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Thermal Comfort Analysis on the Residential Buildings in Sarawak

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Abstract.
Thermal comfort is a subjective response that reflects the contentment between one's state of mind and the current environment. The energy consumption of the building sector has rapidly increased due to improved living standards and rising expectations of residents regarding thermal comfort. Mechanical ventilation, especially air conditioning systems, is essential for hot and humid countries aiming to achieve an ideal indoor comfort condition. However, such cooling systems often consume a significant amount of electricity, which contradicts the concept of energy conservation. Therefore, thermal comfort assessment is a method that can be employed to address this issue. Evaluating the thermal perception of occupants can subsequently facilitate more efficient electricity usage, aligning with the goal of energy conservation. In this study, a thermal comfort analysis was conducted on free-running residential buildings in Sarawak. These buildings were naturally ventilated with minimal use of mechanical ventilation systems. Physical measurements and subjective assessments were employed to evaluate the thermal responses of the residents based on various sensation and comfort scales, including the ASHRAE scale, Bedford scale, thermal acceptability scale, and thermal preference scale. Additionally, the widely used PMV model was utilized to predict the thermal sensation experienced by the residents. The results of the study indicated that the Bedford scale exhibited the highest percentage of acceptable responses, followed by the ASHRAE scale, thermal acceptability scale, and thermal preference scale. The PMV model was observed to overpredict the residents' thermal responses. The comfort temperatures derived from the study were 27.5 ℃, 28.1 ℃, and 26.2 ℃ according to the ASHRAE scale, Bedford scale, and PMV model, respectively. Based on the actual percentage of dissatisfaction that ensures 80% satisfaction, the acceptable indoor temperature range was found to be 27.3 ℃ to 29.6 ℃. Similarly, the acceptable range for relative humidity was 74.0% to 92.0%, and for air velocity, it was 0.18 m/s to 0.66 m/s.

Keywords: thermal comfort, thermal perception, sensation, comfort scales

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1. INTRODUCTION

Energy saving remains a vital issue for decades in the times of increasing environmental problems. Around 30% to 40% of the world's energy consumption is produced by the building sector in preserving comfortable indoor state and to supply power for the electrical devices [1-8]. Consequently, this has led to the increase of energy usage and Greenhouse gas (GHG) emission. Therefore, energy conservation and energy efficiency has become essential to overcome this issue.

Due to the climate condition, Malaysia often experiences relatively high daily temperature and humidity level. Such phenomenon will generate a sense of thermal discomfort and influences indoor comfortability. As a result, residents are inclined to rely on heating, ventilation and air conditioning (HVAC) systems to achieve their ideal indoor environment state which in turn, causing the increase of energy consumption in the building sector [9, 10]. In fact, buildings in Malaysia are discovered to be very electricity consuming [11, 12]. Studies also attested that the energy consumption of the building sector in Malaysia has increased drastically over the years [11, 13]. Based on the research done by worldwide energy consumption, 19% of the energy in Malaysia is spent on residential sector [14-16]. Thus, it is necessary to determine the demanded comfortable parameters through thermal comfort analysis in order to tackle this issue.

2. LITERATURE REVIEW

Thermal comfort is an important element in occupants' perceptions and behaviours in the use of energy in buildings [17-19]. In other words, thermal comfort is defined as a state in which heat balance across the body is in equilibrium with its environment [20, 21]. The idea of thermal comfort is complicated as it varies from person to person [22]. Different occupants may experience identical comfortable level at different thermal environments and in contrast, they may also perceive differently under the same thermal environment [23].

Thermal comfort can be affected by several factors such as the condition of indoor and outdoor environments, climate types, human factors and also geographical location of the countries [24]. It is also discovered that occupants tend to maintain and improve their existing comfortable state by adjusting their physical, physiological and psychological behaviour towards the environment [25-27]. All these findings have ascertained that a specific value cannot be allocated to thermal comfort [28].

The recommended acceptable thermal comfort conditions by ASHRAE Standard are summarized in Table 1.

Table 1: Recommendations of ASHRAE Standard [26, 29, 30].

