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Adaptive Thermal Comfort Model for Air-Conditioned Lecture Halls in Malaysia

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***Abstract*—**This paper presents an adaptive thermal comfort model study in the tropical country of Malaysia. A number of researchers have been interested in applying the adaptive thermal comfort model to different climates throughout the world, but so far no study has been performed in Malaysia. For the use as a thermal comfort model, which better applies to hot and humid climates, the adaptive thermal comfort model was developed as part of this research by using the collected results from a large field study in six lecture halls with 178 students. The relationship between the operative temperature and behavioral adaptations was determined. In the developed adaptive model, the acceptable indoor neutral temperatures lay within the range of 23.9-26.0°C, with outdoor temperatures ranging between 27.0-34.6°C. The most comfortable temperature for students in lecture hall was 25.7°C.

***Keywords*—**Hot and humid, Lecture halls, Neutral temperature, Adaptive thermal comfort model.

I. INTRODUCTION

NOWADAYS, people might expect a more comfortable and healthful environment in the buildings they occupy, with a higher standard of living [1]. Hence, indoor air quality (IAQ) and thermal comfort of a building have become the main aims for HVAC engineers, because they are of great importance for high quality buildings [2]. For instance, a better indoor air quality can be achieved with the increase of the ventilation rate, so that air pollutants can be diluted [3]. The way buildings are designed and operated means that the amounts of energy used in the HVAC system and its impacts are important in constituting a 'comfortable' thermal environment [4]. Comfort problems will always occur after a period of operation due to reasons such as unsuitable temperature set points and improper fresh air intake.

As defined by the ASHRAE Standard, thermal comfort is a situation where a person feels satisfied with the temperature of the surrounding environment [5], [6]. In designing a building involving people occupying it, the most significant aspect to be considered is the thermal comfort [7]. It is believed that thermal comfort in a working space will affect labour efficiency and productivity [8].

In the late 1960s, the predicted mean vote (PMV) model developed by Fanger was regularly used in determining thermal comfort of occupants in buildings [9]. Fanger's model is a prediction of a numerical index by combining four physical variables and two personal variables to measure the perception of occupants of the thermal condition in the building [10], [11]. The physical variables are air temperature, air velocity, mean radiant temperature and relative humidity. The two personal variables, meanwhile, are clothing insulation and activity level.

The PMV model is a flexible tool, which can be utilized in different indoor environments with different HVAC systems, clothing values and activity levels. Besides that, the PMV model is represented by a 7-point thermal sensation scale consisting of the following:

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Since the PMV model is used globally, the wide range of climates, variety of building types and the broad measurement of the thermal environment are causing discrepancies between actual and predicted thermal sensation. It is argued that the PMV model, which was developed from laboratory studies, has restrictions with regard to environmental parameters, since they are quite different from those in real buildings [12].

Furthermore, it was also suggested that people might prefer to not feel 'neutral' on the thermal sensation scale, because occupants in hot climates might prefer a sensation of slightly cooler than neutral, while occupants in cold climates might prefer a sensation of slightly warmer than neutral [13]. In other words, a majority of people would prefer a sensation on the warm side of neutral if it was cool outdoors and vice versa [14].

Nowadays, most air-conditioned buildings with a centralized system face the same problem, which is either the space is too cold or too warm [15]. This is frequently encountered in tropical countries, because the PMV model is unsuitable for a hot and humid climate. Thus, the adaptive model is important for establishing thermal comfort for occupants and at the same time conserving energy.

Barlow and Fiala suggest that future service engineers and architects should have a better understanding of thermal adaptation and occupants' thermal comfort. They should focus more on the indoor climate and 'human aspects' in order to include adaptive models in their building design work [16]. By having this functional design, a building can achieve the thermal comfort level expected by occupants while at the same time reducing energy usage [17].

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In summary, even though many amendments were made to the Fanger PMV model, there is still no standard comfort model that could be applied globally. The reason for this is that every individual's expectations of comfort temperature are different, and it is a mistake trying to design a new standard in thermal comfort that will be applied to a large group of people all around the world. Furthermore, standard thermal neutrality is not necessarily the perfect thermal environment, since many occupants prefer a non-neutral environment.

Until now, there is still no study on adaptive thermal comfort model for hot and humid climates, Malaysia. The outdoor temperature could rise above 30°C during daytime and seldom drop below 20°C during night-time. Thus, there is a need for researcher to conduct a comprehensive study on adaptive thermal comfort model in Malaysia for the use of building services engineer locally and other hot and humid countries widely. A comprehensive study should be performed for different kinds of buildings, such as hospitals, offices, lecture halls and museums in order to determine the adaptive model for each of these buildings.

