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ANALYZING AND EVALUATING A PMV-BASED THERMAL COMFORT MODEL IN CONTROLLING AIR CONDITIONING SYSTEM

Aidil Sukri Ahmad[a], S. A. Abdul Shukor[a*], Karl Kohlhof[b], Zul Azhar Zahid Jamal[c], Azizul Mohamad[a]

[a]School of Mechatronic Engineering, Universiti Malaysia Perlis, 02600 Perlis, Malaysia
[b]Faculty of Information, Media and Electrical Engineering, Cologne University of Applied Science, 50679 Cologne, Germany
[c]School of Microelectronic Engineering, Universiti Malaysia Perlis, 02600 Perlis, Malaysia

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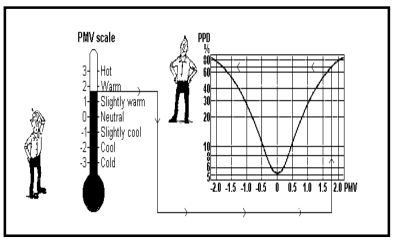
*Corresponding author
shazmin@unimap.edu.my

Graphical abstract



Abstract

The usage of air conditioning system to create a thermally comfortable environment in tropical countries is often a must, not necessarily luxurious any longer. However, the extreme usage of the system will lead towards higher consumption of energy and higher cost. A promising energy efficient model developed based on the Predictive Mean Vote (PMV) is analyzed and evaluated here to distinguish its workability. This model only requires the user to enter their respective PMV value (from -1 to +1) and the respective parameters will be inserted into the air conditioning system, which is based on the standard thermal comfort ISO 7730. Analyses and evaluations were done based on the measurements from human subjects and their feelings towards the surroundings were recorded to see the performance of the model. From here, more than 91% of the subjects agree with the parameters used in defining their thermal comfort. This proves the workability of the model towards controlling the air conditioning system in creating a thermal comfort ambience at lower energy consumption, and further simulative investigations are appreciated before implementation.

Keywords: Thermal comfort, Predicted Mean Vote (PMV), air conditioning system

Abstrak

Penggunaan sistem penghawa dingin di negara-negara tropika tidak lagi melambangkan kemewahan, malah amat diperlukan. Walau bagaimapun, penggunaan terlampau boleh menyebabkan penggunaan tenaga dan kos yang tinggi. Satu model berdasarkan PMV dianalisa dan dinilai di sini untuk mengenalpasti keupayaannya. Model ini hanya memerlukan pengguna untuk memasukkan nilai PMV (dari -1 ke +1) dan parameter yang sesuai akan dikenalpasti untuk mengawal sistem penghawa dingin, berdasarkan kepada piawaian keselesaan terma ISO 7730. Analisis dan penilaian dibuat berdasarkan subjek manusia dan keselesaan mereka dicatatkan untuk menilai keupayaan model. Hasil kajian menunjukkan lebih daripada 91% daripada subjek bersetuju dengan parameter yang digunapakai oleh model. Ini membuktikan keupayaan model dalam mengawal sistem penghawa dingin untuk keselesaan terma pada penggunaan tenaga yang lebih rendah, dan kajian simulasi pada masa hadapan amatlah dihargai sebelum perlaksanaan.

Kata kunci: Keselesaan terma, Predicted Mean Vote (PMV), sistem penghawa dingin

1.0 INTRODUCTION

Thermal comfort has always been an important aspect in human life, as it contributes towards health and welfare of human beings. Thermal comfort is being defined as a condition of mind that expresses satisfaction with the thermal environment [1]. The physical basis of comfort has been influenced by the thermal balance of the body. The heat produced by the body's metabolism must be dissolute to the environment. Otherwise, the body would overheat. In other word, if the rate of heat transfer in higher than the rate of heat production, the body cools down and we feel cold; if the rate is lower, we feel hot [2].

There are several parameters that could contribute towards human thermal comfort, which includes physiological condition like clothing and activity of human, as well as physical factors like room air velocity, relative humidity and temperature. The physical factors are usually measured by the electronic of the comfort climate conditions. When the parameters are measured properly, the air conditioning system could be used to control the room's air draft to generate a thermally comfortable condition in the room.