Season	Operative temperature	Acceptable range
Winter	22 °C	20 °C - 23 °C
Summer	24.5 °C	23 °C - 26 °C

The Malaysian Standard 1525 [31] stipulates a "comfort cooling zone" where the indoor temperature should be maintained within 23 °C to 26 °C to sustain the thermal comfort of the non-residential buildings. Table 2 summarizes the indoor comfort temperature of various countries with different building types as well as different ventilation systems applied.

Table 2: Comfort Temperature of Different Countries.

Country	Malaysia [32]	Indonesia [11]	Singapore [8]	India [12]	Hong Kong [13]
Comfort Temperature	25.7 °C	29.2 °C	28.8 °C	28.0 °C	23.7 °C
Comfort Temperature Range	23.9 °C – 26.0 °C	26.0 °C – 29.2 °C	27.1 °C – 29.3 °C	26.0 °C – 32.5 °C	19.1 °C – 24.8 °C
Building Type	Lecture Halls	Free running buildings	Classrooms	Offices	Offices
Ventilation Type	Air-conditioned	Natural and mechanical ventilated	Mechanical ventilated	Natural Ventilated	Air-conditioned

The Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) method developed by Fanger have been used worldwide to predict and assess indoor thermal comfort in buildings [33]. PMV uses a seven-point index from ASHRAE scale to measure the thermal comfort sensation of the respondents in a given environment under a steady state condition [34-36].

Many field studies indicated that PMV model fails to predict the thermal sensation of occupants living in "free running" buildings, not only in hot climates but also in temperate climates [37]. The failure to predict the sensation happens because the PMV model cannot take into account complicated human interactions with their surrounding environment by changing their behavior and slowly adapted by adjusting their expectations and preference [37]. The inapplicability of the PMV index in tropical buildings is found in many studies due to the overestimation of actual thermal sensation of the occupants [11].

The adaptive approach to thermal comfort is based on the findings of surveys of thermal comfort conducted in the field. The fundamental assumption of the adaptive approach is expressed by the adaptive principle where people react in ways to restore their thermal comfort if there is a change which causes thermal discomfort to them [38-41]. In other words, the people's satisfaction with an indoor climate is achieved by matching the actual thermal environmental conditions at the existing time and space with their individual thermal expectations [40].

Therefore, the adaptive approach in thermal comfort analysis is comparatively more applicable for setting the thermal comfort standards in the buildings due to its characteristics which can consider the adaptation of people towards their thermal environment. In addition, using the adaptive method to find the thermal comfort conditions is found to be energy saving as well [42].

3. METHODOLOGY

The two main procedures involved in the study were field measurements and thermal

comfort analysis. Figure 1 shows the key elements within these two main procedures respectively. Physical measurements and subjective assessments were carried out under field measurements while thermal comfort analysis was performed through ASHRAE scale, Bedford scale, thermal acceptability scale, thermal preference scale and PMV model.

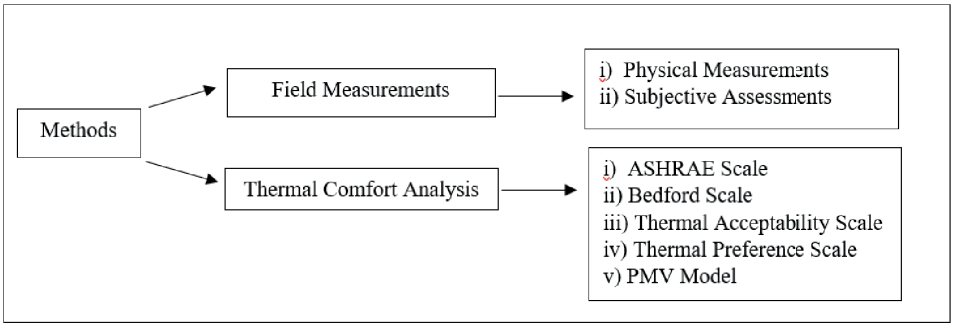

Figure 1: Main Procedures of Thermal Comfort Study.

