

## Examination of thermal comfort in a naturally ventilated hostel using PMV-PPD model and field survey

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**ABSTRACT :** The application of Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indices for thermal comfort quality assessment in naturally ventilated (NV) buildings in warm-humid climate has been observed to lead to overestimation of occupants' comfort and dissatisfaction levels. The thermal comfort quality in a naturally ventilated hostel located in Obafemi Awolowo University, Ile-Ife was determined using PMV and PPD indices. The measured indoor air temperature and relative humidity were 28.1-34°C and 30.8%-75.5%. The subjective assessments showed that more than 80% of the respondents were comfortable (PD < 20%) while the PPD index predicted that 58% of the occupants were not comfortable. The calculated PMV index on the average was +1.63. There was no correspondence between the thermal conditions predicted by PMV-PPD index and actual comfort vote. Fanger's PMV-PPD model cannot be used to predict indoor climate in the study area as it overestimated occupants' comfort and dissatisfaction levels.

**KEY WORDS:** PMV-PPD model, thermal comfort, NV hostel, field survey.

### I. INTRODUCTION

Based on the relevant statistics, people spend 80% of their lifetime indoors [Wei et al., 2011]. Indoor environment, therefore, should be made safe, healthy and comfortable as much as possible. It has been shown that the productivity will be increased by 15% when occupants are satisfied with their thermal environments [Kim and Kim, 2007]. In students housing it has been found that thermal comfort affects the academic performance, intellectual capability and development of students [Dhaka et al., 2013; Appah-Dankyi and Koranteng, 2012]. Fanger [1972] also believed that human intellect performance and perception in general will reach its maximum potential if human being is in a comfortable thermal condition. Zhang et al. [2009] observed that thermal comfort also played a very important role in the provision of quality sleeping environment for occupants of hostel buildings. A quality night sleep has been observed to play a significant role in allowing adequate daytime functioning: concentration, attention and comprehension as well as learning level [Sekhar and Goh, 2011; Lin and Deng, 2006]. Sleep has been shown also to be an important factor that affects students' health [Teli et al. 2012].

Naturally ventilated buildings (NV) used the freely available resources of wind and solar energy and with proper design, they could represent an alternative technique for reducing the energy consumption in buildings and for creating sustainable thermal comfort and healthy indoor conditions [Stavarakakis et al., 2012]. According to Stavridou and Prinos [2013] natural ventilation promotes not only protection and restoration of indoor air, but also sustainability and energy saving. Despite these acclaimed benefits, the results of recent studies conducted on NVBs often deviated from the actual scenario [Cândido et al., 2010; Haase and Amato, 2009]. Respondents demanding for cooler environment and more air movement were more numerous than those demanding for warmer and less air movement and that they did not provide a significant cooling potential during hot season in warm-humid tropical climate. Besides this, the issues that often arose and complained about by residents of NV hostel buildings were that; less comfortable indoor environment in their inhabited buildings because of high temperatures in the building and that air movement was less effective and these problems were mainly noticed in the afternoon. Recent trends showed a heavy usage of mechanical ventilation devices for effective distribution of air in securing thermal comfort. This led to tremendous amount of energy required for improving indoor thermal environment.

It is well known that poor thermal comfort forced the users to look for high energy alternatives to achieve thermal comfort [Indraganti, 2010]. With the ever growing awareness for a need to reduce building energy use and the roles naturally ventilation can play in achieving this goal, it is therefore important to study the adequacy of natural wind in providing thermal comfort in buildings. Examination of thermal comfort may help in recognizing the agents of thermal problems in buildings and important variables responsible for this trend in higher energy usage. In Nigeria, several researchers have investigated indoor thermal environment and occupants' thermal comfort in climate responsive design buildings using field surveys and theoretical analyses [Olanipekun, 2012; Adunola and Ajibola, 2012; Adebamowo and Olusanya, 2012; Adunola, 2011; Adebamowo and Akande, 2010]. However, many of these studies were biased towards family residential buildings, although few studies were noted in office and hospital buildings. Besides, many of these researchers characterised the thermal comfort of buildings they studied from a microclimatic perspective, only a very few papers employed the PMV and PPD indices in the analysis of the indoor climate. Currently, there has been no discussion on the examination of the suitability of PMV and PPD indices in naturally ventilated hostel buildings. There is another matter that seems to be not investigated at all in the past studies; calculating the percentage of dissatisfied on the basis of the judgement of those people who voted  $\pm 2$  and  $\pm 3$  is consistent with the subjective judgement of those people who rated the environment as acceptable. Therefore, it is the intention of this study to fill this gap, by providing information on the applicability of PMV and PPD indices to evaluate the thermal comfort in this type of dwellings where the use of non-air conditioning was employed, focusing on a naturally ventilated hostel building in Obafemi Awolowo University, Ile-Ife. The first objective assessed the indoor thermal conditions of the selected hostel through measurement of microclimatic parameters. The second objective characterised the indoor thermal conditions of the selected hostel using PPM-PPD model and Percentage Dissatisfied (PD) index based on questionnaire. The third objective investigated the actual thermal sensation of the students to their environment. The fourth objective examined the compatibility of the PMV-PPD model with the actual thermal sensation of the students. Finally, the applicability of PMV-PPD index in the selected NV hostel was investigated.

## II. RESEARCH METHODOLOGY

The selected method in this research is field survey. Field studies allowed for analyses of many of the contextual factors and other factors than those that can be simulated in climate chamber, as the subjects provided responses in their everyday habitats, wearing their everyday clothing and behaviour without any additional restrictions. In the field survey people are able to act as 'meters' of their environment [Adebamowo and Olusanya, 2012]. The field study was conducted in hot season from January to March, 2013. Meteorological data showed that hot season in Ile-Ife is characterised by high humidity and temperature with low air movement.

### Climate and characteristics of the selected hostel building

In this study, a prototype for the examination of thermal comfort in hostel buildings was presented using PMV-PPD model in addition to field measurement of thermal comfort parameters and thermal sensation vote (TSV) of occupants. The field survey was carried out in a naturally ventilated hostel building located on the campus of Obafemi Awolowo University, Ile-Ife. The city of Ile-Ife is located on latitude  $4^{\circ}35'N$  and longitude  $7^{\circ}30'E$ . Ile-Ife, situated in the well-known "Southwest" part of Nigeria, is about 250 km away from Lagos (former capital city of Nigeria). Within a warm-humid tropical area, the town has its unique climatic characteristics of evident rain and dry seasons that correspond to the months of April to October and November to March respectively [NIMET, 2009].

The hostel building is a low-rise reinforced concrete structure of three floors and oriented at 15 degrees to the true north [as shown in Fig.1]. The walls were made of sandcrete hollow blocks. The thickness of the external and the internal wall (north, south, west, and east walls) is 300 mm. The building is rectangular in shape, being 65m long, 12 m wide and 10 m high. Its window is 1.5 m wide by 1.8 m high and consisted of wooden/aluminum frame and single (4mm) common plain glass. The window to wall ratio (WWR = 0.35). The hostel building with its north-south facing windows, is in the midst of other hostel buildings of similar height and construction. Purposive sampling was adopted for the selection of the hostel due to insufficient measuring equipment and was specifically selected for thermal comfort performance analysis as regards to its implementation of bioclimatic design strategies. Specifically, passive design strategies related to the use of natural ventilation for cooling, important thermal mass, orientation and morphology of the building were optimised, overhangs are dimensioned to ensure reduced solar gain and avoidance of direct solar heat gain during the year, similar construction map and layout, same material and walls as other hostel buildings, besides the availability and will of the occupants to take part in the investigation.

