Investigating the applicability of PMVe-PPDe model in non air-conditioned hostel building

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ABSTRACT

To make PMV-PPD model applicable in NV buildings, Fanger proposed PMVe-PPDe model by including an expectancy factor (e). However, there are conflicting reports as regard the applicability of the model in NV buildings. Using the data obtained from physical measurement of (air temperature, relative humidity and air velocity) using Kestrel model 4500, questionnaire survey and observation considering class II protocol, the applicability of PMVe-PPDe model in a NV hostel building was investigated. All the measured environmental variables fell below the comfort range recommended by ASHRAE standard 55 and ISO 7730 standard. Most (85%) of the calculated PMVe values fell within the comfort range recommended by ASHRAE standard 55 and ISO 7730 standard. The obtained PPDe results showed only a slight overestimation (8.9% about) of the percentage of dissatisfied under neutrality conditions. The study concluded that PMVe-PPDe is applicable in NV hostel in this climate. According to the findings of this study, it can be concluded that the Fanger's basic approach for the assessment of the thermal comfort is effective also in naturally ventilated hostel environments if a right expectancy factor is applied.

Keywords: NV environments, thermal comfort in hostel, PMVe-PPDe, expectancy factor.

1.0. Introduction

One of the most important considerations for occupants of educational buildings in terms of their academic performance and development is provision of comfortable indoor environment [1, 2]**.** This is because comfortable indoor microclimate helps in stabilizing their moods and assisting in making them healthy, thus positively influences their intellectual capability and development [3, 4, 5]**.** Taking into account that optimal indoor climate is very important for ensuring comfort, productivity and academic development as well as health of occupants, a good estimation of built environment not only offers comfortable thermal sensation for students, but it also determines the amount of energy that will be consumed by cooling and heating systems in the buildings. Besides, accurate models for predicting thermal comfort during the design phase of a building can also be beneficial in avoiding mal-performance in the use phase [6]. One of the first studies related to this was conducted by ASHVE in 1925, resulting in an index known as effective temperature (ET) [7]. In another study conducted by Vernon and Warner [8]**,** the corrected effective temperature (CET) was developed. Both were used worldwide as indices in thermal comfort studies. However, from the early 1970s, the most common and preferred thermal comfort indices are predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) [9, 10]. The model has become the foundation of international thermal comfort standards such as ISO 7730 [11] and ASHRAE Standard 55 [12]. While the PMV index has been found to be ideal for evaluating static and air-conditioning spaces [7, 13, 14], however, it has been proven that the PMV-PPD model is inadequate in case of naturally ventilated buildings [15, 16, 17]. The model predicted warmer thermal environment, overestimated thermal sensation and dissatisfaction than what occupants felt [18, 19, 20, 21, 22, 23]. Nguyen et al. [13] and Zhang et al. [24] noted that its inapplicability was because the model does not take into account human adaptation and expectation that occurred in real buildings**.** Givoni [25] believed that discrepancies between ISO 7730 and the field studies were due to errors in Fanger`s equations rather than adaptive behaviour. Wang et al. [14] also observed that the failure to predict the thermal sensation happened because the advantages of laboratory studies in designing well controlled conditions which allowed identification of the impacts of particular factors are not possible during field surveys. Fanger and Toftum [26] acknowledged this and proposed expectancy factor (e) to make the PMV-PPD model applicable in non-air-conditioned buildings in warm climate. The corrected PMV-PPD value (PMVe-PPDe) is believed capable to predict occupants' thermal sensation in warm climate if it multiplied by an appropriate expectancy factor (e) that varies from 0.5 to 1 depending on the climate and popularity of air-conditioned building. In recent years, the PMVe-PPDe model and its applicability in NV buildings in warm climate has been examined and validated by some authors [13, 24, 27, 28]**; t**he conclusions from these studies showed conflicting results as regard its applicability in NV from hot to warm humid tropical climates. They however recommended that further investigations under different climatic areas and environments could be useful to obtain more specific expectancy factor values. Unfortunately in Nigeria, this topic has not been investigated in the past and few results available in literature may be hard to applicable due to the different climates and environment. The model was verified in this study. In addition, the study compared the percentage dissatisfied form questionnaire survey and numerical PPD index based on Fanger`s approach.