In summer or for tropical countries like Malaysia, the use of air conditioners and fan are very essentials in creating thermal comfort inside a room. The occupants would set the degree of cooling and fan speed according to her/his choice intention and they have higher tendencies to set into maximum cooling, which yield to uncomfortable climate problem according to the standard as well as consuming extra energy and cost. Furthermore, this may not guarantees thermal comfort achievement [3].

To overcome the above problem, researchers in [4] have developed a smart thermal comfort model based on the PMV value. According to this model, users just need to define their desired thermal sensation value, from +1 (slightly hot) to -1 (slightly cold). From here, respective value of air conditioning system can be determined and be used to create a thermally comfortable environment as defined by the operators. However, this model has not been proven yet on its workability. Therefore, it is good to have a research work to analyze and evaluate the effectiveness of this model before it can be implemented in the real air conditioning system, as it has a lot of advantages that can be exploited.

There are several existing methods developed in helping people to create a thermally comfortable environment indoors. In [5], the aim is to investigate the difference between a floor heating system and a wall-mounted air conditioning unit in terms of the thermal sensation and the energy consumption using the coupled simulation of convection-radiation-thermoregulation. However, the difficulties in getting the measurement values at the same postures and positions do not guarantee its workability.

Thermal radiation and human body thermoregulation were used by [6] to predict human thermal sensation, while in [7], building materials were studied as part of thermal energy storage in determining efficient heating and cooling of buildings, but they carries long-term thermal behavior that might not suitable for lifelong thermal comfort.

There are also a number of surveys conducted in verifying the suitable thermal comfort conditions that can be applied. However, most of them were conducted only to find out the suitable and preferred temperature / parameters for tropical countries like Malaysia and Singapore [8] [9] and during summer in Japan [10] and Australia [11], while some did the survey to find out a suitable model that can be applied towards specific place such as India [12] and Japan [13].

Due to the above gap in current literature, this research is conducted with the following objectives:

i) To determine the thermal comfort of users in small room in tropical countries, specifically in Arau, Perlis, Malaysia area
ii) To investigate occupants' perception of thermal comfort on current controlling method of the air conditioning system
iii) To prove on the workability of the selected PMV-based model

In this research, survey is being done as it is the best technique to obtain the data authentically and accurately in achieving these objectives.

2.0 PMV-BASED THERMAL COMFORT MODEL

The PMV-based model used here is developed by Shukor, *et al*. [4] in 2007. The model adapts the thermal comfort equations as derived by Fanger in 1972 [14], where six parameters are used in defining human's thermal comfort – air temperature, air velocity, humidity, mean radiant temperature, person's activity and clothing level. PMV works on a scale ranging from -3 (cold) to +3 (hot), where 0 represents the thermally neutral sensation (refer Table 1). Fanger also introduced the Predicted Percentage of Dissatisfied (PPD) index when PMV is applied, which represents the relationship of PMV with the percentage of occupants who may not satisfied with the value. Although the percentage will not get below 5% of dissatisfaction as according to Fanger [15], but in this model, PPD is not relevant as the model concentrates towards the application for small indoor areas (with around two / three occupants). Figure 1 shows the relationship of PMV with respect to PPD.

Table 1 The thermal sensation scale of PMV

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

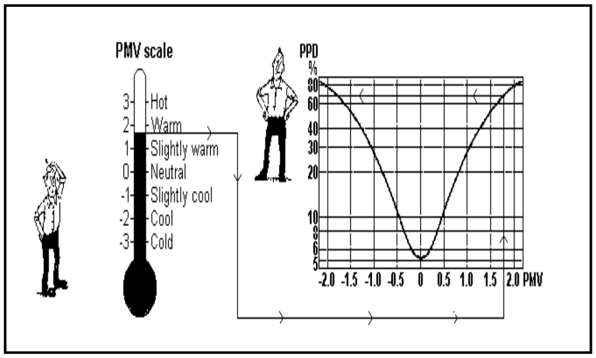


Figure 1 The relationship of PMV with PPD [15]