3.1. FIELD MEASUREMENTS

The physical conditions which consisted of indoor air temperature (T_a), globe temperature (T_g), outdoor temperature (T_{out}), relative humidity (RH) and air velocity (v_a) were measured at 1.1 m above the floor level [43, 44]. The setups of the devices are illustrated

in Figure 2 and Figure 3. The devices used were hygrometer model testo 625, hot wire anemometer model TA 888 and globe thermometer. Hygrometer testo 625 was used to measure the indoor air temperature, outdoor temperature and humidity level while hot wire anemometer model TA 888 was used to measure indoor air velocity of the residential buildings. On the other hand, globe thermometer was used to obtain the globe temperature.

Figure 2: Set up of the Devices.

Field surveys were carried out by distributing the questionnaires to the residents of every residential area to evaluate their thermal conditions. The questionnaires were clarified verbally to the residents to ensure that they conveyed their immediate thermal response on their indoor environment. The aspects of the questionnaires included residents' thermal perception based on ASHRAE scale, Bedford scale, direct votes of acceptability and thermal preference scale. Activity level and clothing insulation of the respondents were also added into the assessments as personal parameters.

3.2. THERMAL COMFORT ANALYSIS

The thermal perceptions of the respondents from each residential area were evaluated based on different scales in the questionnaire, ASHRAE scale, Bedford scale, thermal acceptability scale and thermal preference scale. Beside the aforementioned scales,

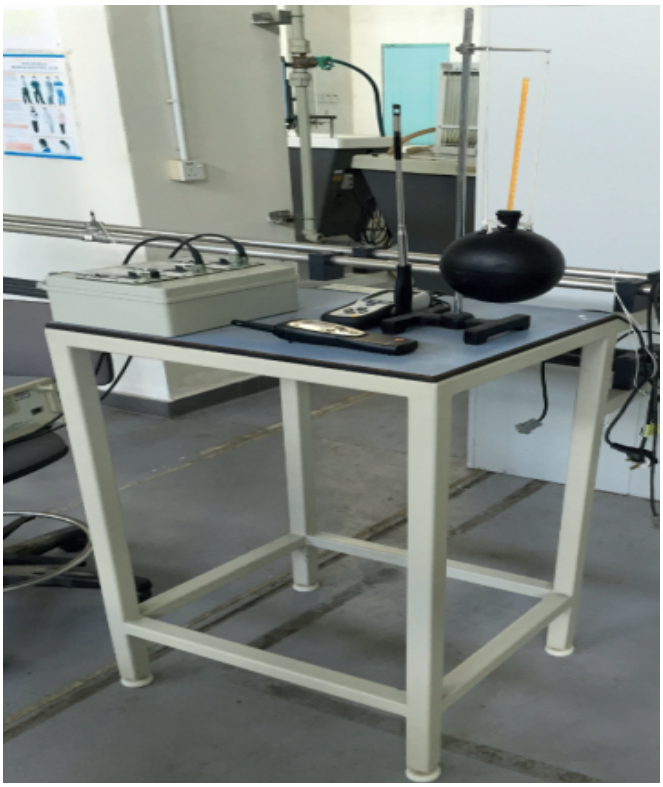

Figure 3: Devices Located 1.1m above the Floor Level.

the information acquired from the questionnaire can be applied into Fanger's model (PMV model) to assess thermal comfort as well.

The votes of ASHRAE scale were referred to as thermal sensation vote, TSV. Thermal environment was presumed to be comfortable or acceptable if the votes were within the central three categories of the scale (-1, 0, 1). The votes of Bedford scale were referred to as thermal comfort vote, TCV. Thermal environment was assumed to be comfortable or acceptable if the votes were within the central three categories of the scale (-1, 0, 1). The distribution of the votes for ASHRAE and Bedford scale were assessed and analyzed. Regression analysis was used to determine the comfort temperature from ASHRAE scale and Bedford scale. The actual mean vote, MTSV of the thermal sensation votes and MTCV of the thermal comfort votes for each operative temperature were calculated to determine their respective comfort temperature, T_c.

The predicted mean vote, PMV of Fanger's model was used to analyze the thermal environment experienced by the residents. ASHRAE scale was referred in this model since its evaluation was also based on the thermal sensation of the respondents, varying from -3 to 3. The comfort temperature of Fanger's model was obtained through regression analysis. The PMV value was computed by using CBE thermal comfort tool which was complied with ASHRAE Standard 55-2013 [45]. The parameters of operative

temperature, relative humidity, air velocity, activity level and clothing insulation were used in this computation.