(a)



(b)



**Fig. 1:** General view of the case study building (a) roof overhang (b) screen wall

#### **Data collection method**

Thermal comfort logging, questionnaire survey and observation were utilized for data collection in this short-term field study investigation. Using a combination of research methods is common in field studies and helps to balance the strength and weakness inherent in individual data collection strategies.

#### **Objective measurement of the outdoor and indoor environment**

The six physical parameters needed for the evaluation of PMV and PPD indices are air temperature, relative humidity, air movement, mean radiant temperature, metabolic rate and clothing insulation. Typically, thermal comfort field studies measured the first three parameters with instruments and calculated the later three factors from measurements, questionnaire data and observation. In this study, the first three parameters were measured by thermal comfort meter (Kestrel model 4500 pocket and handheld weather tracker. The other three parameters were determined using information derived from measurements, questionnaire data and observation. The measurements of thermal comfort parameters were carried out at three points in each room and at each sampling point each parameter was measured three times to ensure accurate data collection. The average value of each measured variable was used for subsequent analysis. The instrument setup was placed closed to the subjects when recording the environmental conditions, while the respondents filled in the comfort questionnaire. To maximize the reliability of the calculation of the PMV index and minimize the effect of the measurement accuracy on the assessment of the thermal environment, the measurement protocols and the instruments used for the assessment of physical variables were compliance with ISO 7726 [2003]. In order to compare the thermal comfort on the inside of the hostel building with outside thermal conditions, the meteorological data were obtained from the Department of Physics, Obafemi Awolowo University, Ile-Ife.

#### **Subjective measurement**

In the next stage of data collection, questionnaire survey was employed to evaluate the thermal sensation of the respondents regarding the thermal comfort parameters. The questionnaire was divided into four sections: the first section centred on the demographic data of the respondents. The second section of the

questionnaire was used to collect data on the clothing and the activities of the respondents. The third second section asked the respondents to evaluate their thermal environment at the moment of measurement. The last section was a checklist on the use of different thermal environmental controls. However, this was not discussed in this paper. The influence of thermal environment on occupants was assessed using the subjective scales according to the ISO 10551 Standards [2003]. The questionnaire was distributed directly by the researcher in company of research assistants. The survey was done in the rooms of the selected hostel systematically stratified. The number of respondents who answered the questionnaire was 96.

### Thermal sensation model

PMV is an index that predicts the mean value of the votes of a large group of persons on a seven-point thermal sensation scale (see Table 3). To calculate PMV and PPD indices equations derived by Fanger [1970] were used for the evaluation of PMV and PPD indices. The mathematical expression of Fanger's PMV-PPD model are as given by Eqs. (1) and (2)

$$PMV = (0.303e^{-0.036M} + 0.028) \{ (M - W) - 3.05 \times 10^{-3} (5733 - 6.99 (M - W - Pa) - 0.42 (M - W) - 58.15) - 1.7 \times 10^{-5} M (5867 - Pa) - 0.0014M (34 - T_{mrt}) - 3.96 \times 10^{-8} f_{cl} (T_{cl} + 273)^4 - (T_{mrt} + 273)^4 - f_{cl} h_c (T_{cl} - T_{mrt}) \} \quad (1)$$

$$PPD = 100 - 95 \exp(-0.03353 PMV^4 + 0.2179 PMV^2) \quad (2)$$

where  $M$  is the metabolic rate ( $W/m^2$ ),  $W$  ( $W/m^2$ ) is the external work (equal to zero for most activity),  $Pa$  (kPa) is the partial water vapour pressure,  $T_i$  ( $^{\circ}C$ ) is the indoor mean temperature,  $f_{cl}$  (-) is the ratio of body's surface area when fully clothed to body's surface area when nude,  $T_{cl}$  ( $^{\circ}C$ ) is the surface temperature of clothing,  $T_{mrt}$  ( $^{\circ}C$ ) is the mean radiant temperature,  $h_c$  ( $W/m^2C$ ) is convective heat transfer coefficient between the occupant and the environment.

$$T_{cl} = 35.7 - 0.028(M - W) - I_{cl} \{ 3.96 \times 10^{-8} f_{cl} [(T_{cl} + 273)^4 - (T_{mrt} + 273)^4] + f_{cl} h_c (T_{cl} - T_i) \} \quad (3)$$

$$h_c = \max [2.38(T_{cl} - T_i)^{0.25}; \sqrt{12.1 v_{ar}}] \quad (4)$$

$$v_{ar} = v_a + 0.005(M/A_{DU} - 58.15) \quad (5)$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 I_{cl} & \text{for } I_{cl} < 0.078 \\ 1.05 + 0.645 I_{cl} & \text{for } I_{cl} > 0.078 \end{cases} \quad (6)$$

where  $v_a$  (m/s) is the air velocity,  $v_{ar}$  (m/s) is the relative air velocity to the human body, and  $I_{cl}$  ( $m^2/^{\circ}CW$ ) is the thermal resistance of clothing.

$$Ps_1 = -\log^{-1} [30.59051 - 8.2 \log (T_i + 273.16) + 0.0024804 (T_i + 273.16) - \frac{3142.31}{T_i + 273.16}] \quad (7a)$$

$$Ps_2 = 0.1333 \exp [18.6686 - \frac{4030.31}{T_{mrt} + 235}] \quad (7b)$$

To decrease the calculation error, the partial water vapour pressure was obtained using

$$Pa = \frac{Ps_1 + Ps_2}{2} RH \quad (8)$$

where  $RH$  (%) is the relative humidity of the indoor air.

$$A_{DU} = 0.202 W_b^{0.425} + H_b^{0.725} \quad (9)$$

It can be observed from Eqns (1) – (9) that the calculation of PMV is an iterative process.

With a computer program developed in Microsoft Excel software based on the algorithms proposed in the ISO 7730 standard [2005], the values of PMV index were estimated using all the four environmental parameters (air temperature, MRT, air velocity and relative humidity) and the two personal variables (activity and clothing of respondents) collected during the monitoring period as input parameters. The MRT was determined using the regression model proposed by Nagano [2004]. Clothing thermal insulation and metabolic rates values were determined from the individual clothing articles indicated in the survey responses and observation made during the survey. Based on this information and observation and using the standard lists, the clothing insulation (clo) was estimated using the summation formula [ANSI/ASHRAE Standard 55-2004]  $I_{cltot} = \sum I_{clu,i}$  where,  $I_{cltot}$  was the insulation of the entire ensemble and  $I_{clu,i}$  was the insulation of the individual piece of garments. On the average the values of the clothing ensemble insulation and the metabolic rates of the respondents were calculated as 0.42 clo and 1.06 met respectively. Based on the calculated PMV, the thermal comfort of the space was determined from Table 1. For comparison purpose, the appropriate range for thermal comfort were  $-0.5 < PMV < 0.5$  and  $-1.0 < PMV < 1.0$  in which 90% and 80% of people have comfort sense.