PMV is being defined as [14]:

$$PMV = (0.303e^{-0.036M} + 0.028)[(M - W) - H - E_c - C_{res} - E_{res}] \quad (1)$$

where, the fulfillment of body's energy balance need to be considered to maintain thermal comfort. Body energy balance stated that the heat produced by the metabolism should be equal to the amount of heat loss from the body [15]:

$$Heat\ produced\ in\ body = Heat\ lost\ from\ body$$
$$M - W = H + E_c + C_{res} + E_{res} \quad (2)$$

where:
M = metabolic rate
W = effective mechanical power
H = dry heat loss
E_c = evaporative heat exchange at the skin
C_{res} = respiratory convective heat exchange
E_{res} = respiratory evaporative heat exchange

Draught rate, DR, is also important as it is needed to determine turbulence, Tu, in [15]:

$$T = 34 - [(DR/(v - 0.05)^{\wedge}0.62\ )/(37v(Tu/100) + 3.14)] \quad (3)$$

where:
T = air temperature
v = air velocity

However, in this model, some of the parameters are fixed:
i) Mean radiant temperature, t_r = 25°C
ii) Clothing level, I_{cl} = 0.155 m²°C/W
iii) Person's activity, M = 58.15 W/m²
iv) Effective mechanical power, W = 0 W/m²
v) Turbulence, Tu = 0%

This is due to several reasons / assumptions:
i) The model is developed specifically to be applied for indoor applications in tropical countries / summer time, which reflects the mean radiant temperature and the respective clothing level value. Plus, air conditioning system is usually used as the mechanism to create the thermal comfort ambience.
ii) Occupants are mostly doing sedentary work, which in return, shown in the values of person's activity and effective mechanical power.
iii) Turbulence of 0% is due to its availability in offering lower energy consumption.

All these values are set based on standards as described by the International Organization of Standardization (ISO) Geneva and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [1] [16]. More details on the development of the model can be referred to [4] and [17].

The uniqueness of the model which makes it chosen to be tested and applied here is how it works in controlling the air conditioning system to create a thermal comfort surroundings based on the user's desire. Instead of the normal operation of the system which requires users to define their own air temperature and air velocity of the system, here, users are only requested to insert the value of their longing thermal comfort (from -1 to +1, with 0.5 increment / decrement to suits geographical background applications) – i.e., if they want a slightly warm ambience, they can insert +1 to the controller; on the other hand, if they just arrived from somewhere hot and need coolness, they can just press -1 for a slightly cool environment. From these values, plus with information on current's relative humidity, RH, the model will determine the suitable parameters (air velocity and air temperature) that can be used in order to ensure the air conditioning system works accordingly. By doing this, it actually could make the air conditioning system to work efficiently, as people tends to put it into maximum coolness, which lead into higher energy consumption at higher operating cost.

Figure 2 shows on the final operating model that can be used to control air conditioning system. The model has been set to have 100% operation at 16°C air temperature, 0.5 m/s air velocity (fan speed) and 0% operation at 28°C air temperature, 0.0 m/s air velocity, which is based on average working operation of an air conditioning system. Meanwhile, the working region is being categorized accordingly to make sure all available air temperature and velocity range are considered.

Taking an example of functionality of the model at RH = 70% (as shown in Figure 2), it can be observed that for a PMV = 0 (neutral), the air conditioning system should be operated at 50.75% on of the cooling (air temperature ≈ 22°C) and 55% on of the fan (air velocity ≈ 0.275 m/s). By applying these, the energy consumed and the operating cost of the air conditioning system can be reduced dramatically.

