# A Modified Fanger's Model for Malaysia Climate

[1]Pau J. S., **[1]William K. S. Pao, and [2]Kee K.K.

**Abstract**

Thermal comfort is the condition of mind, which expresses satisfaction with the thermal environment. The unwavering need to have thermal comfort in tropical climate has caused excessive use of air conditioning, resulting in the issue of energy over-consumption. One of the solutions is to run air conditioners at the minimal energy level to reduce wastage. There are two approaches in thermal comfort research, namely the deterministic *engineering* approach which is based on Fanger's heat balance model and the person-environment *architectural* approach, which is collectively called the Adaptive Method. Adaptive Method has slowly been accepted in the thermal comfort research as it regards humans as an adaptive being that is dynamic in nature and has the ability to adjust to environmental changes. This research aims to integrate adaptive theories into Fanger's model to widen the application of Fanger's model in tropical countries, particularly in Malaysia. The research has proposed the limitation of PMV to ±1.3 for 80% occupant satisfaction, with an increment of ±0.3 from the original limitation of PMV as in ASHRAE Standard. The increment provides tolerance to adaptive mechanism and dynamic fluctuations of thermal preferences of subjects in tropical countries. It is verified that the new adaptive Fanger's model is applicable in Malaysian HVAC and NV buildings.

***Keywords*:** Thermal comfort, Fanger's Model, Adaptive Model, ASHRAE Standard

## I. INTRODUCTION

Air conditioners play an important role in maintaining humans' comfort in indoor environment. Comfort has become an essential element in modern life. Thermal comfort is the condition of mind, which expresses satisfaction with the thermal environment, as defined by ASHRAE. As going green has gained attention by many governments, energy overconsumption caused by unnecessary air conditioning has created a new issue. The price of human comfort in air conditioned buildings is the depletion of available energy resources. As it is almost impossible to reverse the current trend of using air conditioners, one of the solutions to energy consumption issue is to run the air conditioners at minimal energy [1].

To model the best air conditioner requirements for humans' comfort, researchers have used both experimental and empirical methods [2]. The earliest model in this research area was proposed by Fanger in 1970. Fanger has used first law of thermodynamics in his modeling by considering not only the air temperature, also clothing insulation, metabolism rate, radiant temperature, relative humidity and air velocity. With strong base on scientific theories, Fanger's model has been adopted by ANSI/ASHRAE Standard 55 in 1992. However, the model was found inapplicable in tropical countries with hot and humid climate. With this finding, researchers have proposed another approach which is adaptive model. The adaptive model defined the indoor comfort temperature to be proportional to outdoor temperature. The coefficients of this relationship are varied according to local climate and conditions. Due to its simplicity, more researchers are accepting adaptive model instead of Fanger's. The acceptance of adaptive approach in ANSI/ASHRAE Standard 55 in 2004 has brought a transformation to the research of thermal comfort.

The objective of the present study is to integrate adaptive theories into Fanger's model to widen its application in tropical climates. The adaptive theories studied in this research include various thermal preferences of people in tropical region, people's ability to adapt to the environment and variations in clothing and cultures.

## II. LITERATURE REVIEW

### 2.1 Fanger's Model

Fanger's model is based on the first law of thermodynamics. There are various heat fluxes flowing within the boundary of human bodies and the environment. The heat transfer mechanisms comprise of radiation from surroundings and energy-flux

**Corresponding author

This work was financially supported in part by FRGS/1/2012/TKO7/UTP/45, Universiti Teknologi PETRONAS and Kolej Laila Taib.

[1] Pau J.S. and William K. S. Pao are with the Universiti Teknologi PETRONAS, Tronoh, Perak (phone: +606-368-7012; fax: 605-368-6461; e-mail: William.paokings@petronas.com.my).