2.0. Methodology

The selected method in this research was the field survey. Researchers [29, 30] have argued that field surveys among acclimatized populations are the only way in which comfort standards can relate realistically to people's needs. The underlying assumption of the field survey is that people are able to act as 'meters' of their environment. The whole of measurements has been carried out on the basis of a special protocol for the assessment of the Indoor Environmental Quality (IEQ) in schools [31]. The field study was conducted in hot season in the year 2013. The hot season in Ile-Ife ranged from January to March, characterised by high humidity and temperature with low air movement.

2.1. Climate of the study area

The thermal comfort 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^o35`N and longitude $7^o$30`E. Ile-Ife situated in the well-known "Southwest" part of Nigeria covers the area of 380,000 km^2 and is around 250 km 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.

2.2. Description of the hostel building

The hostel building is a low-rise concrete structure of three floor levels and oriented at 15 degrees to the true north (as shown in Fig.1). The building is rectangular in plan with rooms windows predominantly oriented north and south. The building is 65m long, 12 m wide and 10 m high. The size of each window is 1. 5m wide, 1.2 m high and consisted of aluminum alloy frame and single common glass. The size of the door is approximately 0.9 m x 2.1 m. The hostel building was selected for thermal comfort performance analysis in regards to its implementation of bioclimatic design strategies. In particular, orientation and morphology of the building are optimised (i.e. the building shapes improve solar control; room windows face north and south), the envelope is thermally efficient in both its opaque and transparent parts and overhangs are dimensioned to ensure reduced solar gain and avoidance of direct solar heat gain during the year. Besides, the availability and will of the occupants to take part in the short-term investigation was another consideration. In addition, the building has similar construction map, layout and materials as well as type of walls are the same with all other hostel buildings. It is a representative of typical Nigerian student housing.

2.3. The measurement and the estimation of parameters

Six parameters needed for the computation of PMVe and PPDe indices are air temperature, relative humidity, air movement, radiant temperature, metabolic rate and clothing insulation. The first three indoor climatic factors were measured using Kestrel indoor weather tracker model 4500 and the later three factors were calculated from measurement data and observation. In the measuring rooms, the physical measurements were carried out at three points 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 data loggers acquired data at 1 hour interval manually. The measurements were carried out separately in three sections of the day; morning, afternoon and evening. The measurement ran from January until mid-March, 2013 from 9.00 to 19.00. To ensure constant temperatures during measurements, the windows and doors remained opened. To maximize the reliability of the calculation of the PMVe and PPDe indices and minimize the effect of the measurement accuracy on the assessment of the thermal environment, the field measurements were realised according to the level II respecting the specifications set out in the ISO 7726 [32]**.** The outdoor thermal conditions (ambient air temperature, relative humidity, sun hours and global solar radiation) were obtained from the Department of Physics Meteorological Station of Obafemi Awolowo University, Ile-Ife.

Having measured the environmental parameters, the two personal parameters-metabolic rate and clothing insulation-were estimated in accordance with ASHRAE 55 [12]. The standard provides a checklist of typical activities and their corresponding metabolic rates. Respondents were asked to write out what they were wearing at the time of the field study by means of a clothing checklist that was included in the questionnaire.

Fig. 1: Schematic of the selected hostel building

3.0. The brief review of PMVe and PPDe indices

The values of PMVe and PPDe indices were calculated according to the Fanger [33] model on the basis of the measured quantities and personal variables. The model ISO 7730 proposed by ISO organisation for determination of PMV index within a space is as follows;

$$PMV = (0:303e^{-0:036M} + 0:028)\ \{(M - W) - 3:05 \text{ x } 10^{-3}\ (5733 - 6:99\ (M - W - Pa) - 0:42(M - W) - 58:15\} - 1:7 \text{ x } 10^{-5}M\ (5867 - Pa) - 0:0014M(34 - Tmrt) - 3:96 \text{ x}10^{-8} f_{cl}\ (T_{cl} + 273)^4 - (T_{mrt} + 273)^4 - f_{cl} h_c\ (T_{cl} - T_{mrt})] \qquad (1)$$

where

$$T_{cl} = 35.7\text{-}0.028(M - W) \text{-} I_{cl}\ \{3{:}96\ \mathrm{x}10^{-8} f_{cl}\ [(T_{cl} + 273)^4 - (T_{mrt} + 273)^4] + f_{cl} h_c\ (T_{cl} - T_i)\} \qquad (2)$$

