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A Unified Adaptive Fanger's Model for Thermal Comfort in Tropical Countries

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Abstract. Thermal comfort, which used to be a luxury in life has transformed into a necessity in modern lives. Tropical country such as Malaysia has hot and humid climate all year round. Much air conditioning is required in tropical countries to provide thermal comfort for indoor occupants. Fanger's model is deterministic as it regards the heat fluxes across the boundary between humans and their thermal environment. Fanger's model is adopted by ASRHAE Standard 55 in 1992 but it has over-predicted thermal preferences of those living in tropics. Malaysians who are used to hot and humid climates prefer warmer indoor temperature, as hypothesized in adaptive model. Adaptive model is said to predict thermal comfort more accurately than Fanger's model as it relates the indoor comfortable temperature to outdoor air temperature. The objective of this research is to integrate the adaptive theories into Fanger's model and to synthesize a new thermal comfort model which is expected to accurately predict thermal comfort in tropical countries. As the adaptive theory says that not all peoples' thermal preferences are affected by thermal histories and contextual factors, the new model has proposed a broader operation range of PMV for air conditioner. The increment of PMV range from ±1.0 to ±1.17 for 80% satisfaction requirement is proved to applicable in Malaysia.

Introduction

Air conditioning a technology that improves human's life by providing thermal comfort. Thermal comfort is defined by ASHRAE as the condition of mind, which expresses satisfaction with the thermal environment [1]. The operating range of the air conditioner is important parameters to be determined in researches. The range shall provide the optimum thermal comfort for humans. More researches are required to model thermal comfort due to the inadequacies of Fanger's model in predicting thermal preferences in tropical countries.

Fanger's has regarded six thermal parameters in his heat balance model [2]. According to him, a person will feel comfortable only when the energy fluxes across the boundary between humans and thermal environment is in equilibrium. ASHRAE and ISO Standards which is based on Fanger's model have been established in 1992 and applied globally. Due to the lack of cultural, climate and social dimensions, Fanger's global application has been question [3,4]. To regard these dimensions, another thermal comfort prediction tool has been introduced – the adaptive model. As the model is empirical, it indirectly included the three dimensions which are neglected by Fanger.

According to adaptive model, when there is a change in thermal environment that causes discomfort on a person, the person will adapt to the changes to restore his comfort. Humans can either adapt behaviorally, physiologically or psychologically to make themselves more comfortable [5]. There is a dynamic process taken place in between humans and their thermal environment. Humans are said to be interactive with their thermal environments. The dynamism is hardly to be considered in Fanger's model.

Various field studies conducted by researchers in tropical regions have proven the inaccuracy of Fanger's model. The over-prediction causes energy wasted in air conditioning and yet the dissatisfaction of the indoor occupants. In 2004, adaptive model has gained recognition from ANSI and ASHRAE Standard 55 and European Standard EN 15251 through their established adaptive standard.

Diversity in culture and background of indoor occupants are affecting their thermal preferences. Malaysians who are used to hot and humid climates prefer a warmer temperature than those who have been living in cold climate countries. Culture and background of the peoples are influencing two important thermal parameters which are clothing insulation and metabolism rate. What people wear and what activities are they conducting are difficult to predict, especially in Malaysia, the land with diverse cultures and various ethnic groups.

Literature Review

The Deterministic Model. The scientific model which regarded thermal parameters in predicting thermal comfort is deterministic in its nature. According to this model, the goal for thermal comfort is to achieve an equilibrium between the energy fluxes between human body and thermal environment [6].

The heat transfer mechanism that fluctuates in human's body (here, regarded as a control volume), comprise of radiation from surroundings and energy-flux from human's body. The heat balance is described in terms of predicted mean vote (PMV). The PMV index is created based on thermal chamber experiments and it expresses the quality of thermal environment as mean value votes of a large group of people on ASHRAE's 7-point thermal sensation scale [7]. The 7-point scale is given as in Table 1.

Table 1. ASHRAE 7-Point Thermal Sensation Scale [8].