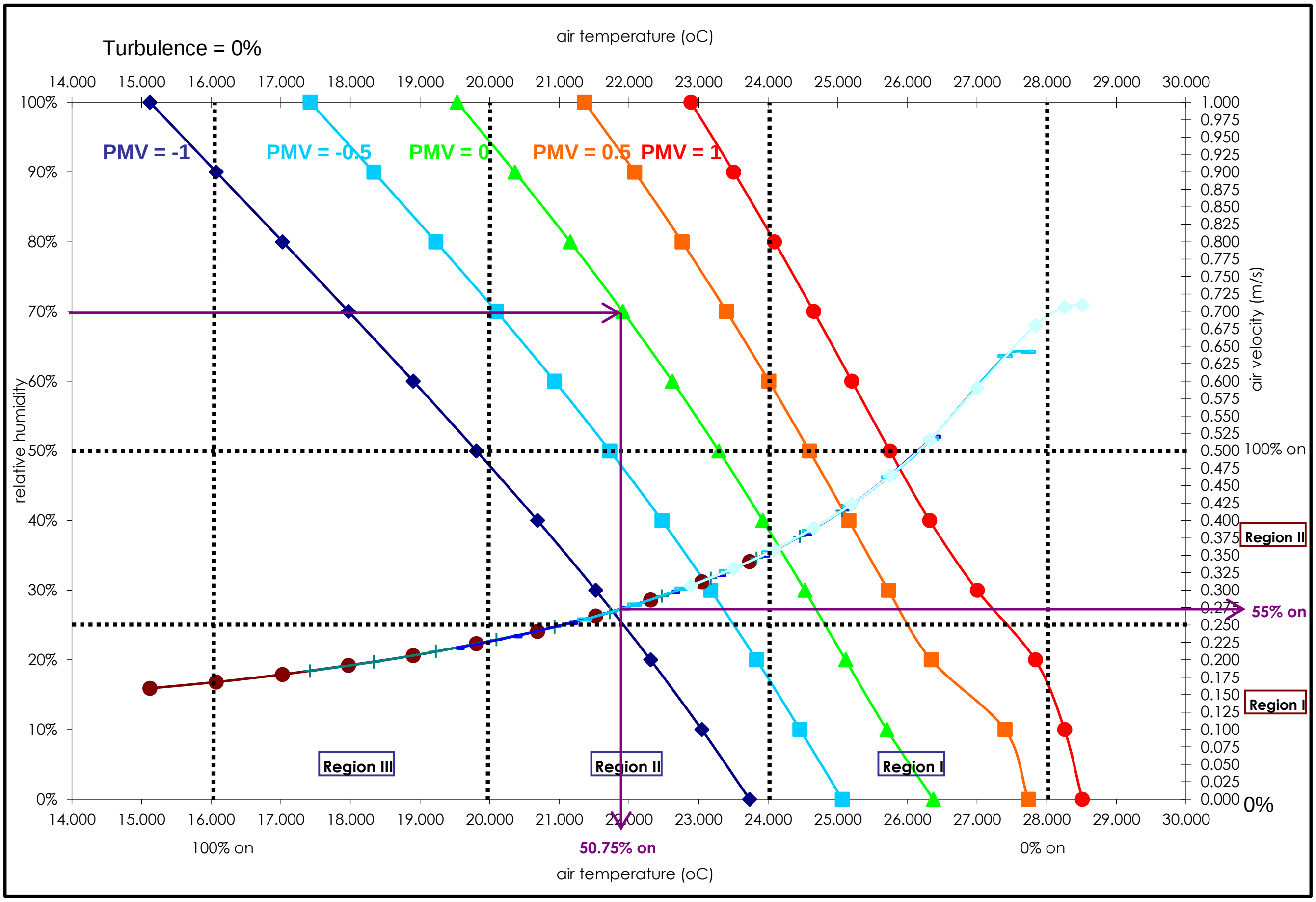


Figure 2 The final operating model, with an example of functionality at RH = 70% for PMV = 0 [4]

3.0 THE SURVEY

3.1 The Selected Room

One of the main objectives in this research is to test the workability of the selected model, before it can be applied further into the air conditioning system. Thus, a room in the School of Mechatronic Engineering, Universiti Malaysia Perlis was chosen to test the model. The room size is 4.7 m x 3.7 m x 2.8 m, which represents most of the available room here that can occupy up to three persons at one time. Natural lighting source is focused only on one side of the exterior windows and a 1 hp air conditioning system is located above the windows. There is no other object that could produce heat available in the room. Figure 3 shows the interior of the selected room.