Thermal acceptability scale was a scale where respondents were asked to assess their thermal environment in a direct way, either they found their environment acceptable or unacceptable. In the thermal preference scale, respondents were assessed based on their thermal preference, either they wanted their indoor ambience to be warmer, no change or cooler. It was presumed that respondents who voted on "warmer" or "cooler" were not satisfied with their environment since they demanded for a change. Respondents who voted on "no change" were assumed to recognize their thermal environment as acceptable.

The upper and lower limit of the comfort temperature, relative humidity and air velocity were determined based on the minimum satisfaction of 80% [46, 47].

4. RESULTS AND DISCUSSIONS

The study was conducted at ten different residential areas with fifty measurement points, covering from day time to night time. The residential buildings chosen were mostly free running buildings with a minority of them using air-conditioned systems.

4.1. THERMAL COMFORT EVALUATION BASED ON VARIOUS SCALES

Since ASHRAE scale and Bedford scale are both a seven-point scale, the votes' distribution between these two scales was compared as shown in Figure 4.

The percentage of votes in the middle 3 categories of Bedford scale was 85.68% which was higher than ASHRAE scale with just 76.65%. This attests that respondents who voted outside the central three categories of ASHRAE scale still identified their environment as comfortable and acceptable.

93.15% of the voters who voted in the central three categories of ASHRAE scale also voted in the central three categories of Bedford scale. 81.82% of the people who voted in the extreme categories (cool and cold) of ASHRAE scale still found themselves comfortable. This is due to the hot and humid contexts experienced by the local residents as those who live in tropical climates tend to prefer a cooler environment.

Around 41.3% of the respondents indicated that they were comfortable even though they voted in the warm and hot categories of ASHRAE scale. The reasons for this include personal preference and personal adaptations. These minority respondents

might prefer a warmer ambience than a cooler environment due to their personal preference. Personal preference could be affected by their personal adaptations especially when they are adapted to a certain climate. People who are accustomed to a warmer climate would find themselves uncomfortable in a cooler environment and vice versa. This suggests that thermal discomfort does not necessarily comply to everyone even if their thermal sensation state is deviated from the neutral point.

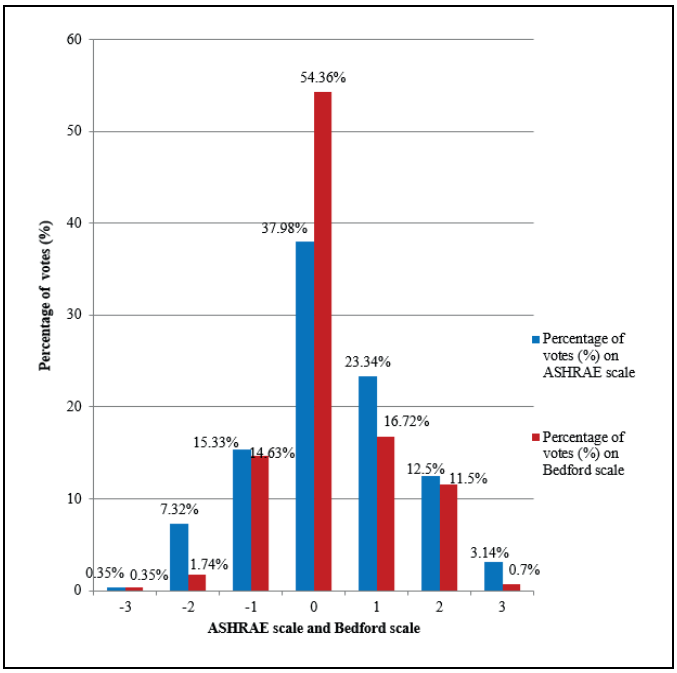

Figure 4: ASHRAE vs Bedford Scale.

Therefore, a comfort scale such as Bedford scale might be a better measure to determine thermal comfort acceptability if compared to ASHRAE scale. Bedford scale emphasizes more on respondents' response to their comfortable state while ASHRAE scale focuses on thermal sensation only. A person who votes beyond the central three categories of ASHRAE scale could still find his or her environment acceptable and comfortable. By using Bedford scale, the deficiency of ASHRAE scale can be avoided.