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

The other index which is a mathematical function of PMV is predicted percentage of dissatisfaction (PPD) [8]. PPD is an index that describes the voting outside three thermal satisfaction scale of ASHRAE [8], as in Eq. 1.

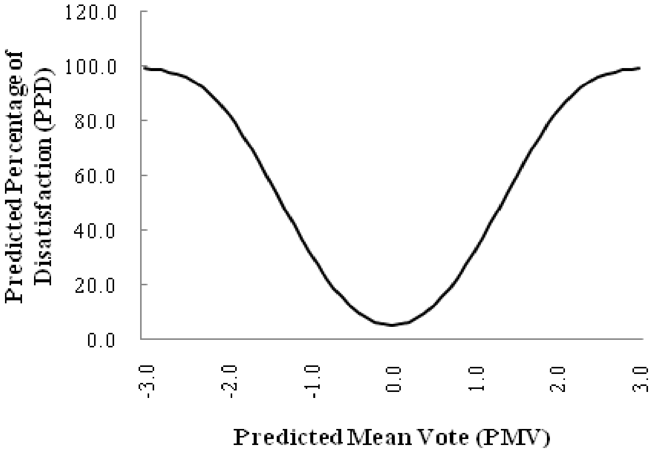

Fig. 1 Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD) curve [8].

$$PPD(PMV) = 100 - 95\exp\left(-0.03353PMV^4 - 0.2179PMV\right) \quad (1)$$

The curve of Eq. 1 is represented in Fig. 1. The goal of air conditioning is to achieve PMV=0 whereas PPD=5 [10]. At PMV=0, which is neutral in ASHRAE's 7-point thermal sensation scale is a condition when the energy entering and exiting a human body is in equilibrium.

PPD predicts the number of thermally dissatisfied persons among a large group of people while the rest of the group will feel thermally neutral, slightly warm or slightly cool. The distribution of individual thermal sensation votes for different values of mean vote has established in ISO 7730-2005 Standard [10], as shown in Table 2.

Discrepancies between the predicted mean votes and actual mean vote from field studies are due to clothing garments, chair insulation, inaccurate estimation of activity and metabolism rate, non-uniformities of measurement, and non-thermal factors, such as demographics [11]. Field studies conducted in Singapore, Indonesia and Thailand have shown similar trend on their results [12,13,14,15].

Table 2. Distribution of individual thermal sensation votes for different values of mean vote [8].

PMV	PPD	Persons predicted to vote [a] %		
		0	-1, 0 or +1	-2, -1, 0, +1 or +2
+2	75	5	25	70
+1	25	30	75	95
+0.5	10	55	90	98
0	5	60	95	100
-0.5	10	55	90	98
-1	25	30	75	95
-2	75	5	25	70

[a] Based on experiments involving 1,300 subjects.

Adaptive Model. The "architectural" model, treats humans, the thermal recipients as active subject that interacts with the thermal environment. The thermal preferences of humans are affected by contextual factors, past thermal history, cultural and technical practices [16]. Contextual factors are climate, building and time [17]. People react in various ways, either adjusting their environment or personal adjustment to restore their comfort when there is a change occurs.

The adaptive model is a linear regression that relates indoor comfort temperature directly with outdoor air temperature, as in Eq. 2 [18].

$$T_{\mathrm{comf}} = A \times T_{\mathrm{a,out}} + b \quad (2)$$

The adaptive comfort chart which relates indoor operative temperature (comfort temperature) to mean monthly outdoor air temperature is shown in Fig. 1. Adaptive mechanisms include behavioral adaptations, physiological acclimatization and psychological adaptations [5]. Occupants in hot and humid climate make daily adjustment to adapt to the thermal environment and this will become their habit in long terms [13,14].

ISO 7730 PMV model is to be modified to improve its performance and accuracy in predicting the actual mean vote [17]. Extended PMV model has included expectancy factor, e into the PMV for the natural ventilation buildings in warm climate [2].

The concept of air temperature thresholds to reduce the need for energy-intensive air conditioning in buildings has been introduced in 2011. By having a broad comfort/acceptable temperature, thus less energy is required to maintain the indoor environment.