3.2 The Subjects

Analyses and evaluations of the model are done based on the measurement taken from 12 subjects in 20's of age from Universiti Malaysia Perlis. Subjects' genders were chosen randomly and there were equal numbers of male and female subjects (6 each). They had variety distributions of weight and height, between 54 kg – 70 kg in weight and 156 cm – 173 cm in height. Some of them wore lab jacket, which is part of the university's uniform. Although the number of subjects is considered as small, their age group represents the highest room occupants here at the university, and they have higher metabolic rates compared to the older people [18]. Details of the subjects are as in Table 2.

Figure 3 The selected room

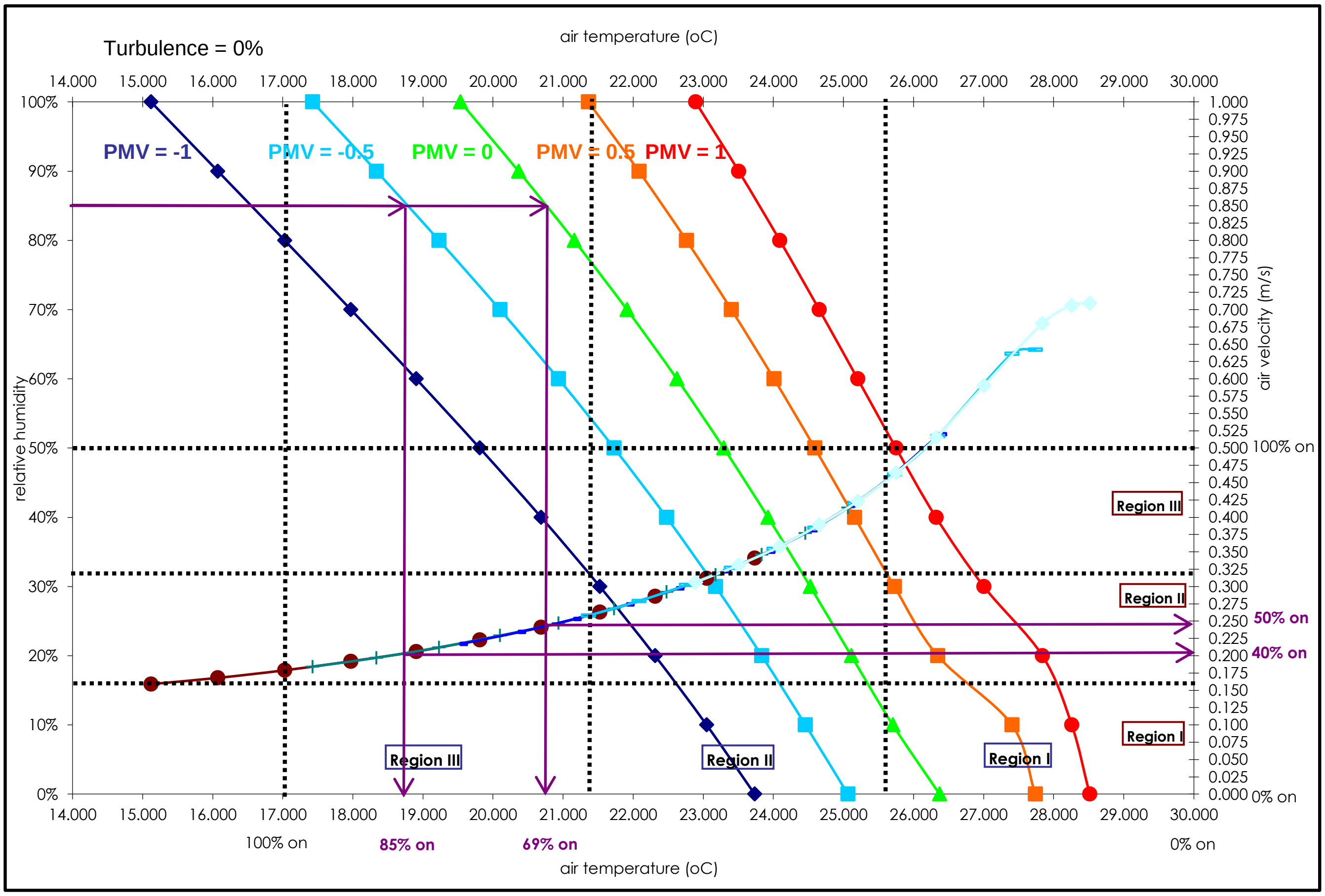


Figure 4 The newly changed model to suits the equivalent air conditioning system used in this survey

Table 2 Details of subjects

Subject No	Gender	Height (cm)	Weight (kg)	Jacket
1	Female	156	54	Yes
2	Female	156	58	No
3	Male	166	70	Yes
4	Female	160	52	No
5	Female	163	52	Yes
6	Female	163	60	Yes
7	Male	173	68	No
8	Male	160	69	Yes
9	Male	169	69	No
10	Male	165	80	Yes
11	Male	170	55	No
12	Female	165	58	No

3.3 The Data Collection Process

The data collection is being done on 20 May 2015 at 11.00 am for 2 hours, considering the time where the hot weather is at the peak. RH is being set at 85%, based on the average reading by Chuping Meteorological Station, Perlis [19]. Before the data collection process, the air conditioning system is set into maximum cooling – 17°C at maximum fan speed – which is the typical setting here[1].