Table 1

The qualitative and quantitative statements of thermal sense

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

Percentage Dissatisfied (PD) index based on questionnaire was also computed. To determine PD index, the number of respondents who expressed discomfort on 7-point ASHRAE thermal comfort sensation scale were determined. The expression of discomfort is known if the respondent answers between (-2, -3) and (+2, +3) to any of the thermal sensation questions, this question was labelled as a discomfort one. Following Pourshaghaghay and Omidvari [2012] methodology the PD index based on the questionnaires in any section of the hostel building was then computed using the following expression

$$PPD = \frac{\text{The number of questionnaire having discomfort label}}{\text{Total number of questionnaire in any section}} \times 100 \quad (10)$$

### III. RESULTS AND DISCUSSION

Environmental conditions during the monitoring period

During the period of the field measurement, the weather conditions vary with time on different days of months. An extremely hot day of every month was chosen as the representative day for the field survey in the present paper. Statistical summaries of measured physical thermal comfort parameters of indoor and outdoor climatic data are provided in Table 2. For the month of January, outdoor air temperature ( $t_a$ ) ranged between 22.5°C and 32.6°C (mean = 29.3°C, STD = 3.21). In February from 25.1°C to 32.9°C (mean = 30, STD = 2.36) and in March from 26°C to 31.8°C (mean = 29.5°C, STD = 1.97) representing temperature swing of 10.1°C, 7.8°C, and 9.6°C, respectively. In January, outdoor relative humidity showed low values in January and fell within 20.36% and 49.34% (mean = 28.86%, STD = 8.70). In February, the relative humidity (RH) fell within 42.88% and 85.82% (mean = 59.01%, STD = 13.99). In March, relative humidity showed high mean value (66.34%) as against January (28.86%) and February (59.015%).

In January, the indoor air temperature varied from 28.4°C and 33.7°C (mean = 30.9°, STD = 1.71), in February from 28.1°C to 33.9°C (mean = 31.2°C, STD = 1.87), and in March from 28.5°C to 34°C (mean = 31.3°C, STD = 1.96) representing temperature swing of 5.3°C, 5.8°C, and 5.5°C, respectively. In January, RH fell within 31.8% and 71% (mean = 46.16%, STD = 12.45). In February, the RH ranged from 30.8% and 75.5% (mean = 45.72%, STD = 14.03) about 4% higher than January record. RH decreased in March with a range of 32.8-66% (mean = 44.48%, STD = 11.89).

Table 2:

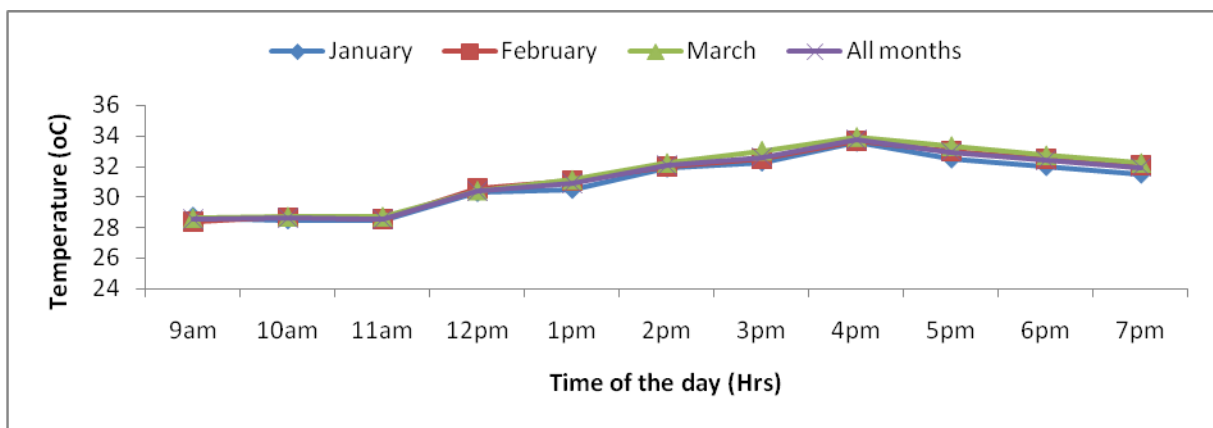
Statistical summaries of measured physical thermal comfort parameters of indoor and outdoor climatic data

Month	Descriptive statistic	$T_o$ (°C)	RH <sub>o</sub> (%)	$T_a$ (°C)	RH (%)	PMV	PPD
Jan	Mean	29.3	28.86	30.9	46.16	1.6	56.65
	Max	32.6	49.34	33.5	71	2.28	87.65
	Min	22.5	20.36	28.4	31.8	0.87	20.83
	STD	3.21	8.70	1.71	12.45	0.49	24.39
Feb	Mean	30	59.01	31.2	45.72	1.61	56.75
	Max	32.9	85.82	33.7	75.5	2.31	88.6
	Min	25.1	42.88	28.1	30.8	0.86	20.81
	STD	2.36	13.99	1.86	14.03	0.53	25.90
Mar	Mean	29.5	66.34	31.3	44.48	1.65	58.32
	Max	31.8	84.02	34	66.3	2.39	90.82
	Min	26	51.19	28.5	32.8	0.88	21.51
	STD	1.98	10.89	1.96	11.89	0.57	27.67
All months	Mean	29.6	51.40	31.1	45.45	1.63	57.81
	Max	32.9	85.82	34.0	75.5	2.24	86.21
	Min	22.5	20.36	28.1	30.8	0.87	21.09

	STD	2.50	19.83	1.81	12.64	0.51	25.29
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Fig. 2(a) and (b) show the profiles of measured indoor air temperature and relative humidity data respectively. The maximum proportion (63.6%) of indoor air temperature fell within 30°C and 33°C while 36.4% ranged between 28°C and 30°C. The lowest temperature was recorded at 9 am in the morning, while the highest temperature occurred at 4 pm in the afternoon. There was minimum deviation of the measured air temperature across the three months (mean  $T_a = 30.9^\circ\text{C}$ ,  $31.1^\circ\text{C}$ ,  $31.3^\circ\text{C}$ ). The low change in various temperature intervals was because for these months the difference between mean radiant temperature and dry bulb temperature is less than  $1^\circ\text{C}$  and wind speed is less than  $0.1\text{ m/s}$ . Similar higher indoor air temperature was also experienced across the three months. According **Djamila et al. [2013]**, the higher temperature variations observed are common with concrete structure in this climatic zone. In comparison with standards, none of the measured temperature data fell within  $23^\circ\text{C}$  and  $26^\circ\text{C}$ , which is the summer thermal comfort zone limits defined by the ASHRAE Standard 55-2004. For all months about 58% of measured RH data was in the range of 30%-70%. 21% of the data fell below 30% while the same percentage (21%) also fell above 70%. The percentage of relative humidity on the higher floor was better than that on the ground floor. The diurnal variation in relative humidity in these three months was moderate (20-42%).