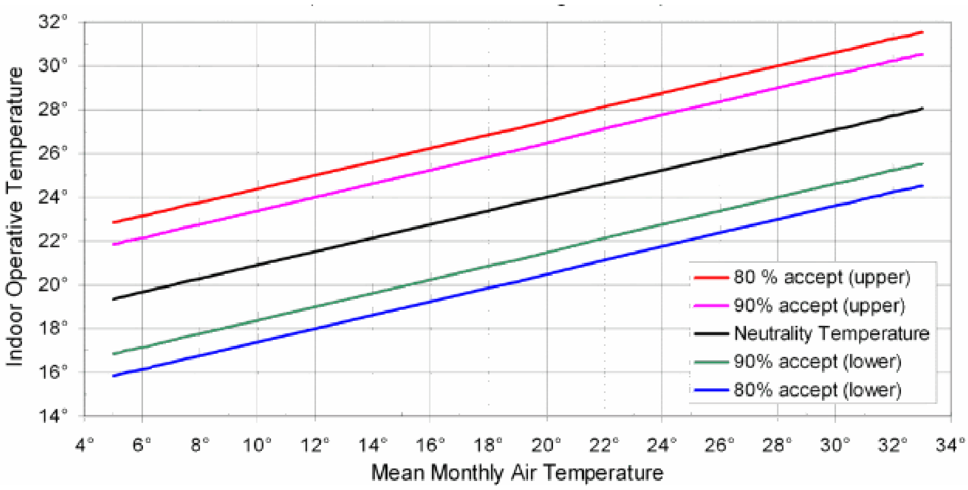

Fig. 2 The adaptive comfort model as proposed by de Dear and Brager in 2001.

Clothing and Thermal Comfort. Clothing is a thermal resistance [19] and impedance to mass transfer [20]. Clothing represents a cultural development [21], a projection of personality, mood, religion, sub-cult and other group affiliations [22]. Clothing is simply defined as a layer of thermal insulation uniformly interposed between human's body surface and their immediate thermal environment [8]. The prediction of thermal comfort can be difficult due to the diversity of clothing insulation in a building can be explained by various reasons, such as genders [23], dress code regulations, response to outdoor environmental conditions [25], material culture [21], comfort level, indoor environment, appropriateness to the job, desire to be fashionable, after-work activities [25]. The focus of this research is on clothing insulation worn indoor affected by corporate dress codes and clothing insulation worn indoors affected by context/setting.

Malaysia's Climate and Thermal Comfort. Located in the tropics, Malaysia has hot and humid climate all year around with average temperature 20°C to 32°C during daytime and 21°C to 27°C during night time [26]. The humidity is rather high, which is 75%. Field studies in Malaysia suggest a wider comfort temperature range than those proposed by ASHRAE Standard 55. Malaysians are acclimatized to higher indoor temperature [27], as it suggests in adaptive model. Air conditioning is a must for Malaysians to feel comfortable during the day [34]. The field studies suggest that neutral temperature for Malaysian lecture hall is 25.3°C [28] whereas the comfort temperature for lecture theatre in Singapore is 25.84°C [29].

Methodology

The scope of the research is to study thermal comfort in lecture hall and student hostel building. Lecture hall is a centralized HVAC building whereas student hostel building is a natural ventilated building. One specific building is selected for each type of building as the subject of study in this research.

The selected buildings located in a local university in Perak, Malaysia. The field study was conducted to study the clothing behaviors and activity level in the two types of building in Malaysian setting. Survey forms that require subjects to fill in their clothing details are distributed to building occupants in the two buildings. The sample size is 100 peoples per building.

Estimation on the clothing insulation values are done by summing the subjects' clothing garment insulation as provided in ASHRAE Standard 55P-200, shown in Eq. 3 [7,22].

$$I_{\text{effective}} = \sum_{j=0}^{n} I_{\text{clo},\,j} \tag{3}$$

An experimental design was set up to find out the impact of each thermal parameter on PMV value. The more critical parameter(s) shall be studied in detail before the union of Fanger’s and adaptive models.