II. BACKGROUND THEORY ON ADAPTIVE THERMAL COMFORT MODEL

A study on adaptive model of air-conditioned building was carried out in sub-tropical Hong Kong by [18]. The adaptive model is developed based on the measurement from 29 offices in summer and 26 offices in the winter. The result shows that the range of acceptable operative temperature for summer and winter are 20.8–25.0^{o}C and 19.5–21.5^{o}C respectively. The neutral temperature, which is the operative temperature at mean thermal sensation vote of zero found from the study is 23.7^{o}C in summer and 21.2^{o}C in winter.

A correlation between indoor neutral temperature and outdoor air temperature was developed by [18]. The adaptive model generated is shown in (1).

$$T_n = 18.303 + 0.158\ T_{out}\ ,\quad R^2 = 0.59 \tag{1}$$

Another study has been conducted to propose an indoor comfort temperature setting for commercial buildings in Pakistan [19]. The correlation between indoor neutral temperature and outdoor temperature obtained for air-conditioned and free-running buildings in Pakistan is as shown in (2) [19].

$$T_n = 18.5 + 0.36\ T_{out}\ ,\quad R^2 = 0.73 \tag{2}$$

Besides the finding discussed above, there are also some other researchers have proposed adaptive thermal comfort model in their own study. According to [20], the relationship between indoor neutral temperature (T_n) and outdoor temperature (T_{out}) is given by (3):

$$T_n = 18.6 + 0.16\ T_{out} \tag{3}$$

Auliciems also developed a correlation for both naturally and mechanically ventilated buildings as shown in (4) [21]:

$$T_n = 17.6 + 0.31\ T_{out} \tag{4}$$

Nicol proposed the adaptive model as shown in (5) [22] for Pakistan and (6) [23] for free-running buildings in tropical climates worldwide:

$$T_n = 17.0 + 0.38\ T_{out} \tag{5}$$

$$T_n = 12.9 + 0.534\ T_{out} \tag{6}$$

Humphreys [24] has determined a correlation for free-running buildings as shown in (7):

$$T_n = 11.9 + 0.534\ T_{out} \tag{7}$$

In another study, the relationship obtained by [25] for free-running buildings is shown in (8):

$$T_n = 13.5 + 0.54\ T_{out} \tag{8}$$

In summary, based on all the findings above, it is discovered that at the current stage, there is no study on adaptive thermal comfort model was conducted in buildings in hot and humid Malaysia. Thus, a field work study in buildings in Malaysia is needed in order to develop an adaptive thermal comfort model for local use.

III. METHODOLOGY

This research was conducted at six different lecture halls in University of Malaya located in Kuala Lumpur, Malaysia. The lecture halls are Lecture Hall A to Lecture Hall F. The field measurements will be described first in sub-section *A*. The subjective measurements will be given later in sub-section B.

A. Field Measurements

According to [6], air temperature, globe temperature and air velocity have to be measured at the ankle, waist and head level. These levels are 0.1 m, 0.6 m and 1.1 m, respectively, above the floor for seated occupants, and 0.1 m, 1.1 m and 1.7 m for standing occupants. However, relative humidity was measured at 0.6 m above the floor for seated occupants and 1.1 m for standing occupants. These thermal comfort parameters together with outdoor temperatures were measured by using a TSI Alnor Thermo Anemometer, KIMO Thermocouple thermometers and KIMO Temperature and Humidity data logger as shown in Table I. Operative temperature is used in defining comfort conditions throughout this paper. Operative temperature is the average of the mean radiant temperature (MRT) and the ambient air temperature, weighted by their heat transfer coefficients. However, operative temperature is calculated as the average of MRT and ambient air temperature without considering the heat transfer coefficient in usual practical applications [26], and also in this paper. MRT is calculated using (9) [26]:

$$T_{mrt}^{\ 4} = T_g^{\ 4} + CV^{-0.5}(T_g\text{-}T_a) \tag{9}$$

where, T_{mrt} = mean radiant temperature; T_g = globe temperature, K; T_a = ambient air temperature, K; $\overline{V}$ = air velocity, m/s; C = 0.247 x 10^9.

TABLE I
INSTRUMENTS DESCRIPTION

Type of instruments	**Measurement parameter**	**Accuracy**
TSI Alnor thermo Anemometer (Model 440-A)	• Temperature • Relative Humidity • Air velocity	*Operating range* Temperature:-10 to 60°C RH: 0 to 90% Velocity: 0 to 30 m/s *Accuracy* Temperature: ± 0.3 °C RH: ± 3% Velocity: ± 3% of reading or ± 0.015 m/s, whichever is greater *Resolution* Temperature: ± 0.1 °C RH: 0.1% Velocity: 0.01 m/s
KIMO Thermocouple thermometers (TK100)	• Globe temperature	*Operating range* From -200 to 1300*a*? ? *Accuracy* ± 1.1 °C or ± 0.4% of reading, whichever is greater *Resolution* 0.1°C
KIMO Temperature and Humidity Datalogger (KH-100-AO)	• Temperature • Relative Humidity	*Operating range* Temperature:-20 to 70*a*? ? RH: 5 to 95% *Accuracy* Temperature : ± 1% of reading or ±0.4°C, whichever is greater RH: ± 2.95%

B. Subjective Measurements

In parallel with the field measurements, the students in lecture halls were requested to fill in the questionnaire as shown in [28]. A total number of 178 students took part in this survey during their lecture period. The questionnaire included a survey on occupants' personal particulars, comfort votes, activity levels and clothing insulation.