(a)



(b)

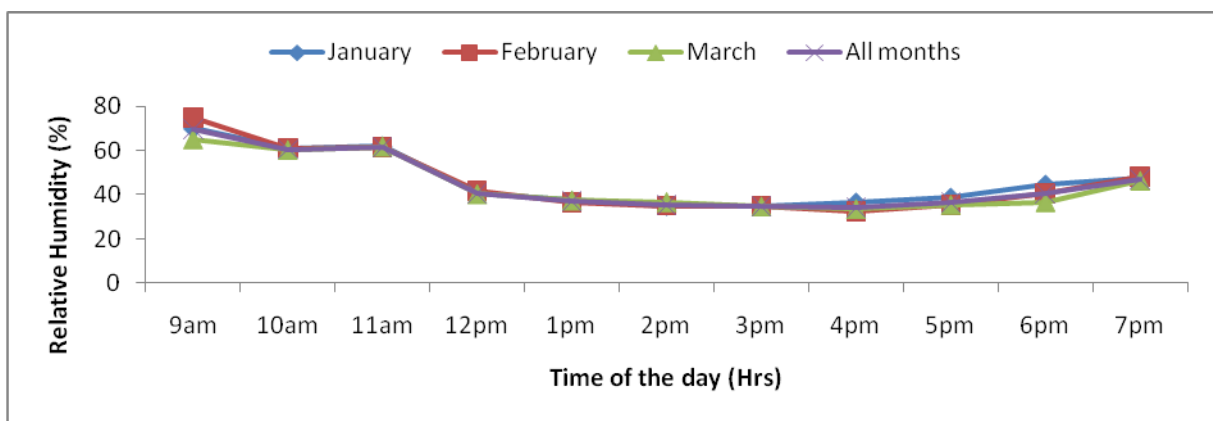


Fig. 2: Profiles of measured indoor environmental variables (a) Air temperature data (b) RH

Relationship between indoor and outdoor climatic data

**Fig. 3** shows the relationship between the indoor and outdoor environmental variables recorded during this survey. The indoor environments followed the outdoor conditions closely. There was a close match of indoor air temperature with outdoor temperature climate, which is a key feature of NV buildings that is greatly different with a constant indoor temperature in AC (Fig. 3 (a)). The change in the indoor temperature was similar to the change of the outdoor temperature, but the difference between the indoor and outdoor temperatures was

small. In most cases, the indoor temperature was always higher in comparison to outdoor temperature. So, it can be concluded that, this thermal behavior may lead to discomfort. The relative humidity of the indoor condition during this study was lower than the outdoor relative humidity except in January when low values of relative humidity were recorded may be due to prolonged harmattan with dry spell (Fig. 3 (b)). The indoor temperature correlated strongly with outdoor temperature ( $r = 0.7742, 0.8011, 0.918, N = 96, p < 0.01$ ), outdoor RH but their relativities were negative ( $r = -0.5598, -0.8684, -0.7306, N = 96, p < 0.01$ ) and robustly with indoor RH as well ( $r = -0.8393, -0.8905, -0.9058, N = 96, p < 0.01$ ). Indoor RH showed a significant relationship with outdoor RH ( $r = 0.9406, 0.9178, 0.9651, N = 96, p < 0.01$ ). This makes humidity an important variable for thermal comfort in this area. The same tendency between indoor and outdoor temperature correlation was noted in Indraganti et al. [2013] and Hwang et al. [2009] studies.

The temperature profiles also provided important information regarding temperature swing and time lag between maximum temperatures of both indoors and outdoors of the hostel. The indoor and outdoor temperature swing in these three months was very small. Outdoor temperature swings were  $10.1^{\circ}\text{C}$ ,  $7.8^{\circ}\text{C}$ , and  $5.8^{\circ}\text{C}$  for the months of January, February and March respectively. The corresponding indoor temperature swings were  $5.1^{\circ}\text{C}$ ,  $5.5^{\circ}\text{C}$  and  $5.6^{\circ}\text{C}$  for the above months, respectively. Maximum temperature swing inside the hostel was  $5.6^{\circ}\text{C}$ , which is quite acceptable for naturally ventilated buildings [Singh et al., 2010]. The difference between the maximum outdoor and indoor temperature was  $1.1^{\circ}\text{C}$ . The highest outdoor temperature was  $32.9^{\circ}\text{C}$  and occurred at 03:00 pm while the highest indoor temperature noted for all sample hostels was  $34^{\circ}\text{C}$ , occurred at 4 pm. This gave a temperature difference of  $1.1^{\circ}\text{C}$  and time lag of 1 h. This time lag also provides critical information regarding the insulation level of the hostel.

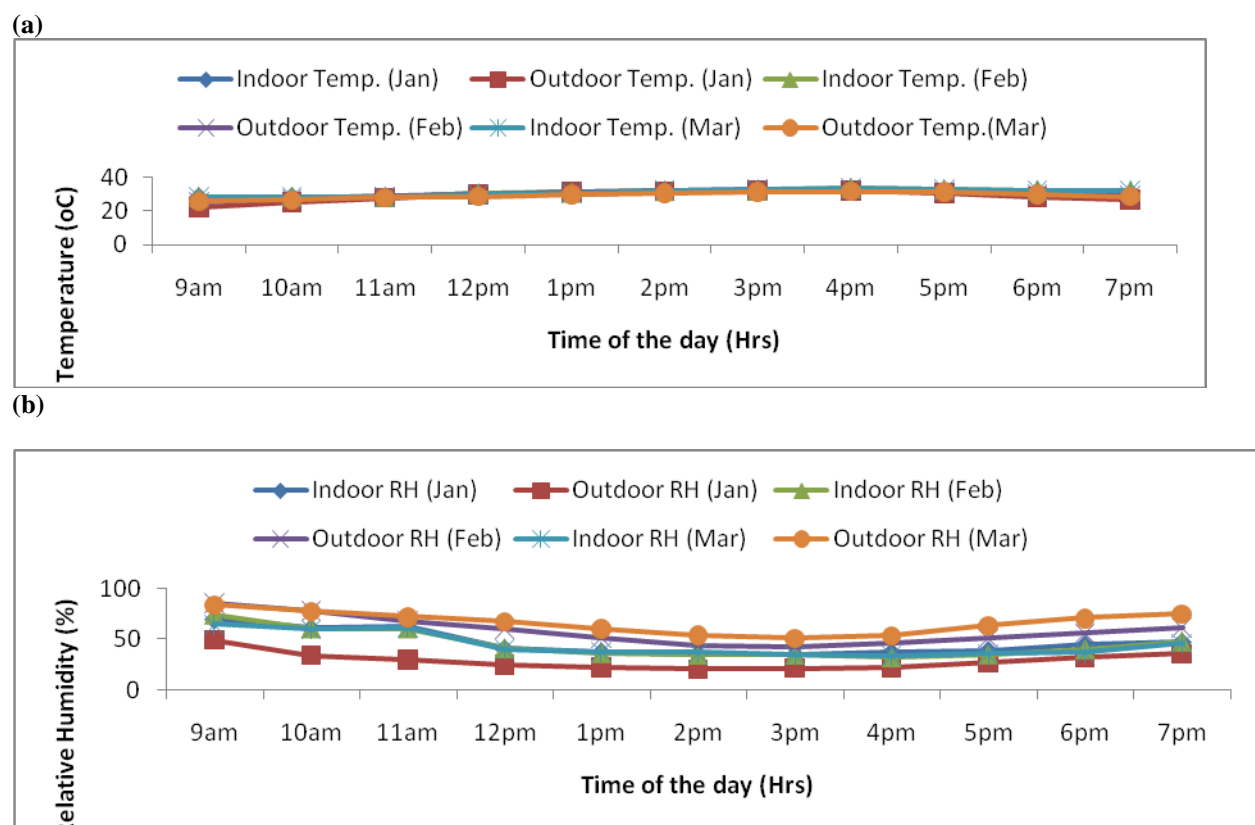


Fig. 3: Relationship between the indoor and outdoor environmental variables (a) Relationship between the indoor and outdoor air temperature (b) Relationship between the indoor and outdoor RH