The distribution of individual thermal sensation votes for different values of mean vote is normalized to obtain a new function that represents the distributions. The new function is renamed as probability satisfaction distribution function (PSDF), replacing predicted percentage of dissatisfaction (PPD). 80% satisfaction can be represented by 80% probability under the function curve and this is obtained through integration the curve symmetrically on PMV=0.

In fact the normalized function is compared with original PMV-PPD function. Field studies results have been used to computed to validate the union of Fanger’s and adaptive model. The computations of PMV values based on thermal parameters obtained for Malaysian setting are done using Microsoft Excel Visual Basic and Applications (VBA) functions.

Results and Discussions

Impact Level of Thermal Parameters. The relationship between thermal parameters and PMV value is able to be described in a linear regressed function as in Eq. 4. The parameters with higher modulus of coefficient are those more impactful parameters in predicting PMV value.

$$\begin{aligned} PMV = {} & -19.04 + 0.01447 \times RH + 2.287 \times Met - 3.159 \times Vel + 3.046 \times Clo \\ & + 0.164 \times Tr + 0.294 \times Ta \end{aligned} \tag{4}$$

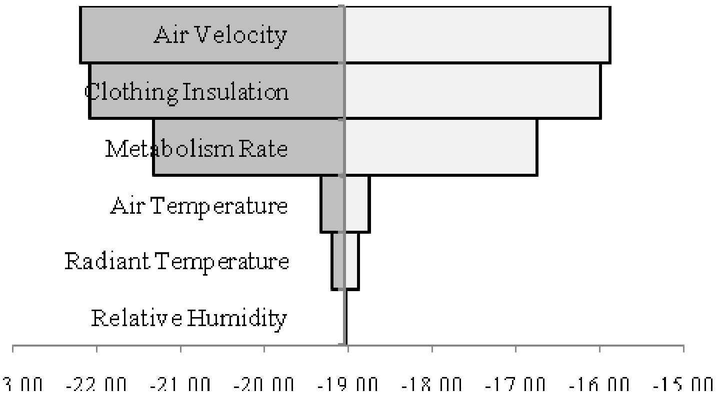

Fig. 3 Tornado chart showing the different impact level of thermal parameter on PMV

The results of experimental design can be represented as Tornado chart as in Fig. 3. The mean of PMV is 19.04 which imply that this model is biased to colder thermal sensation. The more impactful parameters are air velocity, clothing insulation and metabolism rate whereas air temperature, radiant temperature and relative humidity are less significance parameters to PMV.

Air temperature, air velocity and relative humidity are parameters which are hardly being controlled by indoor occupants as they are controlled by air conditioning. On the other hand, indoor occupants have more control on clothing insulation and metabolism rate. As for example, a person might put on thicker clothing and moving about in order to make himself warmer when the thermal environment is cold. The two parameters are key parameters to integrate adaptive theories into Fanger’s model.

The Unified Model. The revised PMV-PPD model has transformed PPD index to predicted percentage of satisfaction (PPS). The transformed curve is a bell curve, as in Figure 4 and the equation of the function is given in Eqn. 5. As required by ASHRAE Standard, it is required for thermal comfort environment to achieve at least 80% satisfaction. This criterion is achieved when PMV falls in between -1.0 and +1.0, as per the shaded region in Fig. 4.

$$PPS(PMV) = 95\exp\left(-0.03353PMV^4 - 0.2179PMV\right) \quad (5)$$

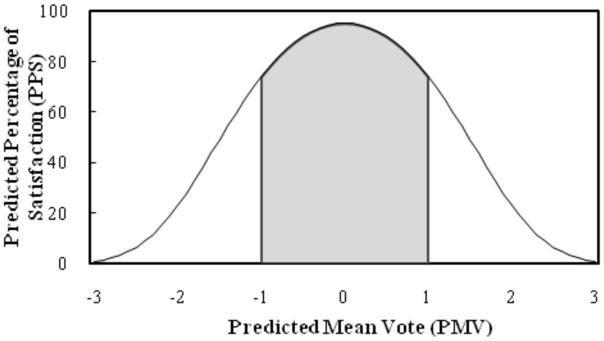

Fig. 4 Predicted percentage of satisfaction (PPS) versus predicted mean vote (PMV). 80% of satisfaction fall in the range of -1.0<PMV<+1.10.