Thermal comfort analysis is concluded in Figure 5 where the acceptability of various scales was assessed.

According to the bar chart shown in Figure 5, Bedford scale possessed the highest acceptability votes with 85.68% followed by ASHRAE scale, 76.65% and thermal acceptability scale, 73.52%. The percentage of acceptable votes for thermal preference scale was recorded to be 32.06% which is relatively low if compared to other scales. This is because the thermal preference scale assesses respondents based on their preferred comfortable state. Respondents might respond based on their personal preference rather than assessing their present thermal environment. Therefore, thermal

preference scale is not a suitable scale to evaluate the thermal comfort perception of the respondents.

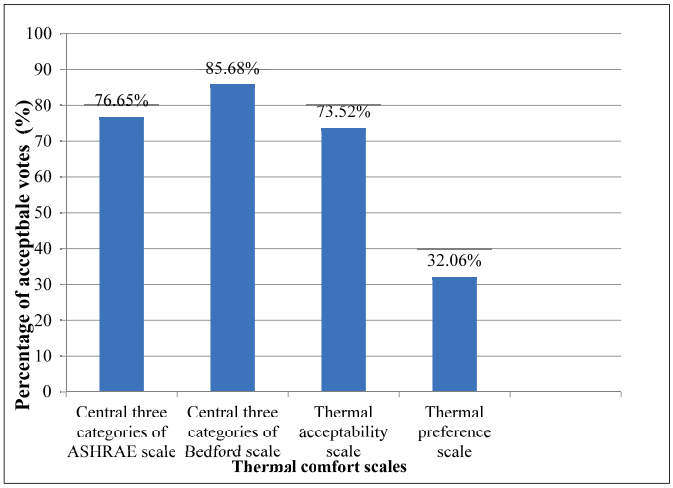

Figure 5: Percentage of Acceptable Votes for Various Scales.

It was presumed that the central three categories of ASHRAE scale and Bedford scale can represent thermal satisfaction. However, the percentage obtained from Bedford scale was around 10% higher than the percentage of ASHRAE scale. This is because some of the residents who voted outside the central three categories of ASHRAE scale still found themselves comfortable. Thus, this indicates that extreme sensations of ASHRAE scale do not necessarily represent thermal discomfort.

Since the votes of central three categories of ASHRAE scale and Bedford scale were postulated to be acceptable and comfortable, thermal acceptability scale should demonstrate the highest acceptance level in terms of percentage. However, in this study, the acceptable percentage of thermal acceptability scale was lower than the percentage found on ASHRAE scale and Bedford scale. It is because there were residents who identified their thermal environment as not acceptable even though they had voted in the acceptable criteria of ASHRAE scale and Bedford scale.

Another reason which leads to this occasion is the information shortage on thermal acceptability scale. By asking residents to respond to either “acceptable” or “unacceptable”, it is difficult to evaluate their thermal responses accurately. Thus, ASHRAE scale and Bedford scale are better thermal comfort indicators since they carry weighted information of the respondents.

4.2. COMFORT TEMPERATURE

Comfort temperature, which can also be referred to as neutral temperature, was determined by using ASHRAE scale, Bedford scale and Fanger's PMV model. According to Figure 6, 7 and 8, the comfort temperatures based on ASHRAE scale, Bedford scale and PMV model were found to be 27.5 °C, 28.1 °C and 26.2 °C respectively.