In this study, the actual mean vote (AMV) which is the comfort votes collected from the questionnaires is to be used in comparison to the predicted mean vote (PMV) as calculated based on Fanger's thermal comfort model. The ASHRAE Thermal Comfort Program [27] will be used to calculate the value of the PMV and the predicted percentage of dissatisfied occupants (PPD). The program inputs are air temperature, MRT, air velocity, relative humidity, activity level and clothing insulation of the occupants. The outputs are PMV and PPD.

IV. RESULTS AND DISCUSSION

Surveys were done in six lecture halls in Kuala Lumpur, Malaysia. The total number of students who took part in the subjective measurement was 178 people. The physical parameters and the results from the subjective measurement are shown in Tables II and III, respectively.

TABLE II
PHYSICAL PARAMETERS MEASURED AND CALCULATED IN LECTURE HALLS

Lecture Hall	Point	T_{air} (°C)	T_{globe} (°C)	V (m/s)	RH (%)	MRT (°C)	T_{op} (°C)
A	1	24.0	24.0	0.14	51.2	24.0	24.0
	2	22.1	24.3	0.24	48.5	26.8	24.5
	3	21.2	23.6	0.21	47.4	26.1	23.7
	4	19.7	23.3	0.23	46.0	27.3	23.5
	5	19.1	22.7	0.21	46.5	26.6	22.8
	6	19.1	22.5	0.16	46.4	25.7	22.4
B	1	21.3	22.4	0.22	61.8	23.7	22.5
	2	21.4	22.5	0.12	62.5	23.4	22.4
	3	21.0	22.6	0.17	62.6	24.2	22.6
	4	20.9	22.6	0.10	63.1	23.9	22.4
	5	21.0	22.7	0.16	62.4	24.3	22.6
	6	21.0	22.7	0.10	63.0	23.9	22.5
C	1	21.9	22.7	0.18	69.8	23.5	22.7
	2	22.2	22.7	0.10	68.0	23.1	22.6
	3	22.8	22.7	0.10	68.8	22.7	22.7
	4	22.7	22.7	0.12	67.1	22.7	22.7
	5	22.1	22.7	0.12	69.6	23.2	22.6
	6	22.0	22.6	0.21	69.7	23.3	22.6
D	1	22.9	22.1	0.11	49.1	21.4	22.2
	2	22.1	22.1	0.12	47.4	22.1	22.1
	3	22.2	22.2	0.12	48.2	22.2	22.2
	4	23.2	22.1	0.10	48.5	21.3	22.2
	5	22.0	22.2	0.21	49.9	22.5	22.2
	6	21.8	22.2	0.15	48.5	22.6	22.2
E	1	21.4	22.4	0.16	48.1	23.4	22.4
	2	21.6	22.3	0.19	48.2	23.0	22.3
	3	21.8	22.3	0.18	47.7	22.8	22.3
	4	21.4	22.3	0.17	48.5	23.2	22.3
	5	21.6	22.4	0.17	49.0	23.2	22.4
	6	21.0	22.3	0.11	50.7	23.3	22.2
F	1	24.6	25.8	0.10	61.4	26.6	25.6
	2	24.6	25.6	0.09	61.8	26.3	25.4
	3	25.0	25.2	0.14	63.4	25.4	25.2
	4	25.3	25.2	0.10	63.8	25.2	25.2
	5	25.3	25.3	0.09	62.1	25.3	25.3
	6	25.3	25.2	0.09	61.5	25.1	25.2

A. Behavioral Adaptations

A behavioral adaptation is an action a person might take to achieve thermal comfort by changing their body's heat balance. Behavioral adjustment can be classified into three categories: personal adjustment, technological adjustment and cultural adjustment. Personal adjustment comprises the modifying of activity, clothing, posture, consuming hot or cold food or drinks, moving to other locations and so on. Technological adjustment includes modifying the environment or surroundings, such as turning on or off air-conditioners and opening or closing windows. Cultural adjustments include having a siesta on a hot day and scheduling activities accordingly [4].