The convective heat transfer coefficient h_c (W/m^{2}C) can be valued by means of the following relation:

$$h_c = \max\ [2{:}38(T_{cl} - T_i)^{0{:}25};\ \sqrt{}12.1v_{air}] \qquad (3)$$

The relative air velocity is given as:

$$v_{ar} = va + 0{:}005(M/A_{DU} - 58{:}15) \qquad (4)$$

The ratio of a clothed man's surface area to a nude man's surface area (f_{cl}) can be estimated using the following expression:

$$f_{cl} = \{ \begin{array}{l} 1{:}00 + 1{:}290 I_{cl} \text{ for } I_{cl} < 0{:}078 \\ 1{:}05 + 0{:}645 I_{cl} \text{ for } I_{cl} > 0{:}078 \end{array} \qquad (5)$$

Saturated vapour pressure Ps (kPa) is approximately computed as:

$$Ps_1 = \text{-}\log^{-1}[30{:}59051\text{-}8.2\log (T_i + 273{:}16) + 0{:}0024804\ (T_i + 273{:}16) - \frac{3142.31}{Ti + 273.16}] \qquad (6a)$$

$$P_{S2} = 0.1333\exp\ [18.6686 - \frac{4030.31}{Tmrt + 235} \qquad (6b)$$

To decrease the calculation error, the partial water vapour pressure may be obtained using Eq. (7).

$$Pa = \frac{Psi + Ps2}{2} RH \qquad (7)$$

where,

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

A_{DU} (m^2) is the body surface area of a human calculated according to Dubois formula as a function of the body weight W_b (kg) and the body height H_b (m) as:

$$A_{DU} = 0{:}202 W_b^{0{:}425} + H_b^{0{:}725} \qquad (8)$$

The Mean Radiant Temperature (MRT) required for the computation of PMVe and PPDe indices was computed following the procedure laid out in Nagano [34] where;

$$T_{mrt} = 0.99 - 0.01\ (r^2 = 0.99) \qquad (9)$$

The Predicted Percentage Dissatisfied (PPD) index, which is the estimation for the number of persons who sense dissatisfaction from thermal conditions, is computed from PMV value by the following relation:

$$PPD = 100\text{-}95\exp\ (-0.03353PMV^4 + 0.2179PMV^2 \qquad (10)$$

The parameters in the above equation are defined as: M is the metabolic rate in watts per square meter of the body surface area, W is the effective mechanical power, in watts per square meters, equal to zero, I_{cl}: is the thermal resistance of clothing, in square meters degree Celsius per watt, F_{cl}: is the ratio of surface area of the body with clothes, to the surface area of the body without clothes, t_a: is the air temperature, in degree Celsius, t_{mrt}: is the mean radiant temperature, in degree Celsius, V_a: is the relative air velocity in meter per second, P_a: is the water vapour partial pressure in Pascal, h_c: is the convective heat transfer coefficient, in Watts per square meter degree Celsius, t_{cl}: is the clothing surface temperature, in degree Celsius.

The PMVe-PPDe model can be expressed as:

$$PMVe = e.\ PMV \qquad (11)$$

$$PPDe = 100\text{-}95\exp\ [-\ (0.03353PMVe^4 + 0.2179PMVe^2] \qquad (12)$$

It can be observed from Eqns (1) – (10) that the calculation of PMV is an iterative process. In this work, the values of PMVe and PPDe indices were computed using a program developed in Microsoft Excel software based on the algorithms proposed in the ISO 7730 [11] for the purpose of this study. Concerning clothing insulation and activity level, ASHRAE Standard 55 [12] was referred and the respondents were required to note down their particular types of attire and activity level. The average values for the clothing ensemble insulation and the metabolic rates of the respondents were 0.42 clo and 1.06 met. Based on the calculated PMVe-PPDe, the thermal comfort of the hostel was determined from Table 1.