### Results of PMV and PPD indices

The results of the calculated values of PMV and PPD indices across different months and floors are shown in Tables 3 and 4. For the sample months, the calculated PMV index on the average was +1.63 while the calculated value of PPD index was 57.8% and these indicated that the hostel was observed to be in between

“slightly warm” and “warm” category and that approximately 58% of respondents were predicted to express dissatisfaction with the environment. Table 4 showed that in January when the PMV was +1.60, the PPD was 56.65%. In February, when the PMV was +1.63 PPD value was 56.75% while in March when the PMV was +1.65, PPD was 58.32%. In terms of floor performance (Fig. 6), the PMV values on the ground were lower as its values showed (PMV values = +1.37, +1.54 and +1.57) as against second floor with (PMV = +1.65, 1.67, 1.71]. Based on Table 5, the worst thermal conditions occurred on the second floor across the different months. The t-test on data presented in Tables 5 and 6 revealed that there was no noticeable difference between the PMV values across all floors and different months. This was due to the fact that in these months there was no much difference in the measured indoor environmental variable. The PMV-PPD model was also verified with a set of observations obtained in some previous field studies in NV buildings. It was found through comparison that the values of PMV and PPD indices of the present study were very similar with those obtained by Dhaka et al. [2013], Wafi et al. [2011] and Mohazabieh et al. [2010] in their studies on NV buildings.

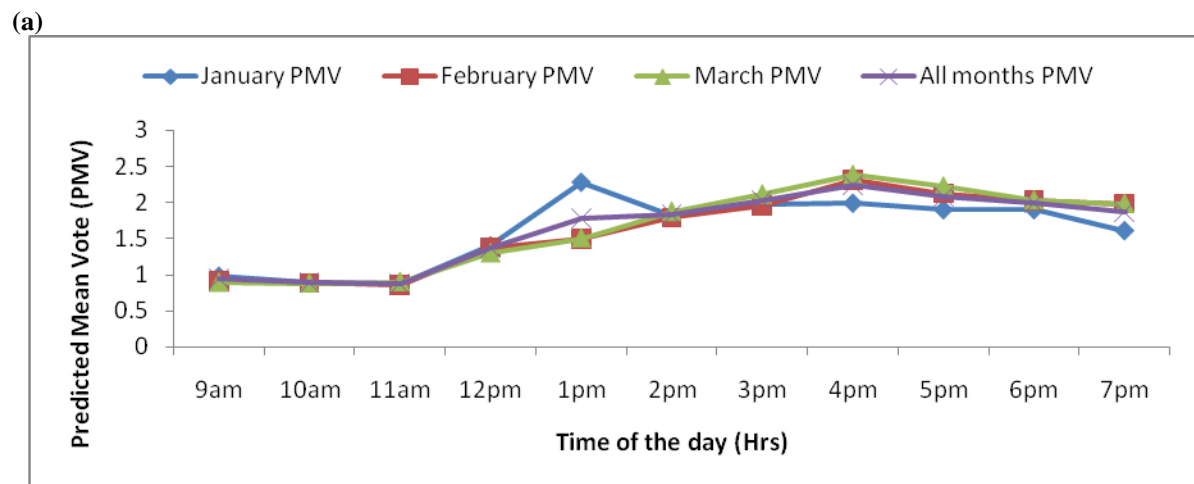
**Table 3**  
Summary of PMV and PPD indices across different months

	January	February	March	All months
PMV	1.60	1.63	1.65	1.63
PPD	56.65	56.75	58.32	57.81

**Table 4**  
Summary of PMV an PPD indices by floors across different months

	January			February			March		
	Grd	Sec	All	Grd	Sec	All	Grd	Sec	All
PMV	1.37	1.65	1.53	1.54	1.67	1.64	1.57	1.71	1.64
PPD	44.41	58.41	53.22	53.27	59.5	58.04	54.48	61.25	57.81

Fig. 4 shows the profile of the PMV values versus time of the day. For the sample months, the range of calculated values of PMV index fluctuated from -0.87 to +2.39 and the majority of them were between +1.37 and +2.24 regardless of the month. It was also observed that for the day and at different time, the PMV values fluctuated rapidly with time because of the drastic fluctuation of solar radiation. Although, the hostel building is protected from direct solar radiation, it was found that there was an increasing trend for the PMV values-directly influenced by the outdoor conditions with time from morning (+0.82-+1.08) to afternoon (1.25-2.39). This showed that outdoor conditions play a role in influencing indoor thermal environment (i.e. PMV values). While the main climatic elements affecting building thermal comfort level (PMV) are solar radiation, air temperature, humidity, wind and rainfall [Mohazabieh et al., 2010; Markus and Morris], solar radiation is the most important element among all, as it influenced the amount of heat transfer to buildings and residents. Besides, the thermo-physical properties, structure, size and orientation are of significant effects on the indoor thermal environment. It is essential for designers to pay more attention to these factors in the early stage of hostel building design.