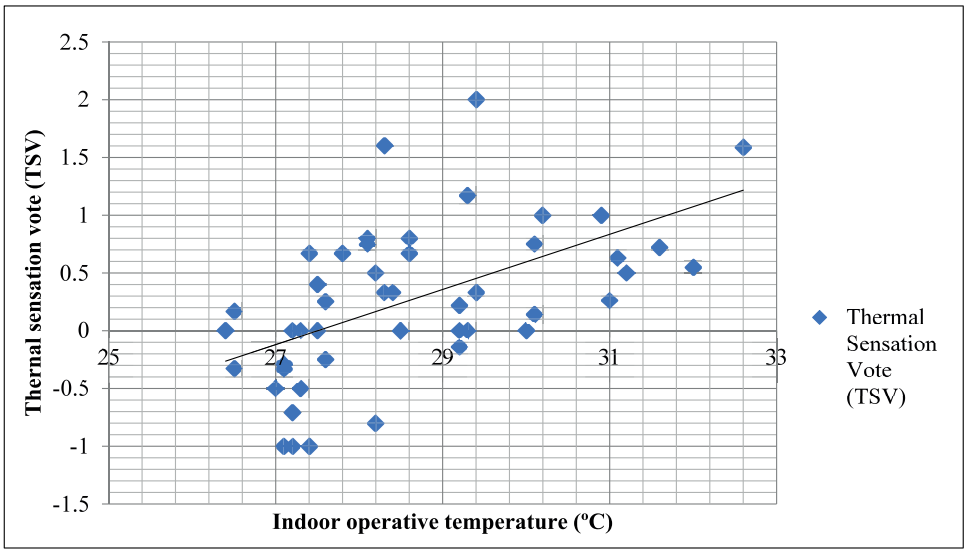

Figure 6: Thermal Sensation Votes against Indoor Operative Temperature.

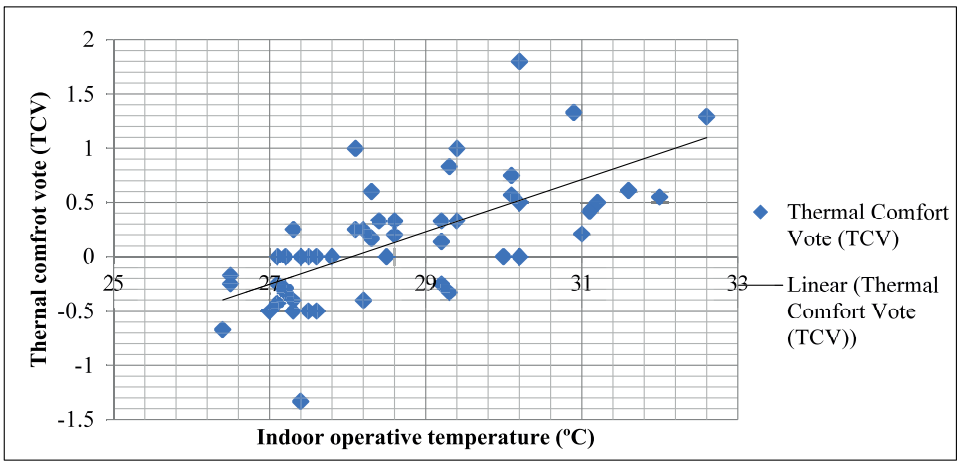

Figure 7: Thermal Comfort Votes against Indoor Operative Temperature.

Most of the studies are comparing the comfort temperature of ASHRAE scale and PMV model as there is always discrepancy found between these 2 scales. In this study, the difference of comfort temperature between ASHRAE scale and PMV model was found to be 1.3 °C. This finding is significant because if the setting of indoor comfort temperature is prescribed wrongly, it could affect the total amount of energy consumed in building sectors, particularly on ventilation systems.

In this study, the comfort temperature obtained from Bedford scale was 0.6 °C higher than the one from ASHRAE scale. If this comfort temperature is used as a standard setting for indoor environment, more energy can be conserved while thermal comfort of the residents can be preserved concurrently.