Behavioral adaptation indicates that individual humans themselves can maintain their own thermal comfort. A person tends to take corrective actions if he/she is in a thermally uncomfortable condition. Behavioral adaptations are commonly represented by clothing insulation, activity level and air velocity as shown in the following sub-section.

TABLE III
SUBJECTIVE MEASUREMENTS OF OCCUPANTS IN LECTURE HALLS

Lecture Hall	Point	met	clo	AMV	APD (%)	PMV	PPD (%)
A	1	1.15	0.75	-0.25	25.0	-0.07	5.0
	2	1.00	0.54	-1.50	25.0	-1.15	33.0
	3	1.00	0.76	-1.17	16.7	-0.77	17.0
	4	1.08	0.54	-1.00	0.0	-1.23	37.0
	5	1.00	0.63	-2.50	100.0	-1.49	51.0
	6	1.00	0.36	-2.00	100.0	-2.39	91.0
B	1	1.08	0.60	-0.20	40.0	-1.08	30.0
	2	1.00	0.58	-1.60	80.0	-1.14	32.0
	3	1.12	0.72	-1.40	20.0	-0.62	13.0
	4	1.00	0.50	-2.00	100.0	-1.36	43.0
	5	1.00	0.72	-1.40	20.0	-0.89	22.0
	6	1.00	0.72	0.20	20.0	-0.71	16.0
C	1	1.00	0.72	-1.50	25.0	-0.83	20.0
	2	1.10	0.65	-1.25	25.0	-0.43	9.0
	3	1.00	0.63	-1.50	25.0	-0.73	16.0
	4	1.20	0.72	-1.50	25.0	-0.12	5.0
	5	1.16	0.37	-1.40	40.0	-0.94	23.0
	6	1.00	0.72	-2.00	100.0	-0.92	23.0
D	1	1.00	0.61	-0.80	40.0	-1.16	33.0
	2	1.00	0.63	-1.75	75.0	-1.19	35.0
	3	1.00	0.72	-1.50	25.0	-0.92	23.0
	4	1.00	0.63	-1.50	25.0	-1.04	28.0
	5	1.00	0.72	-1.40	20.0	-1.17	34.0
	6	1.13	0.54	-0.50	50.0	-1.17	34.0
E	1	1.04	0.72	-1.40	20.0	-1.04	28.0
	2	1.00	0.72	-1.50	25.0	-1.14	33.0
	3	1.00	0.72	-1.40	40.0	-1.10	31.0
	4	1.00	0.66	-1.40	40.0	-1.25	38.0
	5	1.24	0.67	-1.40	20.0	-0.56	12.0
	6	1.00	0.63	-1.50	50.0	-1.13	32.0
F	1	1.06	0.72	1.57	57.1	0.51	10.0
	2	1.03	0.73	1.00	0.0	0.30	7.0
	3	1.06	0.57	-1.29	28.6	0.05	5.0
	4	1.06	0.52	-1.00	0.0	0.10	5.0
	5	1.06	0.72	0.00	0.0	0.44	9.0
	6	1.06	0.49	-0.57	0.0	0.00	5.0

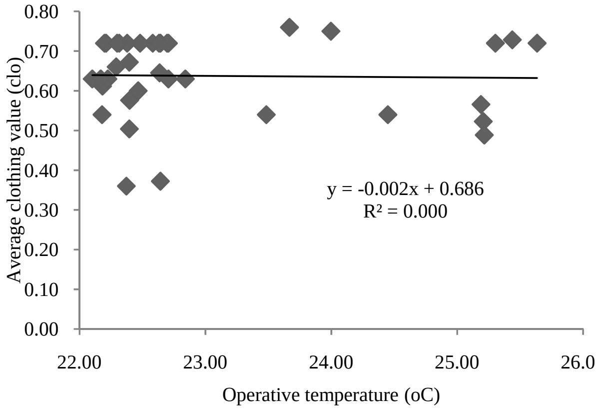

Fig. 1 Relationship between clothing insulation and indoor operative temperature

1. Clothing Insulation

Clothing insulation, which is measured in the 'clo' unit, is basically an estimation of the insulating properties of clothing using tables from [28]. The clothing value is determined from the aforementioned table based on an occupants' garment checklist in the questionnaire. In order to achieve thermal comfort, clothing plays an important role as one of the behavioral adaptations of people. Note that the clothing value of hospital workers in this research study is without taking consideration of the chair insulation. The relationship between the clo value and indoor operative temperature for the lecture halls is shown in Fig. 1.