The final operating model in Figure 2 is altered to match the air conditioning system's operation (from 17°C to 30°C, with three settings of fan speed – minimum, medium and maximum). Figure 4 above shows the same graph with slightly different working region to make it equivalent with the air conditioning system, while Tables 3 and 4 summarizes the working regions.

Table 3 Region of operation for air temperature

Air temperature (°C)	Region
30.00 – 25.67	Region I
25.68 – 21.35	Region II
21.35 – 17.00	Region III

Table 4 Region of operation for air velocity

Air velocity (m/s)	Fan speed	Region
0.00 – 0.16	Minimum	Region I
0.17 – 0.32	Medium	Region II
0.33 – 0.50	Maximum	Region III

[1] Based on author's observations

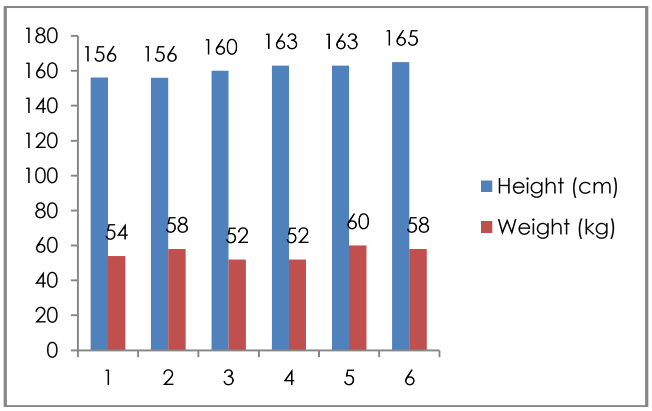
Subjects were then invited into the room and being placed nearby the air conditioning system. Questions were then being asked in collecting the data:

i) How are you feeling with the ambience now? (which reflect current comfortability with maximum cooling)
ii) From slightly cool (-1) to slightly warm (+1) range, how would you rate your desired comfort? (this is to get subject's opinion on what range should he / she enter to the air conditioning system in creating his / her desired thermal comfort ambience)
iii) How are you feeling with the ambience now? (which reflect on the new setting of air conditioning system)