[2]Kee. K.K. is with Kolej Laila Taib, Sibu, Sarawak. (e-mail: kkkee@klt.edu.my).

from human's body.  In order for humans to feel comfort, the net of flow of these heat fluxes shall be zero [4]. Predicted Mean Vote (PMV) index has been used to quantify the thermal sensation of humans.  PMV is an index which expresses the quality of thermal environment as mean value votes of a large group of people on ASHRAE's seven point scale [6].  A person should feel comfortable when the thermal sensation is neutral, which is at scale 0 in PMV.  At this point, it is expected the predicted percentage of dissatisfaction (PPD) should be at the minimum [5].

Fanger established two indices for thermal comfort which are Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD) [5]. PMV expresses the quality of thermal environment as mean value votes of a large group of people on ASHRAE's 7-point thermal sensation scale [6].

TABLE 1 ASHRAE 7-POINT THERMAL SENSATION

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

Fanger has related PPD to PMV as a mathematical function based on the results he obtained in his thermal chamber studies.  The function is represented in Eqn. 1.

$$PPD(PMV) = 100 - 95\exp\left(-0.03353PMV^4 - 0.2179PMV^2\right) \tag{1}$$

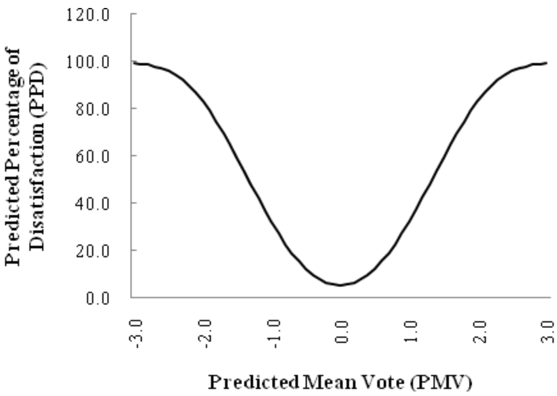


FIG. 1 Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD) curve.

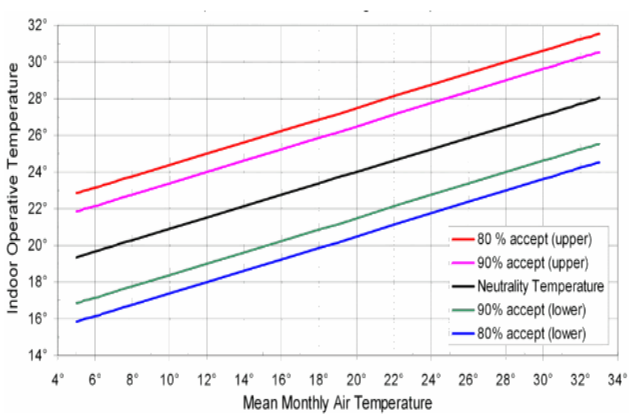


FIG 1(b). The adaptive comfort model as proposed by de Dear and Brager [9].

The relationship between PMV and PPD is clearly shown in Fig. 1(a).  The minimum point (PMV=0, PPD=5) on the curve is the goal of air conditioning system [7].

Fanger's model is regarded as partially adaptive as it accounts for physiological and behavioral adaptations such as clothing insulation and metabolism [8]. Recently, the universality assumption of ISO 7730 and ASRHAE Standard 55 which adopted Fanger's model has been challenged [9]. Discrepancies of the predicted mean votes and actual mean vote from the data collected in field are believed due to clothing garments, chair insulation, inaccurate estimation of activity and metabolism rate, non-uniformities of measurement, and non-thermal factors, such as demographics [8]. The standard shall be improved by considering the dynamic nature of human-surrounding interactions [10]. The discrepancies are also explained by the equations and non steady-state condition [11]. Various field studies had shown that Fanger's heat balance theory failed to explain the comfort temperature range in the buildings with natural ventilation [12]. The field studies that conclude the above statement include researches conducted in Singapore, Indonesia, and the old Havana in Cuba [12, 13, 14, 15].