By referring to Fig. 1, the correlation between clothing insulation and operative temperature for lecture halls in Malaysia is given by (10):

$$Clo = -0.0021\ T_{op} + 0.6866 \qquad (10)$$

Other researchers have done a similar analysis, and their results are as shown in (11)-(13).

$$Clo = -0.04\ T_{op} + 1.73 \qquad [29]\ (11)$$

$$Clo = -0.04\ T_{op} + 1.76 \qquad [18]\ (12)$$

$$Clo = -0.0352\ T_{globe} + 1.3875 \qquad [30]\ (13)$$

Note that (11)-(13) were developed from HVAC buildings, air-conditioned offices and free running buildings respectively. The correlation for lecture halls as shown in Fig. 1 is nearly a horizontal line compared to (11) and (12). This indicates that for students in University of Malaya, their clothing ensembles are almost independent to the indoor operative temperature. It is a norm or culture for university's students to wear a jeans, t-shirt and jacket to lectures. Students always wear a jacket or long-sleeve shirt to class because most of them travel to their faculty by motorcycle. Jacket or long-sleeve shirt with jeans could help to protect their skins from direct sunlight in a hot weather in Malaysia. This makes the custom for all the university's students in their attire.

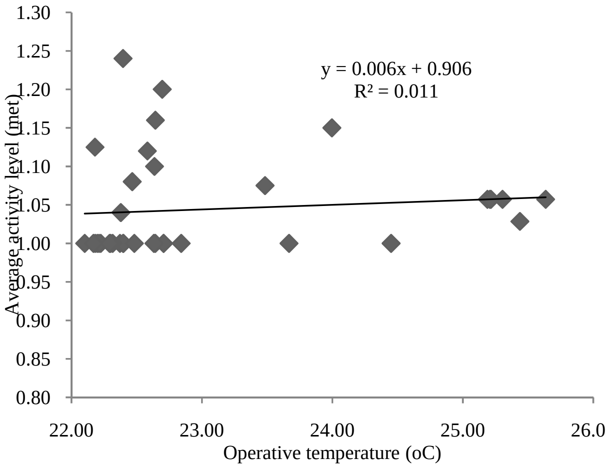

Fig. 2 Relationship between activity level and operative temperature

2. Activity Level

Activity level of occupants is measured in metabolic rate. The metabolic rate is determined based on the questionnaire filled by occupants and the table in [28]. In Fig. 2, it is found that the regression line is almost horizontal with a maximum of 1.24 met, a minimum of 1.00 met and an average of 1.04 met. In this case, the average met is lower than 1.2 met found by different researchers [29], [30] for office buildings because the students always seated quietly in lecture hall compared to office workers, which are doing sedentary work such as typing and filing. Fig. 2 indicates that activity level is independent to the indoor operative temperature. This is acceptable because a person's activity level should depend on his/her job requirement itself rather than the ambient temperature.

3. Air Velocity

Fig. 3 shows the linear regression between indoor air velocity and operative temperature in lecture halls and is depicted in (14):

$$V = -0.0097\, T_{op} + 0.3707 \tag{14}$$

The correlation found by [29] is

$$V = 0.03\, T_{op} - 0.56 \tag{15}$$

The correlation found by [18] is

$$V = 0.02\, T_{op} - 0.35 \tag{16}$$

Note that the slope found in this study is a negative slope, but the slope found by [29] and [18] is a positive slope. According to [6], occupants will prefer a higher air speed at a higher operative temperature. However, from the results obtained in Fig. 3, it shows that air speed is decreasing with an increasing operative temperature. This contrary condition is due to the centralized air-conditioning system in the lecture halls where the air speed is not under students' local control. In this case, the air speed is fully controlled by the air flow from diffusers. A higher indoor air temperature comes from a lower air flow from diffuser. From the theory (Flow Rate=Cross Sectional Area x Velocity), a lower flow rate will gives a lower air velocity. Hence, as depicted in Fig. 3, the higher the indoor operative temperature, the lower the air velocity will be attained.

B. Thermal Acceptability

The correlation between the percentage dissatisfied and the operative temperature is shown in Fig. 4. In order to obtain an actual percentage dissatisfied (APD) below 20% as recommended by [28], the operative temperature range must be 23.9-26.0^{o}C. The temperature range to keep the predicted percentage dissatisfied (PPD) below 20% is 23.5-30.8^{o}C. The wide temperature range for 20% PPD shows that Fanger's model has a higher prediction for the human adaptation ability to changes in the surrounding temperature.