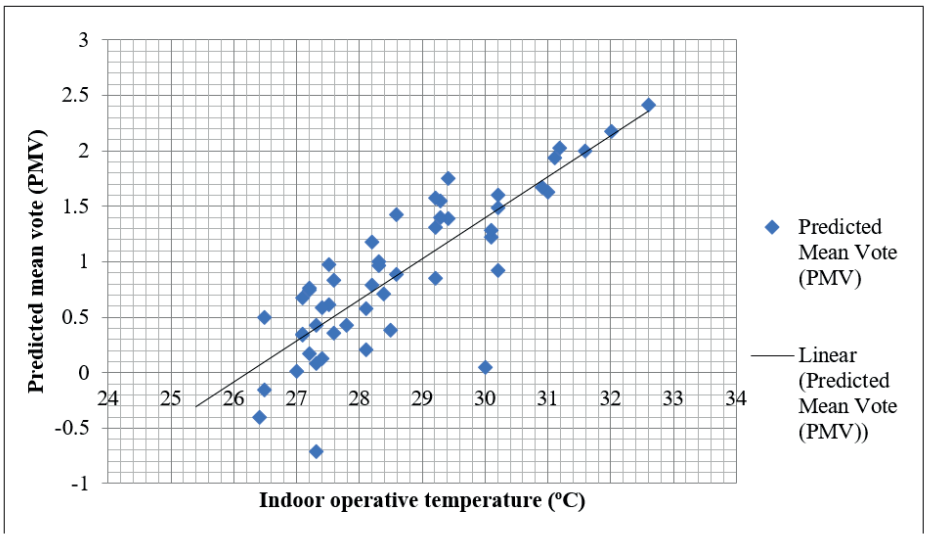

Figure 8: Predicted Mean Votes against Indoor Operative Temperature.

The comfort temperature of the ASHRAE scale of this study was 1.8 °C higher than the findings discovered by Chew [48] where the comfort temperature was found to be 25.7 °C. This is due to the different environment context between the studies. Chew was conducting his assessment in air-conditioned lecture halls while current study was focusing on residential buildings which were naturally and mechanically ventilated. The comfort temperature found by Feriadi [43] in naturally ventilated houses of Indonesia was 29.2 °C, which was higher than the comfort temperature obtained from present study. By comparing to the residential houses which were naturally ventilated without the support of air conditioning systems, it is discovered that residents can adapt themselves to a higher comfort temperature. The thermal comfort study conducted in Singapore also showed similar results [24]. The comfort temperature of classrooms which were ventilated by mechanical cooling fans was found to be 28.8 °C [24]. This proves that different indoor contexts will result in different comfort temperatures. Occupants who implement simple ventilation systems can acclimatize themselves easily to a higher comfort temperature compared to those who rely on heavy cooling systems such as air-conditioners.

Nevertheless, it can be concluded that the comfort temperature obtained from this study is in good agreement with the findings revealed by other researchers.

4.3. UPPER AND LOWER LIMIT OF THE COMFORT PARAMETERS

The upper and lower limit of the adaptive models which included indoor operative temperature, relative humidity and air velocity were determined by using actual percentage dissatisfied, APD and predicted percentage dissatisfied, PPD below 20% [46, 47].

Actual percentage dissatisfied was determined from thermal acceptability scale while PMV model was implemented to calculate the predicted percentage dissatisfied of each indoor operative temperature, humidity level and air velocity. From Figure 9, the acceptable temperature range of actual percentage dissatisfied below 20% was between 27.3 °C and 29.6 °C. The temperature range to keep the predicted percentage dissatisfied below 20% was between 26.4 °C and 28.1 °C as indicated in Figure 10.

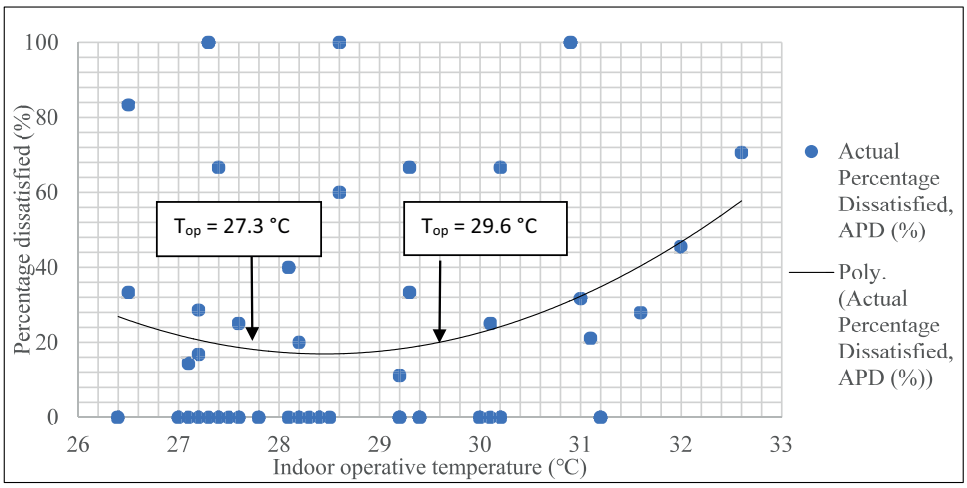

Figure 9: Actual Percentage Dissatisfied against Operative Temperature.