### 2.2 Adaptive Model of Thermal Comfort

A person's thermal expectations and preferences are affected by contextual factor (i.e. climate, building and time) and past thermal histories [11]. The adaptive hypothesize states that "People in warmer climatic zones prefer warmer indoor temperature than those in cold climatic zones" [8]. To restore comfort when the environment changes, people will react in ways, either adjusting the environment or personal adjustment. Humans are treated as active thermal recipient that interacts with the thermal environment. Their perception on thermal comfort is affected by past thermal history, cultural and technical practices [8]. The adaptive model is a linear regression that relates indoor comfort temperature with outdoor air temperature and business culture, such as activities, dress code, etc [16], as shown in Eq. (2).

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

Adaptive mechanism includes behavioral adaptations, physiological acclimatization and psychological adaptations [5]. A person will change its personal variables such as clothing to adapt to thermal changes. Peoples show physiological adaptation by increased metabolic rate or sweating capacity and other physiological changes to adapt to the thermal environment. Psychological adaptation is the change in people's expectation towards thermal environment [8]. However, few literatures discuss on this adaptive mechanism. Occupants in hot and humid climate will adapt to the environment naturally. Often, their daily adjustment to adapt to the thermal environment will become their habit in long terms. The ability to afford air conditioning is also another factor that influences occupants to be more tolerance towards the climate [13, 14, 15].

de Dear and Brager [9] has presented the adaptive comfort chart by relating the indoor operative temperature (comfort temperature) to mean monthly outdoor air temperature, as shown in Figure 1(b). The adaptive approach is said to be more appropriate as the coefficients in Eqn. 2 are varied according to field studies results and it is independent on non-specific description of the season.

New adaptive comfort standard (ACS) has been established for design, operation and evaluation of natural ventilated buildings which saves energy in air conditioning in 2001. ACS has been proven its potential in energy saving through GIS mapping technology [9]. It is suggested ISO 7730 PMV to be modified to improve its usability and accuracy in predicting the actual mean vote [11]. The difference of tropical climate further stressed the urgency of modification of ISO 7730. One of the contribution to this is done in 2002 where expectancy factor, $e$ is included in PMV model to become extended PMV model [17].

### 2.3 Thermal Comfort in Malaysia Climate

Malaysia has hot humid climate with temperature ranging from 20°C to 32°C during daytime and 21°C to 27°C during night time with relative humidity around 75% [18]. High energy is required for cooling buildings in hot and humid climate to provide a comfortable environment for occupants [19, 20]. Field studies in Malaysia suggested a wider thermal comfort range for the hot and humid climatic zones than those proposed by international standards, i.e. ASHRAE Standard 55. This indicates that Malaysians are acclimatized to much higher environmental temperature [21]. Malaysia, with fastest growing building industries worldwide, experienced increased energy demand in buildings. The average temperature for typical towns in Malaysia imply that air conditioning during office hours is a must for people living Malaysia [22]. The prediction of neutral temperature for Malaysian lecture hall setting is 25.3°C [22] while the comfort temperature obtained in lecture theatre in Singapore is 25.84°C [23].

## III. METHODOLOGY

Fanger's heat balance and PMV is calculated based on six thermal parameters, which are air temperature, relative humidity, radiant temperature, clothing insulation, metabolism rate and air velocity. The sophistication of the heat balance equations added difficulty to determine the most critical parameter. It is crucial to identify the most critical parameter as these parameters shall be study in detail for new thermal comfort model. In this research work, the method of experimental design has been utilized to determine the significance of each parameter with respect to PMV- the identification of thermal comfort.

Due to cultural and lifestyle variations in Malaysia, clothing insulation and metabolism are two influential thermal parameters that should be studied to obtain the optimum thermal comfort setting in Malaysia. Two types of buildings, the centralized HVAC building and natural ventilated (NV) buildings are chosen for the observations. The field observation is conducted at lecture halls (HVAC building) and student hostels (NV building) in a local university in Perak, Malaysia. The clothing behaviors and activities levels of subjects are observed and recorded as a data to the research work. Clothing insulation is estimated based on the garment check-list defined in ASRHAE Standard 55P-2003 [6]. The effective insulation values are estimated by cumulatively summing subjects' clothing garment insulation as listed in the garments and effective insulation values in the standard [22].

$$I_{\mathrm{effective}} = \sum_{j=0}^{j=n} I_{\mathrm{clo},j} \qquad (3)$$

TABLE 2 DISTRIBUTION OF INDIVIDUAL THERMAL SENSATION VOTES FOR DIFFERENT VALUES OF MEAN

| 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.

