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Human Responses to the Thermal Comfort in Air-Conditioned Building: A Climate Chamber Study

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Abstract: One of the challenges for engineers in designing comfort indoor environments is merging the need of energy savings and thermal comfort of the occupants. However, to assess complex heterogeneous environments created by novel building systems, there is a need for choosing more sophisticated and precise tools. There are many best ways to evaluate thermal comfort, at the same time the most cost and time-consuming one, various modelling tools are widely used. In this paper, we present a human climate chamber as a methodology for indoor environmental research, to predict the thermal comfort. Along with presenting this methodology, the human climate chamber was demonstrated on five supply temperature representing the indoor environment such as conditions for which thermal sensation was predicted with satisfactory accuracy. Based on the presented results, the overall thermal sensation on the body will be influenced mainly by those body segments that have a greatest thermal sensation under different condition's environment (supply temperature). The overall thermal comfort will follow the warmest environment (26 ºC and 29 ºC) and the coldest in a cool environment (19 ºC and 23 ºC). Furthermore, the overall thermal comfort will closely follow the parts of the body that feel the most uncomfortable in a cool or warm environment. The study found that supply temperature at the 23 ºC indicates that the PMV is comfortable. The value of PMV in a supply temperature set at 23 ºC is 0.26. This study contributes to the body knowledge of thermal comfort towards human in the building.

Keywords: Thermal comfort, climate chamber, air conditioned, PMV/PPD index

1. Introduction

As people in developed countries such Malaysia spend a vast majority of their time indoors [1], it is of paramount importance to design comfortable indoor spaces to ensure the well-being and health of occupants, and thus support productivity at work. New heating, ventilation and air-conditioning (HVAC) systems are nowadays developed in order to reduce the energy demand of buildings. They often make use of the benefits of not conditioning the entire building volume homogeneously, sometimes creating strongly heterogeneous environments [2], which supports the decrease in energy use while still providing acceptable conditions for the occupied areas (e.g., chilled ceiling, radiative panels, personalized ventilation as well as combinations of systems). Additionally, elements of building design such as glazing or solar shades contribute to the complexity of the indoor environmental conditions. Therefore, engineers and designers have to include energy saving strategies while creating thermally comfortable indoor spaces. In a traditional approach

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to indoor spaces' design, occupants are considered as heat sources (together with heat gains from equipment or light [3]) whose presence may influence the desired thermal conditions and air flow in the room. A more user-centered approach shifts the interest towards how the environment influences the occupants' thermal perception and, more specifically, what element of the system might be the source of their discomfort. In the case of existing buildings where uncomfortable conditions are reported, a direct enquiry gives the opportunity to track the source of the problem: occupants can not only state how much discomfort they feel, but also give some precise information related to their individual work space (e.g., feeling of draught at the neck, excessive sun radiation, etc.). In order to adopt a similar approach at the design stage of buildings or new HVAC systems, a human subject study can be performed in a model environment or mock-up, including asking the subjects for thermal sensation and comfort feedback. However, such studies are costly and time-consuming, and ethical committee approval must be obtained prior to the trials, which requires longer study execution periods. Other possibilities to assess the thermal perception of the surrounding environment bring into play modelling solutions with various level of complexity.

In the last decade, a new type of tool has been developed, defined as a human climate chamber with thermoregulation model control, consisting of a physical manikin coupled to a model of human thermo-physiology. The thermoregulation model connected to the manikin predicts the human thermo-physiological response based on real-time data exchange with the thermal manikin, enabling a realistic skin temperature. The human climate chamber could be a good source of thermo-physiological input values for a thermal sensation model, which makes it a promising tool for engineers to design thermally comfortable indoor spaces. Although several thermo-physiological human climate chamber based on full-body manikins have been developed up-to-date [8], most of them were developed and used in clothing research or the manufacturing industry. The existing systems include a thermoregulation model coupled to a single-sector simulator [9]-[11], a full-body manikin [12]-[21], or a body-part manikin (human head manikin) [22], [23]. Most of the existing full-body human climate chamber have been validated only qualitatively and/ or with a limited number of validation cases (up to 8 validation cases by the system [10], [12], [14]-[21] according to Psikuta et al. [8]) and without evaluating the individual components of the simulators. None of the systems has been evaluated with regards to using it for thermal sensation predictions indoors.