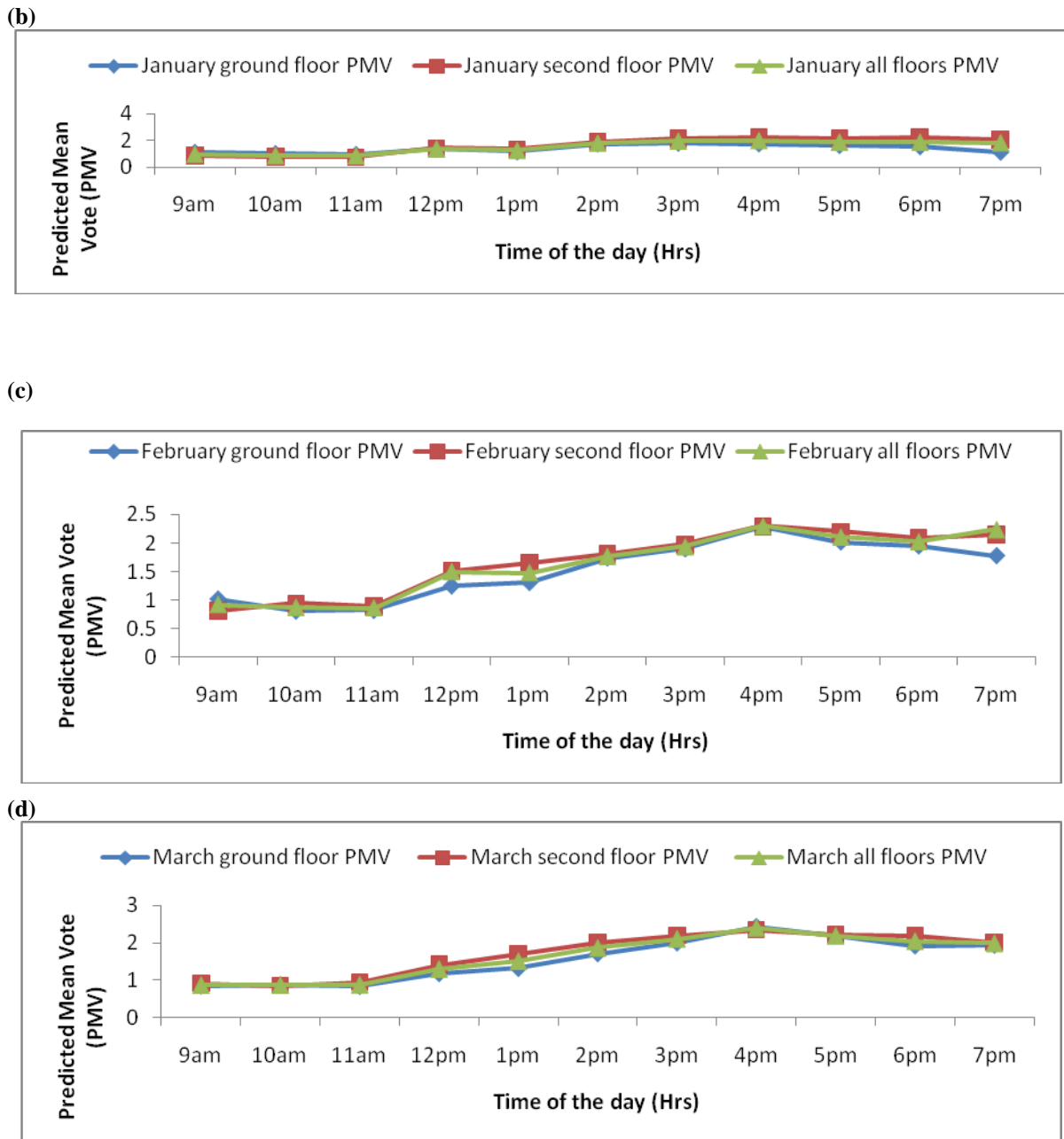


Fig. 4: Time series of PMV values versus time (a) monthly distribution (b) distribution by floor in January (c) distribution by floor in February (d) distribution by floor in March

Fig. 5 illustrated the profile of PPD values plotted against local time for the typical hottest days for the monitoring months. For the three months PPD values approximately fluctuated from 21.09% to 86.21% and great majority of them were between 50% and 70%. From Fig.56, one could observed that there was an increasing trend with time in the PPD values from morning to afternoon directly influenced by the outdoor conditions.

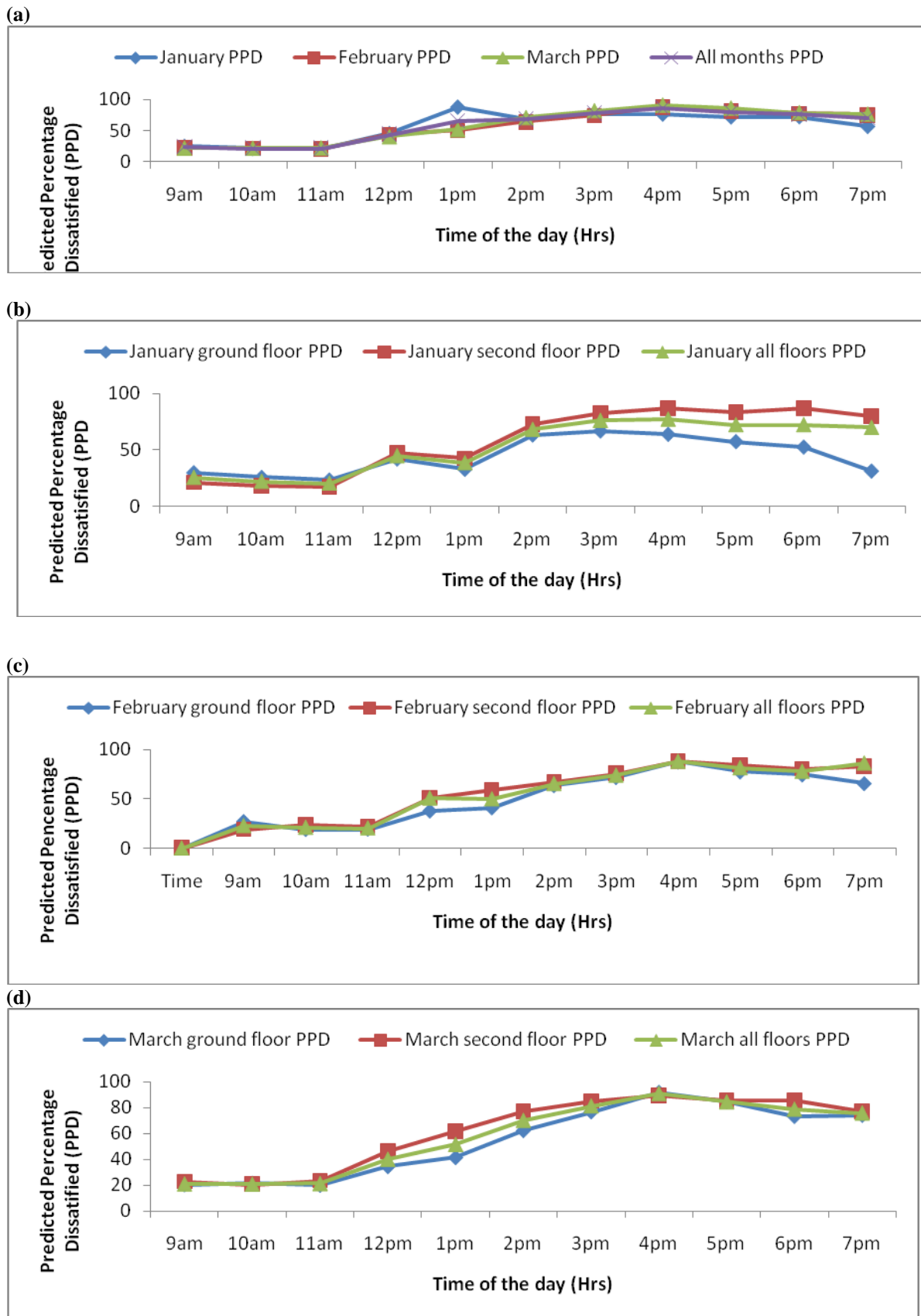


Fig. 5: Time series of PPD values versus time (a) monthly distribution (b) distribution by floor in January (c)

distribution by floor in February (d) distribution by floor in March

The effects of different times of the day on thermal comfort (PMV index) were also analysed. The average indoor PMVs were calculated in three sections of the day and the results are depicted in Fig. 6. The PMV values were not within the acceptable range [-0.5, +0.5] and [-1, +1]. It was observed from this figure that the thermal conditions in the morning were better than those of the noon and the evening hours. The poorest thermal conditions occurred in noon hours between 12.00 and 16.00 pm. However, there was no significant difference between the values recorded.