The function of PPD (PMV) which is obtained from the experimental study in thermal chamber is a distribution of PPD at various PMV. The distribution of individual thermal sensation votes for different values of mean vote established in ISO7730-2005 [23] , as in Table 2 is normalized and expressed in normal distribution function in terms of predicted percentage of satisfaction instead of predicted percentage of dissatisfaction.

To obtain the 80% satisfaction requirement as specified by ASHRAE and ISO Standard, the area under the normal distribution curve is integrated to obtain the satisfaction PMV scale. The field studies result obtained in previous researches and the results of observations are computed to validate the new proposed thermal comfort model. All computations have been carried out using Microsoft Excel Visual Basic and Applications (VBA) functions.

## IV. RESULTS AND DISCUSSION

Using the method of experimental design, a linear regressed function is obtain to determine the influence of thermal parameters on PMV, as in Eqn 4.

$$PMV = -19.04 + 0.01447*RH + 2.287*Met - 3.159*Vel + 3.046*Clo + 0.164*Tr + 0.294*Ta \quad (4)$$

Figure 2 is a better representation of the significance of each parameter on PMV. Air velocity, clothing insulation and metabolism rate are more critical parameters to determine PMV. Out of three, clothing insulation and metabolism rate are used to study in detail in this research. The two parameters are strongly affected by cultural and lifestyle variations, especially in South East Asian countries.

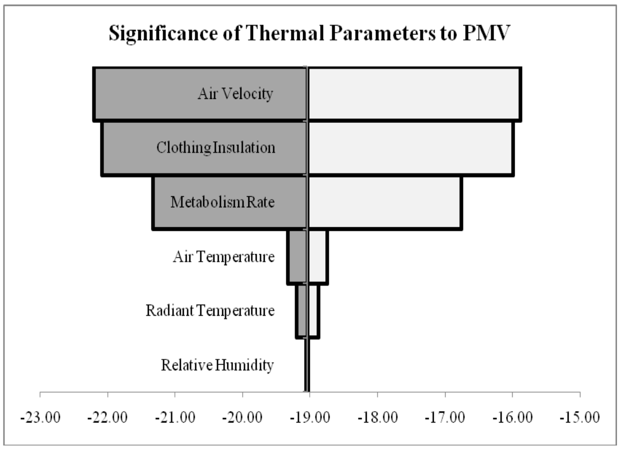


FIG. 2 (a) Significance of thermal parameters on Predicted Mean Vote (PMV).

In the lecture hall chosen for observation, the activities conducted by the occupants are light during the lectures. From Appendix A – Metabolism Rates for Typical Tasks in ASHRAE 55R-2003, the activities are classified as seating, reading or writing/seated quiet (Met = 1.0) and walking about (Met = 1.7). Due to cultural difference, Malay, Chinese and Indian ethnics and other races wear different clothing and the range of clothing insulation is estimated to be 0.36 to 1.1Clo. Besides, the clothing preferences in between genders are also considered.

As for the student hostels, the activities conducted are also light with estimated metabolism rate ranges from 0.8 to 1.2met. The activities are classified as sleeping (Met=0.7), seated/reading/writing (Met =1.0), standing, relaxed (Met=1.2), typing (Met=1.1) and seated quiet (Met=1.0). The clothing worn by students in hostels are lighter than those worn in lecture halls, with estimated clothing insulation ranges from 0.18 to 0.57Clo. It is observed that there are more variations in clothing worn by female than male.