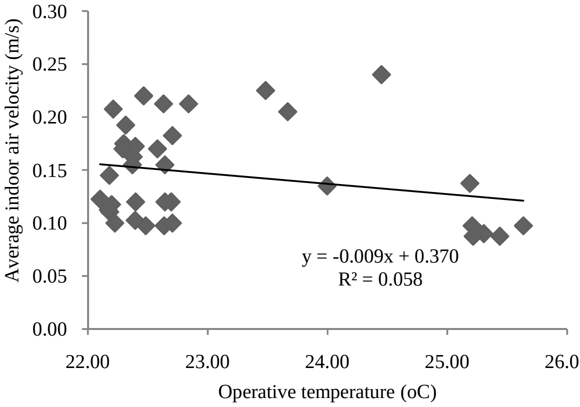

Fig. 3 Relationship between indoor air velocity and operative temperature

Occupants in Malaysia showed a narrower thermal acceptance range of 23.9-26.0^{o}C compared to the predicted value of 23.5-30.8^{o}C when using Fanger's model. The temperature range for a maximum of 20% APD was acceptable because in the present paper, the study focused on air-conditioned lecture halls. In contrast, for a maximum of 20% PPD, the temperature range is too wide and is not practically relevant because it is impossible to have an operative temperature of 30.8^{o}C in an air-conditioned space in Malaysia. Occupants will find 30.8^{o}C to be too hot an environment and thermally discomfort for an air-conditioned space. Generally, the outdoor temperature in Malaysia ranges from 27 to 36 ^{o}C during a sunny day.

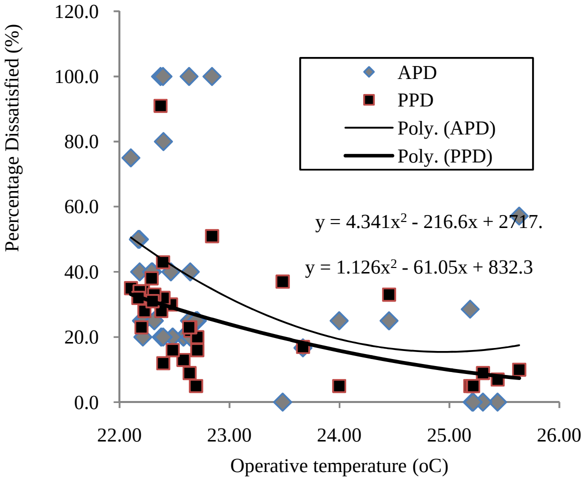

Fig. 4 Graph of percentage dissatisfied versus operative temperature

C. Thermal Neutrality

Thermal neutrality is the operative temperature at the mean thermal sensation vote of zero. From Fig. 5, the neutral temperature for the predicted mean vote and the actual mean vote were 25.0^{o}C and 25.7^{o}C, respectively. The difference of 0.7^{o}C between PMV and AMV is a significant value, and this implies that in the actual case, students in lecture halls prefer a warmer indoor environment compared to the predicted environment from the Fanger's model. This finding is important for local HVAC design engineers, since increasing the setting of people's comfort temperature in an air-conditioning system by 0.7°C could save a significant amount of energy consumed in a building.

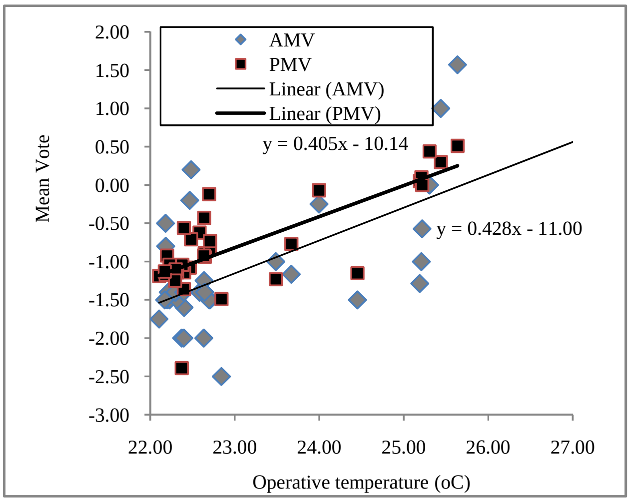

Fig. 5 Graph of mean thermal sensation vote versus operative temperature

V. ADAPTIVE THERMAL COMFORT MODEL

In the last decades, many researchers have developed adaptive thermal comfort models for different countries with different climates. In order to develop an adaptive thermal comfort model, the relationship between the indoor neutral temperature and the outdoor temperature must be determined. Table IV shows the neutral temperature and the outdoor temperature collected from the survey in six lecture halls. Note that the neutral temperature in Table IV is determined from the vote of zero in the correlation between actual mean vote and operative temperature for each lecture hall.

TABLE IV
NEUTRAL TEMPERATURE AND OUTDOOR TEMPERATURE OF LECTURE HALLS

Lecture Hall	T_n (°C)	T_{out} (°C)
A	25.6	33.0
B	24.6	26.3
C	23.9	26.7
D	22.8	26.7
E	25.8	33.9
F	25.3	32.1

By plotting the data shown in Table IV, a linear regression model was generated, as shown in Fig. 6 and (17):

$$T_n = 0.275\, T_{out} + 16.487 \qquad R^2 = 0.7204 \tag{17}$$

Note that the indoor neutral temperature increases by about 1°C for a 3.6°C increment in the outdoor temperature.