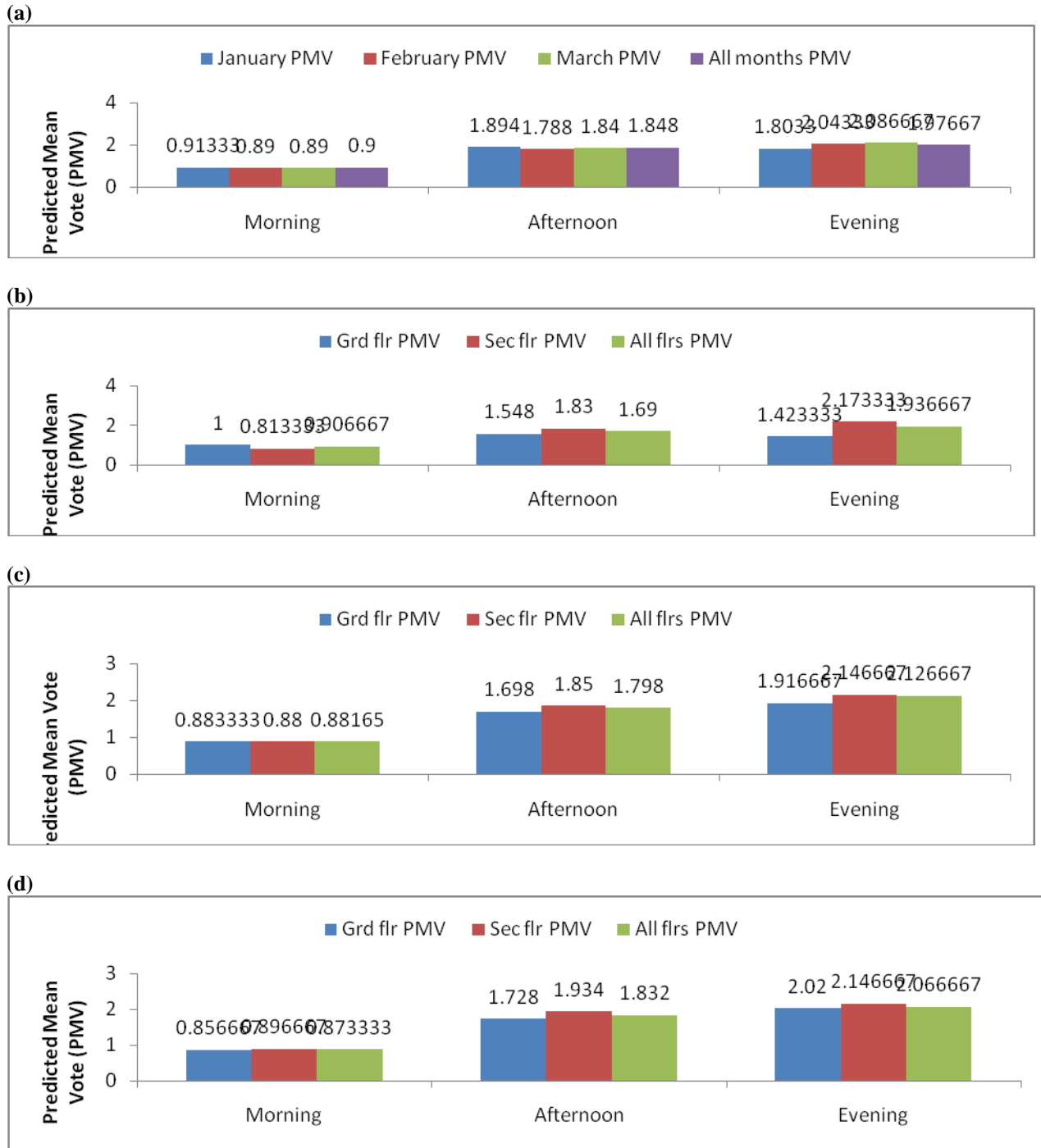


Fig. 6: PMV values by various times of the day (a) distribution by month (b) distribution by floor January (c)

distribution by floor February (d) distribution by floor March

The Percentage Dissatisfied (PD) from the questionnaire survey is presented in Table 5. In all the sections of the buildings and across the different months, the PD values obtained from questionnaire survey were less than 20%. This indicated that the percentage of respondents who were dissatisfied from thermal conditions was less than 20%. Table 5 also compared between the calculated values of PPD index and the Percentage Dissatisfied (PD) obtained from the questionnaire survey. ASHRAE Standard 55 [2004] was designed to provide 80% acceptability of the environment based on 10% dissatisfaction for general (whole body) thermal comfort and an addition of 10% dissatisfaction resulting from local discomfort. By comparing the PPD index and actual dissatisfaction (PD), it was found that there were large differences between the actual dissatisfaction rates and the calculated PPD across the different months. While the calculated values from PPD index showed that as much as 58% of respondents in the hostel building were predicted to have stated a thermal dissatisfaction with their environment, on the other hand, in all the sections of the buildings and across the different months, the PD values obtained from questionnaire survey were less than 20%. This showed that the values of PPD index were not within the acceptable range of 20% in all sections and across the different months as recommended by standard. On the contrary, the PD values were within the acceptable range of 20%. Generally, the value of PPD index based on Eqn. (2) was on the average 38% higher than that which was obtained from actual sensation vote of the respondents (Eqn. 10). Statistical Z-test showed again that there was significant difference between the respondents' opinions (questionnaire survey results) and the computed PPDs ( $p < 0.005$ ). This indicated that the standard PPD of the ISO 7730 and ASHRAE Standard 55 overestimated the level of dissatisfaction in the selected hostel during the hot season. This is a validation of the results of previous studies and also confirmed no agreement between the real sense of thermal comfort in people and the PPD index.

**TABLE 5**  
Comparison of PD from questionnaire with Fanger's PPD index

Indices	January	February	March	All months
Calculated PPD index	56.65	56.75	58.32	57.81
PD (questionnaire survey)	9	14.1	18	13.9

### Thermal comfort on the questionnaire

#### Respondent demographic characteristics

Subjects of this field research were young female students of same age group average 24 years. The sample size varied each month, however, a maximum of 96 subjects voluntarily participated in the short-term survey. They were Nigerian national from different ethnic group (Yoruba, Hausa, Igbo and Edos) living in the surveyed hostel building for at least six months. Table 8 depicted the demographic characteristics of the subjects.

**Table 6**  
Demographic characteristics of the subjects

N=96	Height (m)	Weight (kg)	Age (yrs)	Body surface area	Clothing insulation (clo)
Mean	1.68	58	24	1.65	0.58
Maximum	1.92	75	34	2.14	0.73
Minimum	1.25	47	17	1.41	0.42
STD	8.85	9.6	1.6	0.15	0.14

#### Respondents' real vote

Thermal sensation is the most important human responses to thermal environments and their relationships to a large extent determine the definition of optimal conditions and acceptable ranges. The real vote was based on the respondents vote regarding the thermal comfort of the hostel building. Based on the questionnaire answers of respondents, the characteristics of respondents' real vote value are described in Table 6. The ASHRAE standard 55 [2004] specified that the thermal acceptability should be defined as the condition where 80% of occupants vote for the central three categories (-1, 0, +1). The thermal sensation votes were not the same in all the months. However, there was minimum deviation of the thermal sensation votes across the different months. Comparison among the thermal sensation votes in these months showed that in January 91% of comfort votes recorded by respondents ranged from slightly cool (-1) to slightly warm (+1). The warm and

hot sides of the scale accounted for 9%. The mean thermal sensation vote (MTSV) was +0.45. In February, 85.9% of votes also ranged from slightly cool (-1) to slightly warm cool (+1). The cool side of the scale accounted for 2% and the warm side 12.1% of the votes. The MTSV was +0.56. In March, 82% of respondents perceived thermal sensation as comfortable, votes ranged from slightly cool (-1) to slightly warm (+1). The warm and hot sides of the scale accounted for 18% of the votes cast. The MTSV of respondents were around slightly warm (+0.73). It was observed that, in these three months, there was a biased towards the slightly warm category on the 7-point scale. This is to be expected since the survey was conducted in the hot season.