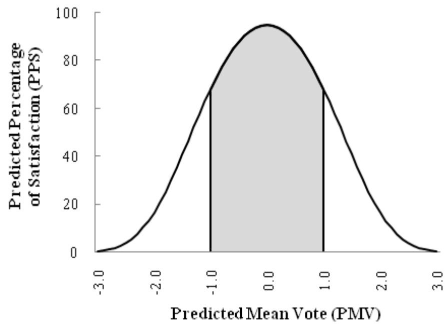


FIG. 2 (a) Predicted PPS vs PMV for 80% satisfaction fall within the range of -1.0 < PMV < +1.0

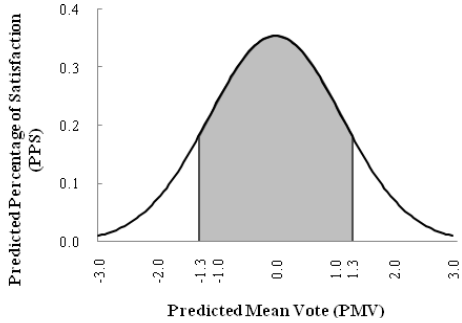


FIG. 2 (b) normalized distribution of PPS versus PMV for 80% satisfaction fall within the range of -1.3 < PMV < +1.3.

As mentioned in ISO 7730, PMV-PPD curve is an inverted Gaussian distribution. To constrain the 80% satisfaction to fall within PMV=±1.0. The PPD function is expressed in quartic exponential function, as shown in Eqn. (1). The transformation of PPD index to PPS index gives a bell curve, similar to normal distribution, as shown in Fig. 2(a). The curve can be represented by the Eqn. (5).

$$PPS(PMV) = 95\exp\left(-0.03353PMV^4 - 0.2179PMV^2\right) \tag{5}$$

Normalization of PMV distribution as in Figure 2(a) has obtained result as in Figure 2(b) with mean of 0 and standard deviation of 1.125. The curve is integrated and the boundary of PMV for 80% satisfaction requirement is determined to be ±1.3. The equation that represents this curve is given in Eqn. (6).

$$PPS^*(PMV) = 0.355\exp\left(-0.395PMV^2\right) \tag{6}$$

Normal distribution is a Gaussian function or better known as the bell curve will have mean equivalent to 0 whereas the variance is equivalent to 1 in standard condition. The result of normalization is a non-standard normal distribution with variance greater than 1 even though the mean fall on 0.

The new normalized model has 80% satisfaction beyond the limit of PMV=±1.0. The increment of ±0.3 PMV for 80% satisfaction is significance as the adaptive theories say that people's thermal expectations and preferences are affected by contextual factor and past thermal histories. When people are adapting to their thermal environment to restore their thermal comfort, the dynamism in this process shall be included in the calculation of PMV. Besides, people living in extreme climate countries will have higher tolerance towards indoor thermal environment [13, 14]. The widened boundary of PMV for 80% gives allowance to the adaptation of humans towards their thermal environment, as explained in the adaptive theories.

Field study result by Yau et al. [24] are used to verify the applicability of the new adaptive Fanger's model in centralized HVAC buildings in Malaysia. The range of metabolism rate and clothing insulation were determined from the field observations done in lecture hall in a university in Perak, Malaysia. For the other thermal parameters such as air temperature, relative humidity and radiant temperature are assumed to abide to the Malaysian Standards, MS 1525:2007. It is estimated about 95% of PMV values calculated based on the above setting and assumptions fall in the range of ±1.3. On the other hand, there is only 67% of PMV fall in the range of ±1.0. Figure 3 illustrates the frequency of PMV values obtained.

Another field study result by Sulaiman et al. [25] is used to verify the applicability of the new adaptive Fanger's model in natural ventilated buildings in Malaysia. Similar assumptions and methodology are applied for this case. It is estimated about 88% of PMV values calculated fall in the range of ±1.3 whereas only 62% of PMV values fall in the range of ±1.0. Therefore, the new proposed PMV range for 80% satisfaction is more applicable to HVAC and NV buildings in the tropical country conditions than the original PMV model.