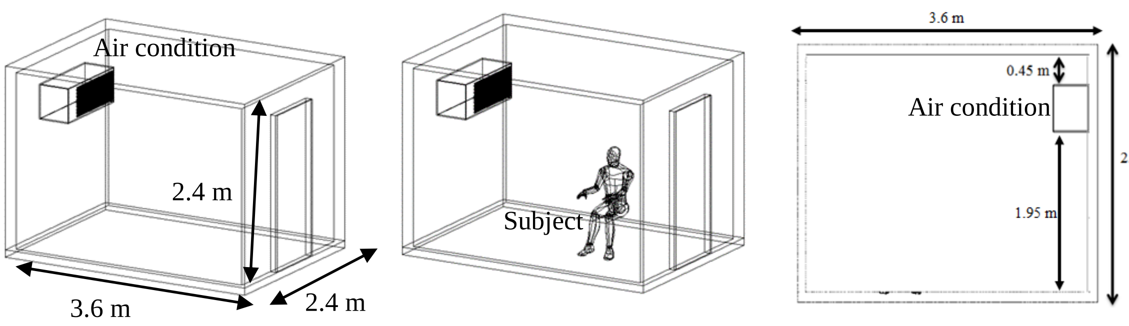
In this paper, a methodology for performing human climate chamber tests in the indoor environment to predict occupants' thermal comfort is presented. This study also can be applied to support the design process of buildings or to evaluate spaces in the room. The thermal sensation predictions were computed based on two models using thermo-physiological input parameters, namely, the DTS by Fiala [4], [5] and the TS by Zhang [6], [7]. Additionally, thermal sensation predictions were calculated based on a purely virtual simulation, that is, with the thermoregulation model as the direct source of input for the thermal sensation models.

2. Methodology

The overall methodology used in this study involves a controlled human climate chamber where the subjects were exposed to a different temperature. Meanwhile, thermal comfort votes were collected from the subjects. Details of methodology in the following subsections.

2.1 Human Climate Chamber

This study was designed to controll conditions of the climate chamber. In order to achieve this model indoor environment has been built in the climate chamber. The experiments were carried out at the Workplaces Ergonomic Simulator Chamber (WES-103) in Universiti Malaysia Pahang (UMP). Fig. 1 shows the model of the indoor environment in the climate chamber. For this study, the York Prestige Ceiling type of air conditioner was used to explore the environment climate in the chamber. This chamber is ideally suited for using in the hot and humid region. The dimension of this air conditioner is 21.8 cm × 108 cm × 63 cm and the chamber only for one person capacity. The material of the climate chamber is Polyurethane insulated panels. Table 1 presented the details of the specification of the climate chamber. Fig. 2 shows the equipment for the measurement of all the various parameters defining the quality of an environment from the thermal, sound, illumination and chemical.



(b)

(a) (c)

Fig. 1 - The layout of the environmental chamber: (a) Environmental chamber with empty; (b) Environmental chamber with occupied; (c) Environmental chamber in side view

Table 1 - Specification of human climate chamber

Property	Result
Density	40-45 kg/m^3
Thermal conductivity	0.017 W/mK
Compressive strength	180-250 kPa
Thermal coefficient	0.239-0.151 W/(mK)
Operating temperature	-68 to 121 ºC

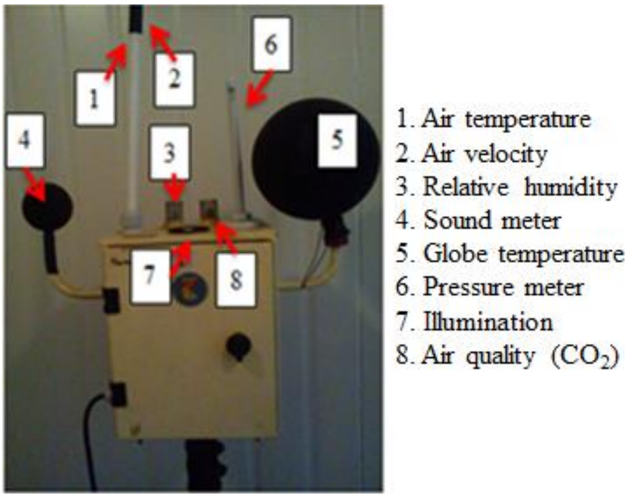


Fig. 2 - Equipment for environmental measurement.