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

PPD index based on questionnaire was also computed. To determine PPD index based on questionnaire in any section of the hostel building, 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 Pourshaghaghy and Omidvari [12] methodology the PPD index based on the questionnaires in any section of the hostel building was then computed using the following expression

$$\text{PPD} = \frac{\text{The number of questionnaire having discomfort label}}{\text{Total number of questionnaire in any section}} \text{ x } 100 \qquad (13)$$

4.0. Results and discussion

4.1. Climate of Ile-Ife during the survey 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 analysis in the present paper. The averaged values of both indoor and outdoor climatic parameters are given in Table 2 for the three months short-term survey period.

Table 2

The average values of indoor and outdoor climatic parameters

Month	Parameter				
	Indoor		Outdoor		
	T_a (^{o}C)	RH (%)	T_a (^{o}C)	RH (%)	Global solar radiation (W/m^2)
January	30.9	46.16	29.3	28.86	346.17
February	31.2	45.72	30	59.01	390.91
March	31.3	44.48	29.5	66.34	394.45
All months	31.1	45.45	29.6	51.40	377.18

A general profile of the outdoor air temperature, relative humidity and the global solar radiation intensity measured in dry season is presented in detail in Fig. 2. Air temperature (ta) ranged between 22.5°C and 32.9°C (mean = 29.6°C, STD = 2.50). The lowest temperature was recorded at 9 am in the morning, while the highest temperature was recorded at 4 pm in the afternoon (Fig. 2(a). Relative humidity (RH) fell within 20.36% and 85.82% (mean = 51.40%, STD = 19.83) (Fig. 3(2). The global solar radiation ranged from 0-788W/m^2 (mean = 377.8 W/m^2, STD=) (Fig. 2(c). In January, the outdoor air temperature (ta) ranged between 22.5^{o}C and 32.6^{o}C (mean =29.3^{o}C, STD =3.21). Relative humidity showed low values in January and fell within 20.36% and 49.34% (mean = 28.86%, STD = 8.70. The global solar radiation ranged from 0-625 W/m^2 (mean = 346 W/m^2, STD =229). In February, the outdoor air temperature (ta) ranged between 25.1^{o}C and 32.9^{o}C (mean = 30, STD = 2.36). The relative humidity (RH) fell within 42.88% and 85.82% (mean = 59.01%, STD = 13.99). The global solar radiation ranged from 0-788 W/m^2 (mean = 390 W/m^2, STD =278). In March, the air temperature variations were narrower, averaging around 29.5^{o}C with a minimum of 26^{o}C and a maximum of 31.8^{o}C. Relative humidity showed high values with a mean of 66.34% against 59.015% in February.