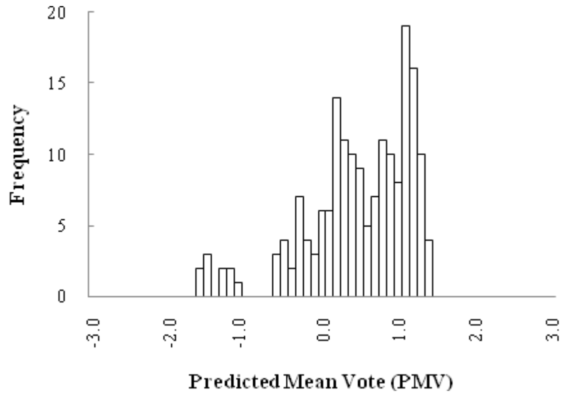


FIG. 3 (a) Distribution of PMV based on Malaysian lecture hall setting with 95% of PMV fall within the range of PMV=±1.3

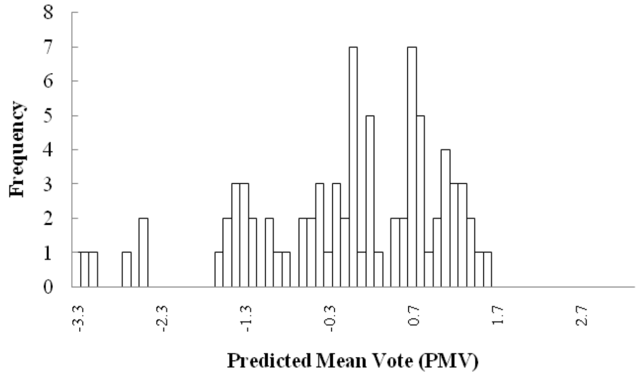


FIG. 3 (b) Distribution of PMV based on Malaysian students hostel setting with 88% of PMV fall within the range of PMV=±1.3.

The 5% of PMV that fall outside the range consist of the case of high clothing insulation, high metabolism rate, low air velocity and at all relative humidity. The 5% also consists of the case low clothing insulation, low metabolism rate, high air velocity and low relative humidity. In practical, people will feel uncomfortably cold when they are wearing thick clothing, doing vigorous activity, no air flow and in a very humid condition. Same goes to the other thermal uncomfortable condition when people are wearing light clothing, doing light work, high air flow and dry air condition.

## V. CONCLUSION

The thermal parameters, metabolism rate and clothing insulation which are considered in Fanger's model has made the model semi adaptive in nature. Fanger's heat balance is a very precise calculation on heat fluxes over the boundary of human body and the thermal environment. Its insufficiency to predict thermal comfort in tropical country can be fulfilled by integrating the adaptive theories into the model. As the adaptive theories say that people's thermal expectations and preferences are affected by contextual factors, such as climate, building, time and thermal histories, there should be a higher tolerances for the limitation of PMV requirements of 80% satisfaction. The increased limitation of PMV for 80% to PMV=±1.3 from the original limitation, PMV=±1.0 gives tolerances to the adaptive mechanism and dynamic fluctuations of thermal preferences in humans. People living in different climate will have different level of tolerance towards indoor thermal environment. The new adaptive Fanger's model has been verified to be applicable in Malaysian HVAC and NV buildings. It is recommended for the adaptive Fanger's model to be applied in Malaysia.

## ACKNOWLEDGMENT

This research is funded by the Ministry of Higher Education Malaysia under the grant FRGS/1/2012/TKO7/UTP/45. The authors would like to acknowledge the financial support given by the MOHE.