2.2 The subject

The summary statistic, as illustrated in Table 2 to help make the important features of a data of subjects stands out. Two most widespread used in summary statistics are the mean and the standard deviation. The mean indicates the centre of the data of subjects, and the standard deviation indicates how to spread out the data subject [24].

Table 2- Comparison summary of demographic information by the subjects with previous study.

Variables	Choi & Loftness [25]	Zhai et al. (2015) [26]		Present study	
Sex	**All**	**Male**	**Female**	**Male**	**Female**
Age (years)	27	26	23	25	24
Weight (kg)	67.4	177	169	72	59
Height (cm)	171	75.2	59.8	165	158
BMI	22.8	24	21	26.5	23.8
A_{DU} (m^2)				1.79	1.60

All 15 subjects were used in this study to measure thermal comfort in air-conditioned building. Table 3 present five supply temperature used in this study (19, 21, 23, 26 and 29ºC). While Fig. 3 show the experiment arrangement in this study. The climate chamber represents an office room whereby the subjects doing multitask such as sitting, writing and printing during study in different supply temperature. All the subjects entered the chamber and spent 10 min to test acclimatize with the room temperature. The task was repeated with five supply temperature setting and it is taken 10 min for one supply temperature and one subject.

In this study, there are five supply temperatures was selected as showed in Table 3. This temperature was selected because in Malaysia, the temperature at 19-23°C was cool and the temperature at 24-29°C was hot. So, in the range of temperature, the authors are looking for a suitable temperature for use in Malaysia's building. So, in this study, the authors observed how the supply temperature changes influenced the human body comfort and thermal sensation.

Table 3 - Supply temperature

No.	Supply temperature, °C
1	19
2	21
3	23
4	26
5	29

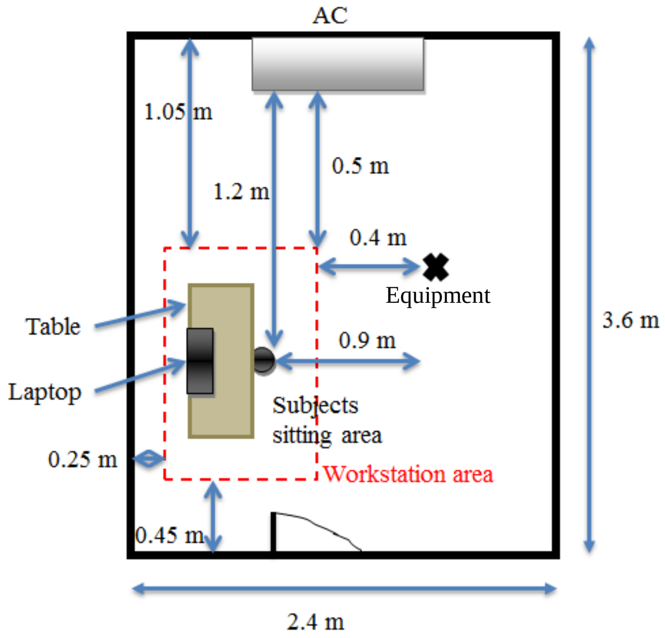


Fig. 3 - The experiment spatial arrangement

All the controls and environmental data collection will be supervised properly and regularly during the study and the data collected in this study were analyzed using Minitab Software.

3. Results and Discussion

Results are obtained in empty and occupied room cases to show the effect of human occupation in a ventilated room on parameters such as radiant temperature (Tr), air temperature (Ta), air velocity (v), PMV and PPD indices.

3.1 Radiant Temperature

Fig. 4 compares the results radiant temperature of non-occupied and occupied under different supply temperature. The graph shows that there has been a steady increase in the five-supply temperature. There were different results between non-occupied and occupied, which is radiant temperature higher when the chamber is occupied. The higher different between non-occupied and occupied is room temperature at 19°C which is 3.1°C. At room temperature 26°C, the difference is 0.8°C and smaller than other room temperatures. The different room temperatures at 21°C, 23°C and 29°C are 1.8°C, 1.0°C and 1.3°C, respectively.