**Table 7**  
Relative percentage frequency of ASHRAE thermal sensation votes

Thermal perception vote	January	February	March
Cold (-3)	0	1	0
Cool (-2)	0	1	0
Slightly cool (-1)	13.6	10.5	8.7
Neutral (0)	41	37	34.3
Slightly warm (+1)	36.4	38.4	39
Warm (+2)	4.5	8.6	11.3
Hot (+3)	4.5	3.5	6.7
<b>Mean vote</b>	<b>+0.45</b>	<b>+0.56</b>	<b>+0.73</b>

#### IV. SUITABILITY OF PMV-PPD MODEL FOR PREDICTING QUALITY OF INDOOR CLIMATE IN NV HOSTEL

Comparison of PMV-PPD model and standard

The PMV-PPD model employed in ISO 7730 Standard is the most accepted and widely applied thermal comfort model. However, its applicability in NV buildings has been doubted for its basis in climate chamber experiments and ignorance of thermal adaptation that usually occurred in real buildings [Zhang et al., 2010]. To ascertain its applicability in predicting the quality of indoor climate in the present building, a comparative analysis was carried out between the calculated values of PMV index and the recommendations of the standard. According to ISO 7730 [2005] an indoor environment is considered very comfortable when the values of PMV index varied between [-0.5, +0.5] and it is comfortable between [-1, +1]. These values lead to a PPD of 20% and 10% respectively. In other words, the values of PMV index between the limits of [-1, +1] and [-0.5, +0.5] correspond to the point where 80% and 90% of the respondents feel satisfied. When PMV is zero that is to say for the perfect case, the PMV is 5%. The comparison of the PMV values across the different months showed that PMV values deviated more from the acceptable range [-0.5, +0.5] and [-1, +1]. It was also observed that all sections did not have suitable thermal comfort in these months as majority of the values of PMV index were not placed within the range [-0.5, +0.5] and [-1, +1]. The comparison of the values of PMV index across the different sections of the day showed that the hostel building experienced poor thermal conditions in this season as their PMV values also deviated more further from the acceptable range [-0.5, +0.5] and [-1, +1]. The thermal conditions fell below 80% and 90% acceptability ranges. More than 80% of PMV results were mainly located in the warmer region (+1, +2) than recommended by the standard. This indicated that the microclimatic conditions observed in the hostel were typical of non-thermal neutrality  $PMV > 0$ . Using statistic Z-test, it was found that there was a significant difference between calculated values of indoor PMV index and the ISO 7730 recommended values ( $p < 0.05$ ). Similarly, the obtained values of PPD index showed similar distribution with a much overestimation of the percentage dissatisfied under neutrality conditions. The calculated values of dissatisfaction (PPD) index were found to be higher (21-86%) than what the standard required. This difference in calculated values of indoor PMV and PPD indices and the ISO 7730 recommended values has also been mentioned by some researchers [d' Ambrosio Alfano et al., 2013; Azizpour et al., 2013; Giuli et al., 2013; Zhong et al., 2012].

Relationship between PMV and TSV

To further ascertain the applicability of PMV index in the selected hostel and for the purpose of discovering whether PMV and TSV were compatible, the statistical distributions of the percentage of acceptability by employing the PMV index and TSV were also verified (Table 7). The results showed no correspondence between the two different approaches. The PMV was found to be always more than the actual thermal sensation measured. The calculation of PMV using Fanger's equation showed that the values of PMV index predicted on the average between slightly warm and warm sensation category (+1.60, +1.63, +1.65) as regards different months and (+1.37, +1.57, +1.65) in relation to floor levels, which were much higher than the

direct comfort votes (MTSV = +0.45, +0.56, +0.73). Based on the above analysis, the Fanger's PMV equation predicted warmer than what respondent actually felt. This showed that the values of PMV index significantly overestimated the actual mean sensation votes of the respondents. The results in terms of voting patterns showed also that the PMV scale of thermal comfort and the thermal sensation of the hostel residents did not have enough compatibility. The values of PMV index showed that less than 80% of respondents were comfortable according to 80% acceptability of ISO 7730, 2005). On the other hand, more 80% of respondents voted for comfortable and satisfaction in their thermal environment. From the above discussion it can be inferred that the PMV vote distributions in this study have reflected that PMV predicted more pessimistically towards uncomfortable warmer prediction. Similarly, the Standard PPD model greatly overestimated the percentages of dissatisfied respondents.

It was apparent from this study that the standard model which addressed only the physical factors in the evaluation of PMV, overestimated the actual thermal sensation, which is probably affected by additional factors such as the actual or perceived level of available control over the environmental conditions, the actual ambient climate outdoor and culturally conditioned expectations. The lack of correspondence between PMV and TSV on the one hand, the disagreement between the actual levels of dissatisfaction and the Standard PPD line on the other hand, and the observed discrepancies compared with standard raised serious doubts as to the applicability, under local conditions, of the standard model in its current formulation. There were many reasons for this thermal comfort behaviour. The PMV model being a heat balance model, did not take all the adaptation of occupants into consideration although it account for clothing, metabolic rate and air velocity modification to a limited extent. Another reason was that the base temperature and clothing insulation ranges of PMV model differed from what we had come across during our survey. The PMV model considered clothing as a passive insulation around the body, but as evidenced in the present study clothing was used in more dynamic ways to alter the micro-climate around the skin. The clothing ensembles encountered in the hostel have tremendous potential for thermal adaptation and the respondents fully exploited this opportunity. This was not included in the PMV model. As Nicol and Humphreys [2004] noted PMV is a model that represents thermal equilibrium as a heat balance 'at a point in time' that cannot fully explained the temporal conditions that occupants experience in reality. In nutshell, PMV completely ignored many behavioural changes of people in Nigerian hostel building. The cumulative effect of these minor sources of error led to the gross deviation of the PMV from the actual sensation. Thus, PMV being a static heat balance model could not explicate this. Humphreys and Nicol [2002] demonstrated with convincing evidence that the errors in PMV are not just confined to NV buildings alone, but are masked by the narrow range of temperatures experienced in AC buildings as well. Our present data adds to this evidence.

**Table 8**  
Comparison of PMV and MTSV

Index	January	February	March
PMV	+1.60	+1.61	+1.65
MTSV	+0.45	+0.56	+0.73

## V. CONCLUSION AND RECOMMENDATION

The applicability of PMV-PPD model in predicting the quality of indoor climate in a NV hostel building in warm-humid area of Ile-Ife was investigated in the present study. In addition, the study examined the existing indoor thermal environmental conditions as well as occupant perception. The key findings from this study were as follows:

- Empirical measurements showed that the physical condition of air temperature, RH and velocity in the hostel were not within the limits set out by the ASHRAE Standard 55 and ISO 7730 Standard. However, occupants found their thermal environment comfortable, satisfying and acceptable.
- The measured indoor air temperature in the hostel ranged between 28.1-34°C. Relative humidity ranged from 30.8% and 75.5%.
- The thermal environment in the hostel was unacceptable to the occupants judging by the values of PMV and PPD indices
- There was no correspondence between PMV model and MTSV. While the calculated PMV index predicted the hostel indoor climate to be between slight warm and warm the MTSV showed it to be between neutral and slightly warm.
- The subjective assessments showed that the occupants were comfortable while the PPD index predicted that 58% of the occupants were not comfortable.

In conclusion, the results of this study confirmed the suggestion by previous researchers about the limitation

of the PMV-PPD model for predicting thermal comfort in NV buildings.

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