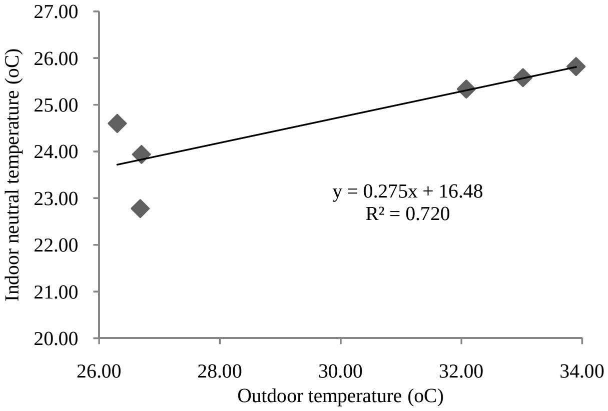

Fig. 6 Adaptive thermal comfort model for lecture halls in hot and humid Malaysia

According to the findings from [18] in the humid, sub-tropical Hong Kong, the neutral temperature increases by about 1°C for every 6°C increase in outdoor temperature. The difference between these results shows that different climates will result in a different thermal sensation. A number of field studies also found that the neutral temperature varies with climate or season [31]. Generally, occupants in warmer climates tend to demonstrate warmer thermal neutrality [29].

From (17), the pattern of the linear regression is approximately similar to those found by other researchers as shown in (1) to (8). The R-squared value in (17) is 0.7204, which is near to unity. Although $R^2 = 0.7204$ shows that the model is acceptable to be applied, but the validity of the data collected from field work still need to be checked. In order to check the validity of the measurement data, bias uncertainty analysis is applied here.

According to [32], in error analysis, the bias uncertainty (B.U.) for measurement parameters can be approximately represented by (18):

$$B.U = (X_{max} - X_{min}) / n \tag{18}$$

where X = measurement parameters such as air velocity, air temperature, globe temperature, relative humidity and outdoor temperature; n = number of readings; X_{max}, X_{min} = maximum and minimum value of the measured parameters.

A set of data is considered valid for use if the error for the bias uncertainty is less than 10% [32]. After calculation, the four basic parameters in this study, which are T_{air}, T_{globe}, RH and T_{out}, are all below 10% error bias uncertainty. Thus, the measured parameters are all valid to be used for determining the adaptive thermal comfort model as shown in (17).

However, the error analysis for air velocity is much higher compared to that of the other parameters. The highest value recorded is 13.79% uncertainty for air velocity. This is because an accurate measurement of a low air velocity is difficult [33]. Also, a more reliable sensor reading is possible only if the air velocity is more than 2 m/s [34]. In the present research, the air velocity measured was in the range of 0.09-0.24 m/s. This shows that the air velocity was very low and difficult to accurately measure. Nevertheless, the bias uncertainty error for air velocity is still at an acceptable level since it is slightly above 10%.

A. Upper and Lower Limits of the Adaptive Model

In order to obtain an adaptive thermal comfort model that is suitable for application in lecture halls in Malaysia, a calibration to determine the upper and lower limits of the model is needed. According to [28], a comfort zone is where 80% of the occupants find the environment thermally acceptable. In other words, a comfort or neutral zone is a zone of maximum allowable 20% occupants' dissatisfaction.

In Fig. 7, for a maximum 20% actual percentage dissatisfied (APD), the range for indoor neutral temperature is 23.9 - 26.0^{o}C. The outdoor temperature range is 27.0 – 34.6^{o}C as shown in Fig. 7. If the outdoor temperature is lower than 27.0^{o}C, the recommended indoor neutral temperature will be constant at 23.9^{o}C. In turn, when the outdoor temperature is higher than 34.6^{o}C, the recommended indoor neutral temperature will be constant at 26.0^{o}C.

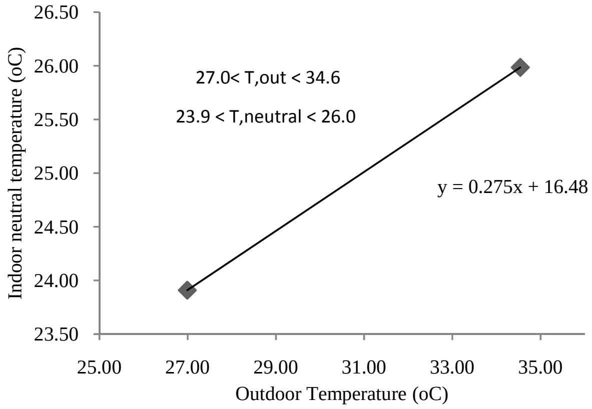

Fig. 7 Upper and lower limits of adaptive thermal comfort model

The adaptive thermal comfort model in combination with the upper and lower limits is important as a good guide to local mechanical engineers, especially in consulting firms. In designing HVAC system, this model can help to reduce the energy consumption as well as achieve a high level of thermal comfort for students in tertiary institutions in the tropics.