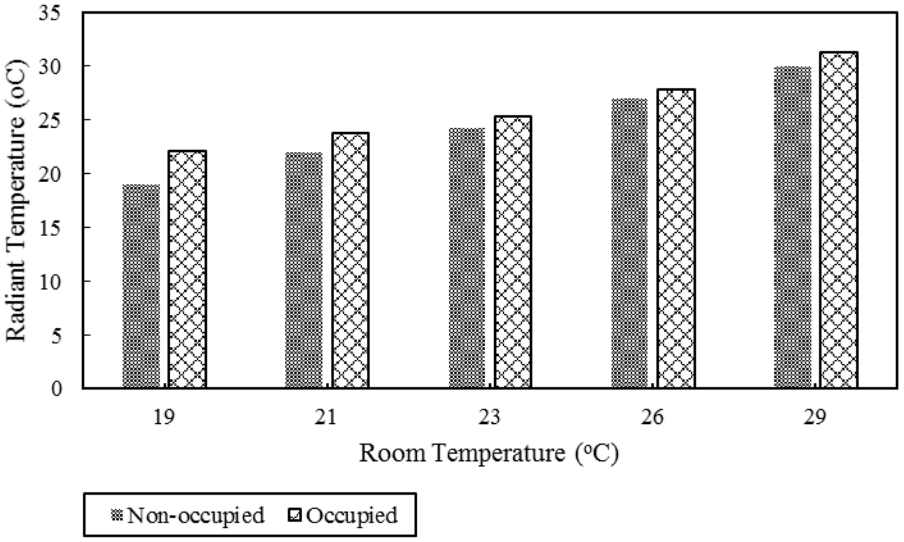


Fig. 4 - Change in radiant temperature of non-occupied and occupied under different room temperature

3.2 Air Temperature

Fig. 5 shows the results air temperature of non-occupied and occupied at different room temperatures. The supply temperatures at 19°C and 26°C of non-occupied space are higher than the occupied. The differences are 0.8°C and 0.3°C, respectively. The minimum air temperature difference is at a room air temperature of 21°C and 23°C, which is 0.1°C. Meanwhile, the different temperature at room temperature 29°C is 0.8 °C. The results of air temperature in this study showed that they're not significantly different, non-occupied and occupied. Fig. 5 also indicates that the higher the supply air temperature, the faster the air temperature rises.

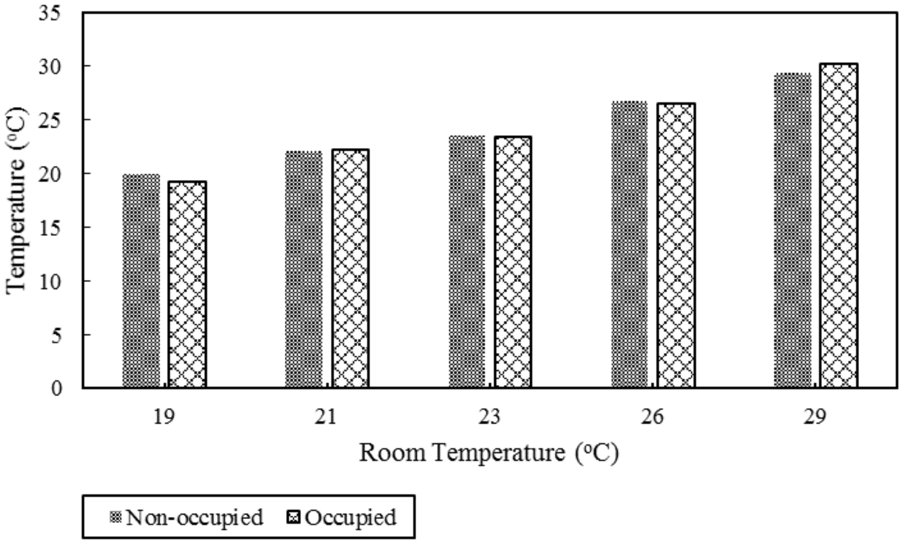


Fig. 5 - Change in air temperature of non-occupied and occupied at different room temperature