The normalization of PMV distribution has resulted in a new function of PMV and probability of satisfaction distribution function (PSDF), as in Eq. 6. The function is plotted as in Fig. 5.

$$PSDF(PMV) = 0.4374\exp\left(-0.6012PMV^2\right) \quad (6)$$

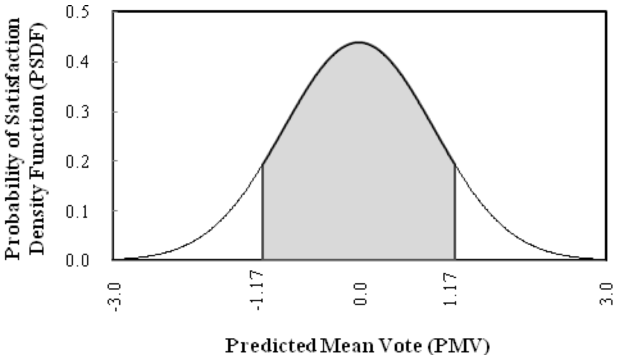

Fig. 5 Normalized distribution of Predicted Percentage of Satisfaction (PPS) vs Predicted Mean Vote (PMV). 80% of satisfaction fall within the range of -1.17<PMV<+1.17.

The standard deviation of the distribution is obtained as 0.912 whereas the mean of the distribution is at 0. The integration of the function symmetrically on PMV=0 has obtain an intersection at PMV=±1.17 for 80% satisfaction. The difference of the PPS(PMV) and PSDF(PMV) curve is evaluated by overlapping the two curve on the same coordinate, as in Fig. 6. The coefficients of exponential functions are omitted. The width of curve PPS is wider than the width of curve for PPS due to the quartic exponential function in PPS curve whereas quadratic exponential function in PSDF curve. The increment of the width of the curve is significant and this is due to the polynomial of exponential function.

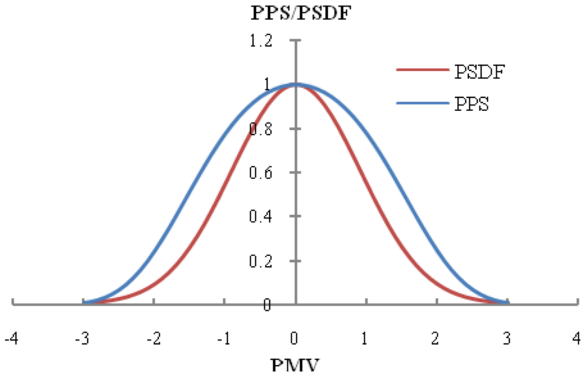

Fig. 6 Comparison of PPS(PMV) and PSDF(PMV) curve

Integrating Adaptive Theories. The same method is used to normalize the distribution of PMV values for the results obtained in field studies conducted in Malaysia and Indonesia, as in Fig. 7 and Fig. 8.

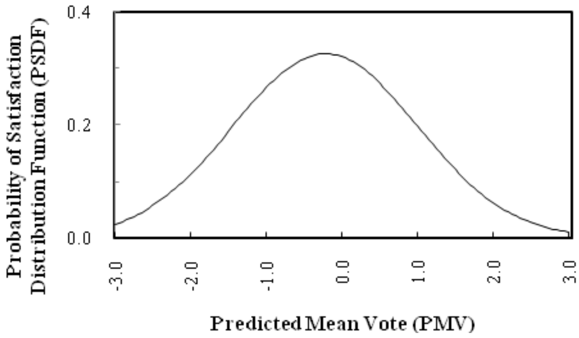

Fig. 7 Probability of satisfaction distribution function in a museum in Malaysia. The standard deviation of the distribution is 1.221 and mean is -0.22 [30].