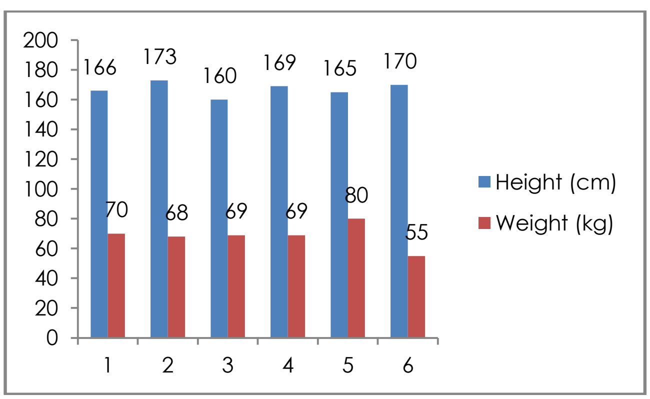
A moderately idle time was taken before question 3 was being asked to ensure the correct ambience was felt by the subject.

4.0 RESULTS AND DISCUSSION

Figure 5 and Table 4 summarizes the background of the selected subjects.



(a)



(b)

Figure 5 The distribution of subjects according to height and weight for (a) female, and (b) male

Table 4 Statistical summary for height and weight distributions of subjects for (a) female, and (b) male

Parameters	Mean	Minimum	Maximum	Standard Deviation
Height (cm)	161	156	165	3.83
Weight (kg)	56	52	60	3.44

(a)

Parameters	Mean	Minimum	Maximum	Standard Deviation
Height (cm)	167	160	173	4.54
Weight (kg)	69	55	80	7.97

(b)

When the first question is being asked, at the air conditioning system setting of maximum cooling (17°C at maximum fan speed), two male subjects reported to feel uncomfortable / warm with the settings, while others feel comfy, which contributes towards 17% of dissatisfaction towards comfortability among all the subjects (33% out of all six male subjects). Upon observations, both subjects were wearing jacket and based on their details, their Body Mass Index (BMI) is above normal / overweight (subject 8 and 10 from Table 2). These could contribute towards uncomfortability feelings towards the ambience. Furthermore, some of the subjects have time to settle down outside the room before being called in, whereas others just came straight to the room upon arriving (after walking from somewhere else). Figure 6 shows the histogram of all subjects with respect to their comfortability with maximum cooling settings.

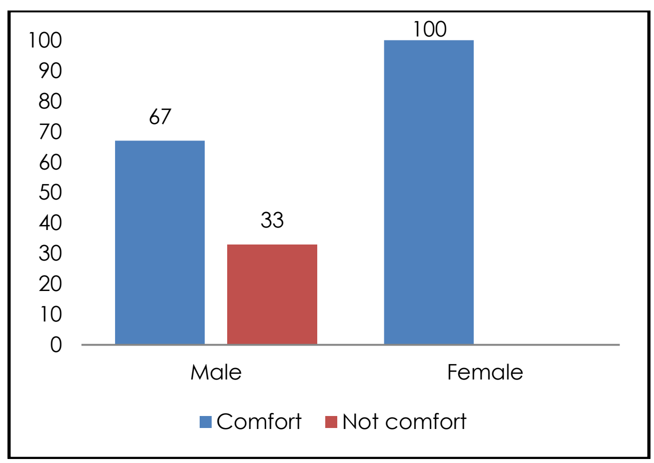


Figure 6 The distribution of subjects' comfortability (in percentage) towards maximum cooling according to their gender

Upon asking about their desired comfort range, 83% of the subjects wanted to have normal / neutral scale as according to the existing ambience (PMV = 0), whereas the previous 17% whom feel uncomfortable with the surroundings (subject 8 and 10) asking for more coolness (PMV = -0.5). Therefore, the air conditioning system was changed accordingly as the model suggested (refer to Figure 4). Table 5 summarizes the subjects' desired comfort and the changes taken to suit their needs while Table 6 shows the settings of the air conditioning system.