3.3 Air Velocity

The air velocity is one of the important parameters for the human thermal comfort; increased air velocity will aid the evaporation of sweat thus leading to a cooling effect, mainly if loose clothing is worn [27]. However, if the air velocity is too high, it may cause discomfort and a sensation of draughtiness. Fig. 6 shows a comparison of air velocity at each supply air temperature between non-occupied and occupied space. It shows that supply temperature at 21°C, 23°C and 26°C for non-occupied is higher than the occupied space, which are 0.16 m/s, 0.22 m/s and 0.08 m/s respectively. Meanwhile, at a supply air temperature of 19°C and 29°C show that occupied space velocity is higher than non-occupied spaces which are, 0.12 m/s and 0.21 m/s respectively. The air velocity trend shows non-uniform, although the temperature supply is the increase. There is a clear trend that the higher the Met, the preferred air velocities are lower.

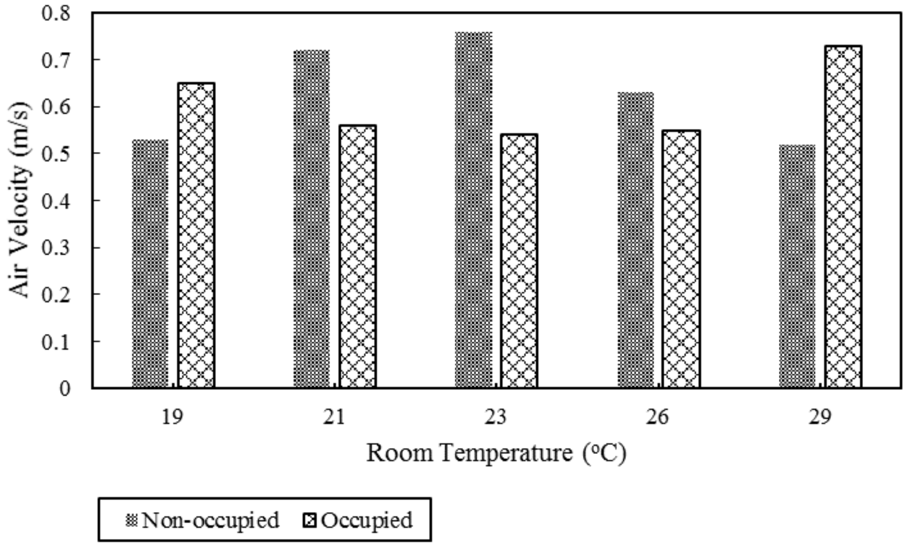


Fig. 6 - Change in air velocity of non-occupied and occupied under different room temperature

3.4 PMV

In order to evaluate the thermal comfort, a subjective and comprehensive index, PMV (predicted mean vote) proposed by Fanger [28] is used to quantitatively assess the thermal sensation of occupants by combining the environmental factors with human factors [28]. The PMV means the expected mean value of the thermal sensation votes of a large group of occupants in a sensation scale expressed from -3 to +3 corresponding to the categories ‘cold’, ‘cool’, ‘slightly cool’, neutral’, ‘slightly warm’, ‘warm’, and ‘hot’. Fig. 7 shows that comparison PMV under different room temperature between non-occupied and occupied. The result PMV shows that non-occupied is higher than occupied. Supply temperature at 19°C and 29°C is almost warm. Meanwhile, supply temperature 21°C and 26°C are slightly warm. Supply temperature at the 23°C indicates that the PMV is comfortable. From this, it is clearly identified that the temperature at 23°C is comfort.