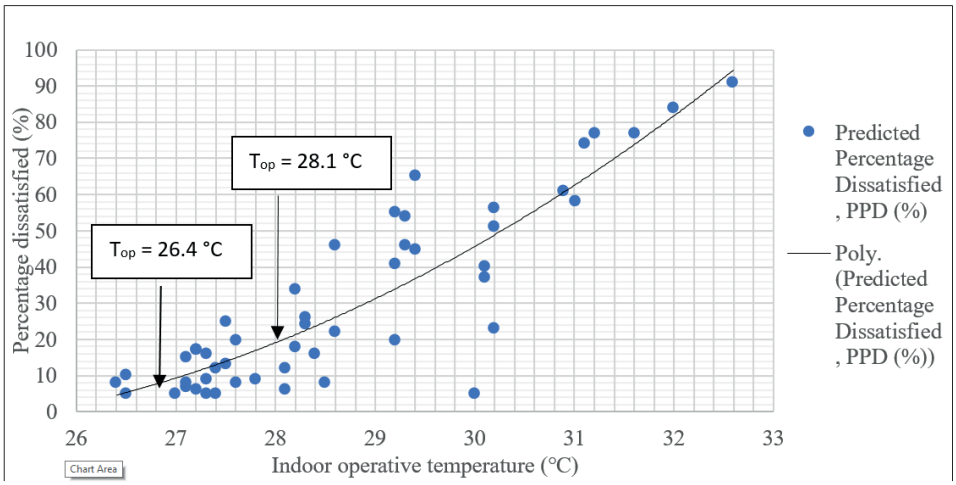

Figure 10: Predicted Percentage Dissatisfied against Operative Temperature.

By comparing Figure 9 and Figure 10, it is observed that the actual percentage dissatisfied below 20% covered a wider temperature range than the predicted percentage dissatisfied. This indicates that the thermal acceptability scale predicted higher human adaptation ability towards their thermal environment. In contrast, PMV model overpredicted the thermal sensation of the people, thus, its PPD value was also affected.

In this study, the maximum acceptable temperature suggested by PPD was 28.1 °C but in fact, the subjects still found the temperature of 29.6 °C acceptable. PPD also predicted that subjects will only feel comfortable at the temperature of 26.4 °C but it was discovered that subjects were already feeling comfortable at 27.3 °C. Therefore, it can be concluded that PMV model underestimated thermal sensation at a higher temperature and overestimated thermal perception at a lower temperature.

The similar findings were found on relative humidity and air velocity. The actual percentage dissatisfied below 20% for the aforementioned parameters were found to be 74.0% to 92.0 % and 0.18 ms^{-1} to 0.66 ms^{-1} respectively whereas the values determined by PPD were 77.0% to 90.0% and 0.32 ms^{-1} to 0.46 ms^{-1} respectively. This shows that PPD of the PMV model has some degree of deficit in analysing the thermal expectation of the respondents. Therefore, actual percentage dissatisfied (APD) is more recommended to be used since it can cover the adaptiveness of the respondents to a wider extent.

5. CONCLUSIONS

Different thermal comfort scales showed different evaluation outcomes. In this study, ASHRAE thermal sensation scale, Bedford thermal comfort scale, thermal acceptability scale, thermal preference scale and predicted mean vote of Fanger's model were used to determine the thermal responses of the residents.

The comfort temperature of 27.5 °C was obtained by analyzing the thermal sensation votes of ASHRAE scale, 28.1 °C for the thermal comfort votes of Bedford scale and 26.2 °C for the predicted mean votes of Fanger's model. This is an important finding as these comfort temperatures can be used as a guideline for the setting of indoor comfort conditions. The comfort temperature defined from Bedford scale is recommended to be used since it can cover a wider temperature range. This consequently will conserve the amount of energy used on ventilation systems and fulfil the thermal comfort state of the residents simultaneously.

The acceptable range for indoor comfort temperature, relative humidity and air velocity of this study were 27.3 ℃ to 29.6 ℃, 74.0% to 92.0 % and 0.18 ms^{-1} to 0.66 ms^{-1}, respectively.

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