Table 5 Summary of changes to the air conditioning system taken to suit subjects' desires

Subject No	Desired Comfort	PMV	Original setting		New setting	
			Air temperature (°C)	Fan speed	Air temperature (°C)	Fan speed
1	Neutral	0	17	Maximum	21	Medium
2	Neutral	0	17	Maximum	21	Medium
3	Neutral	0	17	Maximum	21	Medium
4	Neutral	0	17	Maximum	21	Medium
5	Neutral	0	17	Maximum	21	Medium
6	Neutral	0	17	Maximum	21	Medium
7	Neutral	0	17	Maximum	21	Medium
8	A bit cool	-0.5	17	Maximum	19	Medium
9	Neutral	0	17	Maximum	21	Medium
10	A bit cool	-0.5	17	Maximum	19	Medium
11	Neutral	0	17	Maximum	21	Medium
12	Neutral	0	17	Maximum	21	Medium

Table 6 The new operating value for the air conditioning system as defined by the PMV-based model

Comfort Level	PMV	Air temperature (°C)	Region	Air velocity (m/s)	Region
Normal / neutral	0	21	III	0.250	II
A bit cool	-0.5	19	III	0.200	II

After a while, Questions 3 is being asked to discover their feelings with respect to the new air conditioning system setting. It has been found out that almost 92% of all the subjects agrees on the new settings and believe that it can be used to create thermally comfortable surroundings. This also includes those two subjects who required a bit cool environment. Only one subject (Subject 11) who felt uncomfortable with the new setting, and wished for a slightly cooler surrounding. This may be due to the sudden rise of temperature as it was approaching noon, or some other factors such as uncomfortability towards the physical setting of the room, or not comfortable with the overall survey process. Figure 7 shows the histogram of all subjects with respect to their comfortability with the new air conditioning system settings.

From here, it can be observed that this newly adapted PMV-based model has a big potential to be applied in controlling air conditioning system to create a thermally comfortable environment, specifically for a small room application. This has proven that at a slightly higher temperature with half of the fan speed, the same thermal comfort ambience can be achieved instead of controlling the air conditioning system at 100% operation. From Figure 4, it can be seen that the air conditioning system can be operated at 85% on for the cooling (40% on for fan speed) to create a bit cool ambience, and 69% on for the cooling (50% on for fan speed) to create a neutral ambience, which is at reduced energy consumption and at a lower cost compared to the original setting of maximum cooling.

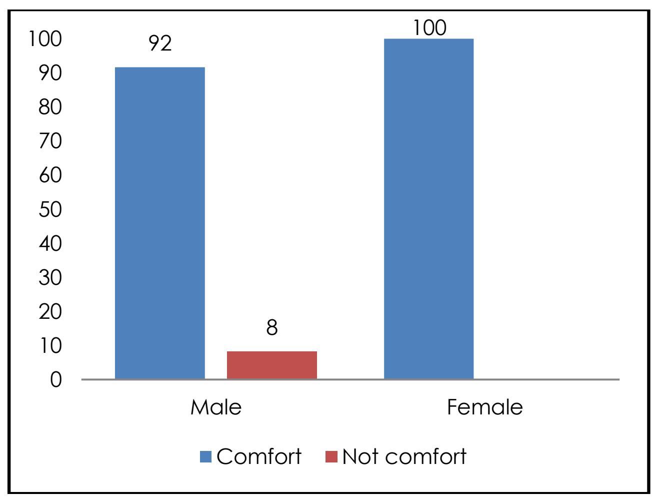


Figure 7 The distribution of subjects' comfortability (in percentage) towards the new air conditioning system setting based on the selected model according to their gender

5.0 CONCLUSION

Developing a thermally comfortable environment in a closed area is very important to establish healthy, comfy and happy surroundings for human. Without a comfortable environment, one may find it is hard to concentrate to do work which associates with the room and furthermore, it can create illness that may affect human welfare. This paper, which focusing on the survey conducted on human subjects, has proven that the chosen PMV-based model can be used to control air conditioning system in creating a thermally comfortable ambience. Since existing, traditional controlling method has tendency for the occupants to set into maximum cooling, which consume more energy at higher cost, to have an alternative in controlling the air conditioning system would be very much welcomed. Further analysis like simulation-based is appreciated, as supplementary verification on the applicability of the model before implementation.

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