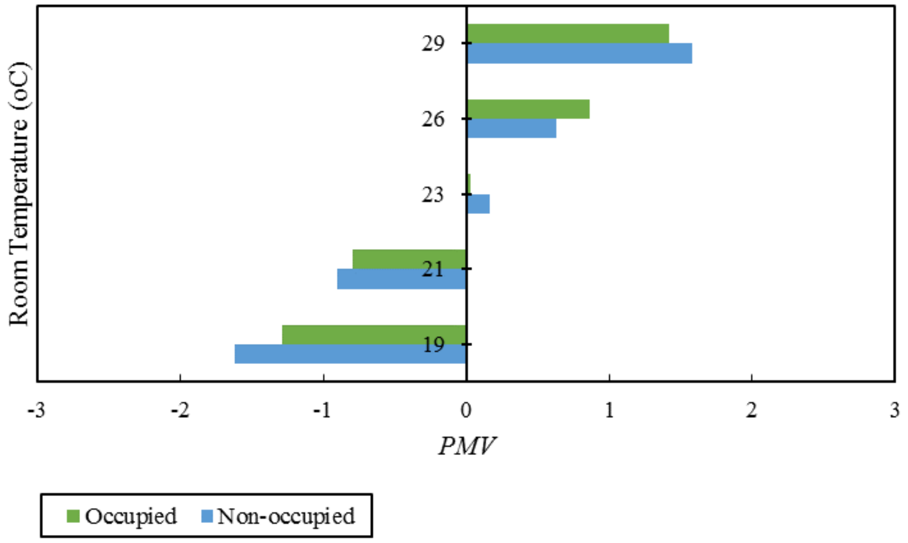


Fig. 7 - Change in PMV of non-occupied and occupied under different room temperature

3.5 PPD

PPD is the reflection from PMV. PPD is aimed to predict how many people feel uncomfortable due to a particular thermal condition in a room. Fig. 8 shows that comparison PPD under different room temperature between non-occupied and occupied. Supply temperature at 19°C and 21°C shows that PPD non-occupied is higher than occupied and the other is occupied higher than non-occupied. The supply temperature at the 23°C shows that PPD is lower than 20 %, this result indicates that 80 % are satisfied with the environment. At the 29°C of supply temperature, 40 % satisfied with that environment, which means 60 % dissatisfied with that environment.

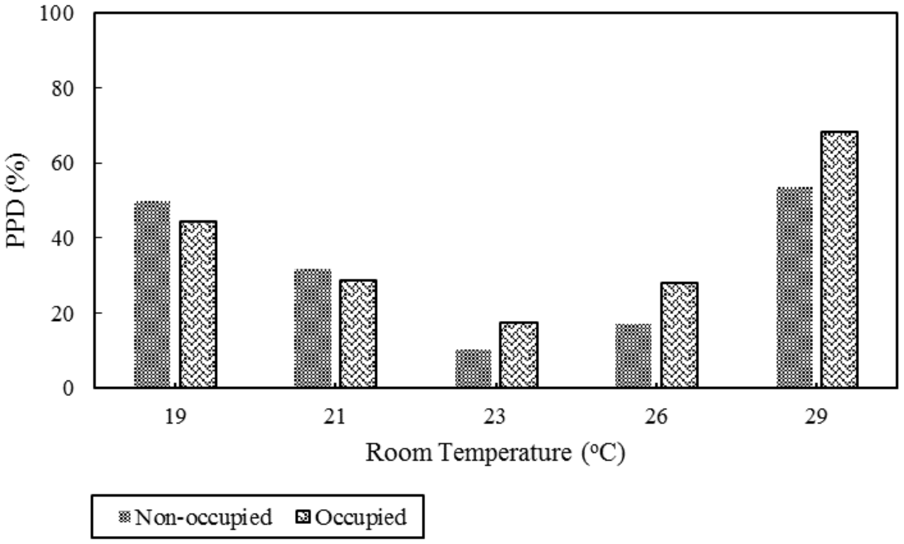


Fig. 8 - Change in PPD of non-occupied and occupied under different room temperature

The overall thermal sensation on the body will be influenced by the body that have the most incredible thermal sensation under different condition’s environment (supply temperature). The overall thermal comfort will follow the warmest environment (26°C and 29°C) and the coldest in a cool environment (19°C and 23°C) according to the PMV value in Table 4.