## REFERENCES

[1] J. F. Nicol, Cooling in a Low Carbon World. Energy and Buildings, *Building Research and Information*, 2009; **37**(4); pp. 345-347
[2] R. d. Dear, *Thermal Comfort in Practice*. Blackwell Munksgaard, 2004.
[3] R. J. de Dear, M. Fountain and G. S. Brager, Expectations of Indoor Climate Control, *Energy and Buildings*, 1996; **24**(3): pp. 533-536
[4] S. Becker, O. Potchter and Y. Yaakov, Calculated and Observed Human Thermal Sensation in An Extremely Hot and Dry Climate. *Energy and Buildings*, 2002; **35**: pp. 747-756
[5] P. O. Fanger, Thermal Comfort 1970

[6] ASHRAE, ASHRAE Standard 55P-2003: Thermal Environmental Conditions for Human Occupancy, American Society of Heating Refrigeration and Air-conditioning Engineers (ASRHAE), 2003.
[7] Halawa EE. Operative Temperature Measurement and Control. MSc Thesis 1994
[8] R. J. de Dear and G. S. Brager, Developing an Adaptive Model of Thermal Comfort and Preferences. Center for the Built Environment UC Berkeley 1998; **104**(1): pp. 145-167
[9] R. J. de Dear and G. S. Brager, The Adaptive Model of Thermal Comfort and Energy Conservation in the Built Environment. *Int. J. Biometeorol*, 2001, **45**: pp. 100-108
[10] J. F. Nicol, Adaptive Thermal Comoft Standards in the Hot-Humid Tropics. *Energy and Buildings*, 2004, **34**: pp. 563-572
[11] J. F. Nicol, M. A. Humphreys, Adaptive Thermal Comfort and Sustainable Thermal Standards for Buildings. *Energy and Buildings*, 2002, **34**: pp. 563-572.
[12] N. H. Wong, S. S. Khoo, Thermal Comfort in Classrooms in the Tropics. *Energy and Building*, 2002, **35**: pp. 337-351
[13] N. H. Wong, H. Feriadi, P. Y. Lim, K. W. Tham, C. Sekhar, K. W. Cheong, Thermal Comfort Evaluation of Naturally Ventilated Public Housing in Singapore. *Building and Environment*, 2002, **35**: pp. 337-351.
[14] J. F. Nicol, Adaptive Thermal Comoft Standards in the Hot-Humid Tropics. *Energy and Buildings*, 2004, **36**(7): pp. 628-637
[15] A. P. Gagge and A. C. Burton, A Practical System of Units for the Description of Heat Exchange of Man with His Environment. *Science*, 1941, **94**: pp. 428-430
[16] K. W. Mui, W. T. Chan, Adaptive Comfort Temperature Model of Air Conditioned Building in Hong Kong. *Building and Environment*, 2003, 38: pp. 837-852
[17] P. O. Fanger and J. Toftum, Extension of PMV Model to Non-Air-Conditioned Buildings in Warm Climates. *Energy and Building*, 2002; 34: pp. 533-536
[18] P. O. Fanger, Energy and Building. In *Climate Responsive Building*, 1985
[19] O. Victor, Design with Climate. In *Climate Responsive Building*, 1963
[20] A. R. Ismail, S. Singh and C. W. Goh, Thermal Comfort in a Closed Air Conditioned ICT Laboratory at Ungku Omar Polytechnic Malaysia. *National Conference in Mechanical Engineering Research and Postgraduate Students*. Universiti Malaysia Pahang 2010: pp. 555-563
[21] A. R. Ismail, N. Jusoh, R. Zulkifli, K. Sopian and B. M. Deros. Thermal Comfort Assessment: A Case Study at Malaysian Automotive Industry. *American Journal of Applied Sciences*, 2009; 6(8): 1495-1501
[22] R. J. de Dear and G. S. Brager, Thermal Comfort in Naturally Ventilated Buildings: Revisions to ASHRAE Standard 55. *Energy Buildings*, 2002; 34: pp. 549-561
[23] ISO, International Standard 7730 (3): Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. International Standard 2005
[24] Yau YH, Chew BT and Saifullah A. A Field Study on Thermal Comfort in Lecture Halls in the Tropics. ISHVAC. Shanghai: ISI/SCOPUS Cited Publication 2011: pp. 309 – 317
[25] Sulaiman RSW, Ismail MR and Egbal MA. A Case Study of the Climate Factor on Thermal Comfort for Hostel Occupants in Universiti Sains Malaysia (USM), Penang, Malaysia. *Journal of Sustainable Development*, 2011; 4(5): pp50-61