. In addition, the relationship between temperature and calculated PMV had R^2=0.9654 and the slope of this regression line was y = 0.3528x – 8.1727 which shows a slightly high gradient slope of the linear regression model relating TSV with temperature. The neutral temperature derived from the PMV regression analysis was equal to 23.2 °C, nearly 1.4°C lower than the regression result of the mean thermal sensation vote. Table 9 shows the comparison between the results obtained from this study which is similar to previous thermal comfort studies.

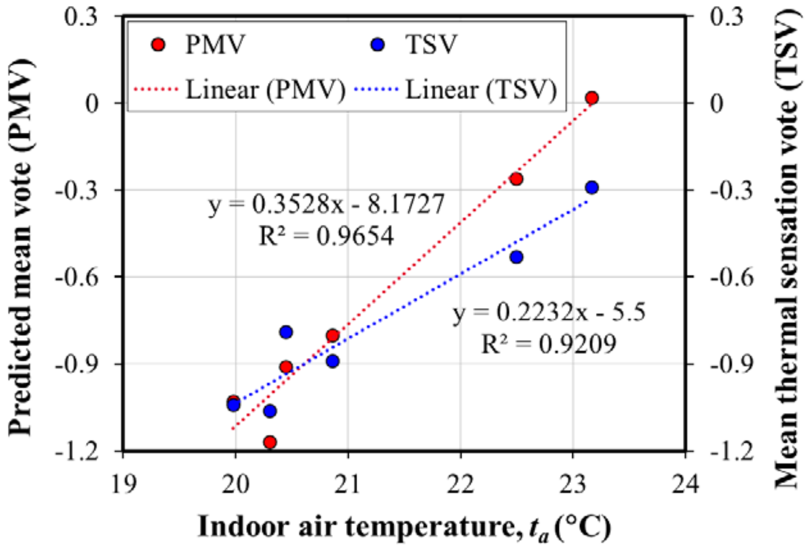

Figure 8: Linear regression through thermal sensation vote (TSV) and predicted mean vote (PMV) vs. indoor air temperature (t_a).

Table 9: Regression formulas from similar studies.

Author	Location	Regression formula	R^2
[21]	University, Malaysia	TSV=0.4973T-13.706	0.625
[35]	Vessel cabin	TSV=0.6084T-13947	
[36]	Office, India	TSV=0.33T-8.86	0.64
[37]	Hospital, Malaysia	TSV=0.398T-9.30	0.93
[38]	University, Malaysia	TSV=0.33T-8.62	0.168
Current study	Malaysia	TSV=0.2232T-5.5	0.9209

4. Conclusion

The assessment of indoor environment quality on the occupants of the bank offices has prompted further research on thermal comfort to ensure the bank office's thermal environment is pleasant and healthy. As such, a site investigation of thermal comfort during working hours of the bank employees was conducted to investigate the thermal comfort sensation. The following conclusions can be drawn: The neutral temperature calculated statistically using linear regression analysis was 24.6 ℃ for bank office employees based on TSV regression. From the PMV regression calculation, the neutral temperature was 23.2 ℃. The predicted neutral temperature from PMV was lower than the neutral temperature from TSV. The values of TSV were smaller than those of PMV. Most of the air temperature in the bank office environment did not meet the Malaysia indoor air temperature standard of ICOP [30], ranging between 23℃ to 26 ℃. Further improvement is required to improve the thermal sensation vote by the employees of the bank offices. Improved thermal comfort will increase the productivity, comfort, and health of the bank employees.

5. Availability of Data And Material

Data can be made available by contacting the corresponding author.

6. Acknowledgement

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