B. Verification of the Adaptive Model

The adaptive model shown in (17) was verified by conducting an experiment in an air-conditioned chamber with 10 occupants sitting and working inside. These 10 occupants performed sedentary work and wore clothing of an average of 0.41 clo. During the experiment, the room temperature was adjusted at a range of 23 - 27^{o}C. The occupants were asked to fill in a questionnaire on their thermal comfort levels for every increment of room temperature. The measurements collected during the experiment are shown in Table V. From the results in Table V, a graph of actual mean votes versus indoor operative temperature was plotted in Fig. 8. Fig. 8 shows that the indoor neutral temperature collected during the experiment was 24.73^{o}C.

TABLE V
MEASUREMENTS DURING EXPERIMENT IN A CHAMBER

T_{air} (^{o}C)	T_{globe} (^{o}C)	V (m/s)	RH (%)	MRT (^{o}C)	T_{op} (^{o}C)	AMV	T_{out} (^{o}C)
22.74	23.00	0.08	68.32	23.17	22.96	-1.70	30.46
22.90	22.90	0.11	69.07	22.90	22.90	-0.40	32.32
24.18	24.50	0.05	70.29	24.67	24.42	0	29.09
24.25	24.40	0.06	71.44	24.49	24.37	-0.30	30.99
24.66	24.50	0.07	70.58	24.40	24.53	-0.10	32.43
24.96	24.90	0.11	70.28	24.86	24.91	-0.10	31.27
26.28	26.20	0.06	75.34	26.16	26.22	0.50	31.00
26.37	27.50	0.09	72.55	28.27	27.32	1.55	32.00
26.42	26.50	0.14	79.99	26.57	26.49	1.10	29.52
27.27	26.20	0.10	69.84	25.42	26.34	1.30	29.23

In contrast, by using the adaptive model proposed in (17), the neutral temperature calculated was 24.97^{o}C at an average outdoor temperature of 30.83^{o}C. The difference between the neutral temperature calculated using the adaptive model and the neutral temperature measured during the experiment was 0.24^{o}C or 0.96 %. This discrepancy is due to the difference of clothing values and activity levels between lecture halls and the experimental chamber. For lecture halls, the average clothing value and activity level are 0.64 clo and 1.04 met, respectively. For the chamber, the average value was 0.41 clo and 1.14 met. This implies that people with a different clothing insulation and activity level will have a different feeling on their thermal comfort level. Since the discrepancy is only 0.96 % as mentioned above, the adaptive model proposed in this paper is valid for use in Malaysian lecture halls.

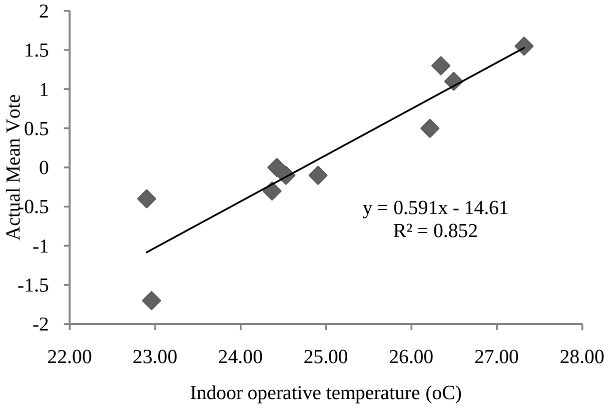

Fig. 8 Actual mean vote versus indoor operative temperature in a chamber

VI. CONCLUSIONS

In this study, the relationship between the operative temperature and behavioral adaptations was successfully established. The adaptive thermal comfort model for hot and humid climates such as Malaysia was also successfully developed based on the linear relation between indoor and outdoor air temperatures. The adaptive model that has been developed in this paper is T_n = 0.275 T_{out}+16.487, with its upper and lower limits of 23.9-26.0^{o}C for indoor neutral temperature and 27.0-34.6°C for outdoor temperature, respectively. This model is suitable for use in lecture halls in Malaysia since the error is only 0.96 % between the neutral temperatures calculated using the aforementioned equations and the neutral temperature measured during an experimental study in a chamber.

The most comfortable or neutral temperature found from the field study in lecture halls was 25.7°C. In comparison to the recommended temperature of 24.0°C by [35], the proposed neutral temperature for lecture halls in this study is 1.7°C higher. This difference of 1.7°C has a significant impact on the energy saving potential of a building, because by increasing the room temperature setting from 24.0°C to 25.7°C, one could decrease the cooling load and thus save a significant amount of energy.

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