The mean values for PMV has been deviated from 0, the requirement of the standard. The standard requirement for PMV=±1.0 for 80% satisfaction to thermal environment has been inapplicable in Malaysia and Indonesia. In order for the model to be adaptive in hot and humid countries, the range of PMV for 80% satisfaction shall be wider to meet the conditions in tropical countries.

The increased range for PMV gives a broader operation range for air conditioner. This is significant to give tolerances for the wide range of thermal expectations and preferences of peoples living in tropical countries. Peoples thermal preferences are not fixed to 0 as some prefers slightly cold or warm temperature. Besides, the wider range of PMV gives tolerance to the dynamic interaction in between humans and their thermal environment. When peoples are adapting to their environment through various mechanisms, the comfort temperature might change accordingly.

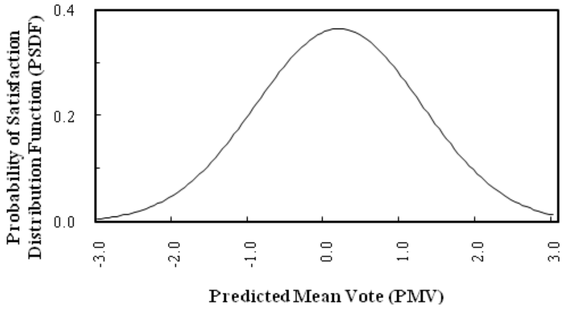

Fig. 8 Probability of satisfaction distribution in an Indonesian building. The standard deviation of the distribution is 1.094 and the mean is 0.179. [31]

Clothing Insulation and Metabolism Rate. The clothing insulation and metabolism predicted from the field studies are summarized as in Table 3.

Table 3. Summary of metabolism rate and clothing insulation in lecture hall and hostel

Types of Building	HVAC (Lecture Hall)	NV (Hostel)
Metabolism Rate (Met)	1.0 – 1.7	0.7 – 1.1
Clothing Insulation (Clo)	0.36 – 1.1	0.1 – 0.57

Validation of Unified Fanger's Adaptive Model. To validate the applicability of unified adaptive Fanger's model in HVAC and NV building in Malaysia, a set of data from field studies are used and the range of each parameter is as shown in Table 4.

Table 4. Data range for each thermal parameter for validation of unified adaptive Fanger's model in HVAC building

Thermal Parameters	HVAC	NV
Clothing Insulation (Clo)	0.36 – 1.1	0.1 – 0.57
Metabolism Rate (Met)	1.0 – 1.7	0.7 – 1.1
Air Velocity (m/s)	0.15 – 0.5	0.15 – 0.5
Relative Humidity (%)	55 – 70	55 – 70
Air Temperature (°C)	25.3	28.5
Radiant Temperature (°C)	27	30

As for HVAC building, about 88% of PMV values calculated are in range of ±1.17 whereas only 67% are in the range of ±1.0. As for NV building, about 73% of PMV values calculated are in range of ±1.17 whereas only 62% are in the range of ±1.0. The unified Fanger's adaptive model predicts thermal comfort in Malaysia better than the original model. However, the unified model is more accurate to be used in HVAC building than NV building.

Conclusion

Fanger's heat balance model has included all the necessary parameters in calculating the thermal sensation of humans, in terms of PMV. The theory of heat balance to achieve thermal comfort cannot be denied. However, due to its deterministic nature, Fanger's model has over-predicted the thermal preferences in tropical countries.

The unified adaptive Fanger's model has integrated the adaptive theories into Fanger's model and a new unified thermal comfort model is synthesized. The model provides a widened allowance for PMV value which is ±1.17 for 80% satisfaction from the normalization of individual thermal sensation votes distribution. Peoples living in tropical countries have higher tolerances to thermal environment and thus the widened range of PMV is necessary. The widen operation range gives tolerances to variations and dynamism of human clothing behavior, thermal preferences, activity level and other contextual factors.

The unified adaptive Fanger's model is a better prediction tool for Malaysia. It is more accurate to be used in HVAC building than NV building.

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