Table 4 - Summarize of effect of occupied in conditioned room

Parameter response	Supply temperature (°C)				
	19	21	23	26	29
Radiant Temperature (°C)	20.32	22.63	25.95	27.26	30.34
Air Temperature (°C)	19.14	22.46	23.84	27.60	30.31
Air velocity (m/s)	0.12	0.08	0.09	0.08	0.08
PMV	-0.1	-0.37	0.26	1.1	2.05
PPD (%)	25.6	8.8	9.1	31.6	77.1

Thermal comfort standards specify comfort for the majority of the occupants in a given space. ASHRAE Standard 55 [29] defines majority as 80 % of the occupants. It assumes that 10 % will experience discomfort due to general thermal sensation and another 10 % due to local thermal sensation. Thermal sensation data of our study also showed high correlation with the thermal comfort of the subjects (Pearson correlation 0.70). A mathematical relationship was constructed between thermal comfort and thermal sensation Eq. (1) (see Fig. 8).

$$TC = 4.02TS - 0.86 \tag{1}$$

Human responses to the steady conditions were analyzed, and the results are shown in Fig. 8. Each point in this figure represents the mean vote of all subjects’ responses for each condition. It can be seen that a straight line fits the data well ($R^2 = 0.70$).

Fig. 8 shows the steady conditions; overall thermal sensation and comfort are correlated with each other closely. Thermal sensation mean vote of 0.77 corresponds to thermal comfort mean vote of 1.28, that is to say, the subjects first felt uncomfortable when their whole-body thermal sensation is 0.77, which is more rigid than the definition proposed by Gagge et al. (1967) and Fanger (1970).

Similar studies were found in the literature [7]. Minor differences in correlation coefficients and mathematically fits between the previous studies and our study exist, which may be due to the complex nature of thermal environments and subjective responses. However, all the studies, including our show that the maximum thermal comfort corresponds with neutral (0) thermal sensation and thermal comfort decreases as the subjects feel warmer. The data of this study were also compared to the predicted percentage dissatisfied (PPD) formula of Fanger, which is also based on the human subject tests.

In the early 1990s, de Dear et al. [30] conducted a climate chamber experiment on college students in the CAC buildings in Singapore, and reported a preferred temperature of 25.4 °C. This temperature is 2.4 °C higher than the temperature obtained in this study (23 °C). The possible reason is the using of air conditioning. According to the field survey [31], over-cooling was a common phenomenon in the CAC buildings in Singapore, with an average indoor air temperature of 23.5 °C. This finding agrees well with the results of Zhang et al. [32] in that a warmer indoor thermal history in warm seasons produced a higher neutral temperature.

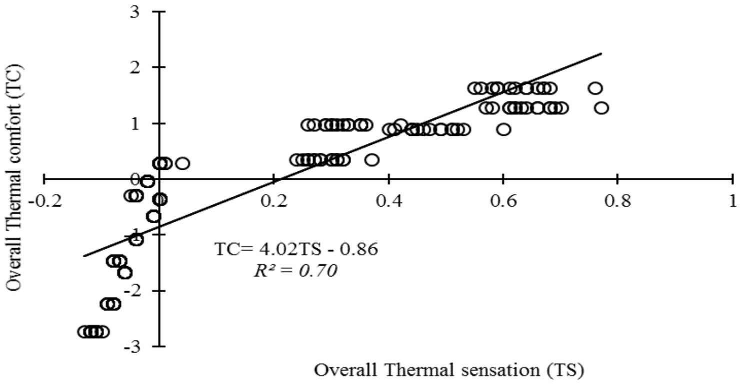


Fig. 8 - Correlation between thermal sensation (TS) and thermal comfort (TC)

4. Conclusion

The present study was to predict occupants' thermal comfort in the air conditioning building. The overall thermal comfort will follow the warmest environment (26ºC and 29ºC) and the coldest in a cool environment (19ºC and 23ºC). The study found that supply temperature at the 23 ºC indicates that the PMV is comfortable. The value of PMV in a supply temperature set at 23ºC is 0.26. At this temperature shows that the subjects are comfortable to do their office task and may lead to increasing performance and productivity. This study contributes to the body knowledge of thermal comfort towards human in the building. This study is the comprehensive thermal comfort study in building and Malaysia's climate. The results of this study provide a better understanding of the general thermal environment and occupants' thermal comfort perceptions of human in the building.

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