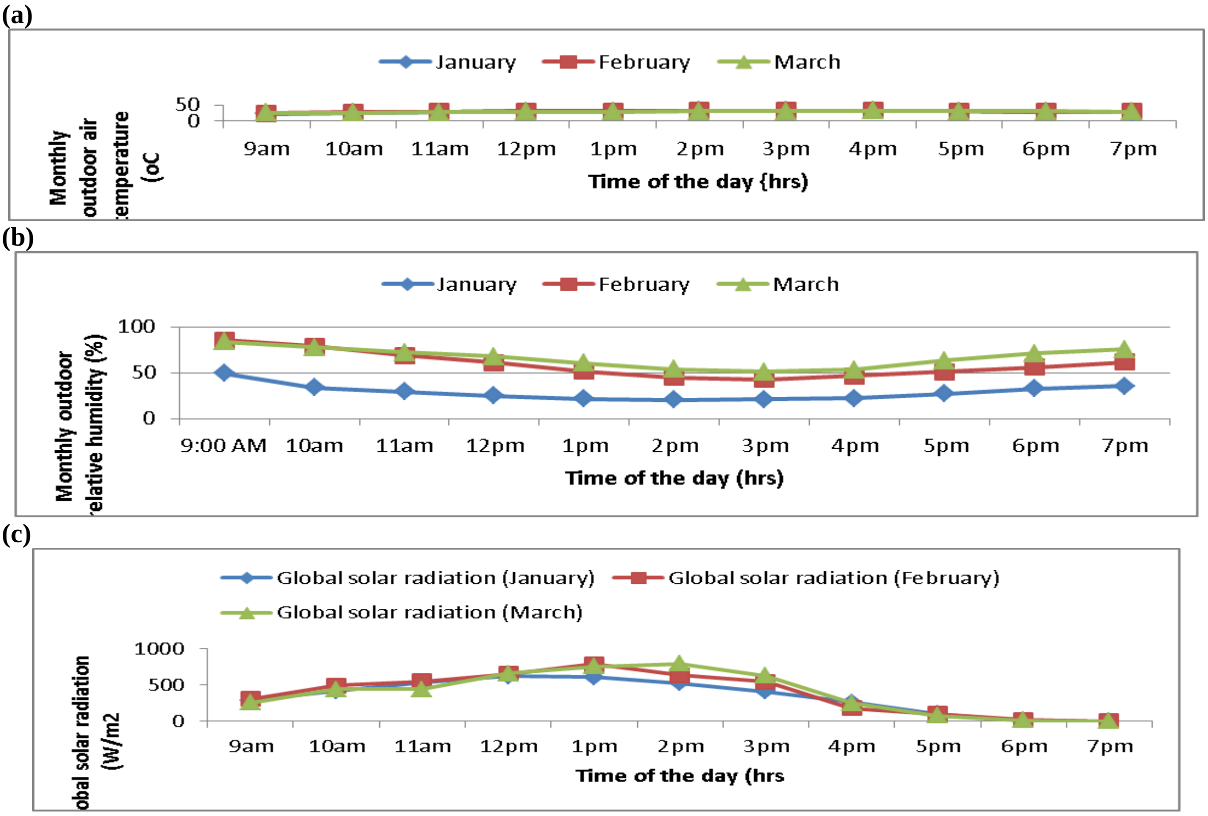

Fig 2: The outdoor environmental variables of the respective days (a) Temperature (b) Relative humidity (c) Global solar radiation

4.2. Indoor thermal environment evaluations

In this study, the indoor thermal comfort was characterised by PMVe-PPDe model mentioned in Section 3. The values of PMVe and PPDe indices were calculated according to the Fanger model on the basis of measured quantities and two personal variables. In order to evaluate the PMVe and PPDe indices, the expectancy factor (e) was assumed to be 0.5 because the weather of this region is warm all year or most of the year and there are few air-conditioned buildings. For comparison purpose, an environment was considered as comfortable when PMVe varies between [-1.0, +1.0]. This value led to a PPDe of 20% for $-1.0 \leq \text{PMVe} \leq +1.0$ respectively [11]**.** The values of PMVe and PPDe indices calculated for different months and sections are depicted in Tables 3 and 4 respectively. For all data the mean value of PMVe index was +0.81 while the value of PPDe index was 28.9% indicating that the hostel was observed to be in between neutral and slightly warm still within the comfort zone limits. Table 3 shows that in January when the PMVe was +0.80, the PPDe was 28.32%. In February, when the PMVe was +0.81, the PPDe was 29.54% while in March when the PMVe was +0.82 the PPDe was 29.16%. In terms of floor performance, PMVe range on the ground floor was the lowest as its mean value shows (PMV values = +0.68, +0.77 and +0.79) as against second floor with (PMV = +0.0.82, +0.83 and +0.86). Data presented in Tables 3 and 4 reveals that there is no noticeable difference in the PMV and PPD values across the months and between the sections of the hostel. This is due to the fact that during these months there was no marked difference among the measured indoor climatic variables. Using statistical Z-test, it is found that there is no significant difference between calculated indoor PMVe and their ISO recommended values ($p > 0.05$).

Table 3
Summary of PMVe and PPDe indices across different months

Index	January	February	March	All months
PMV	0.80	0.81	0.821.65	0.81
PPD	28.32	29.54	29.16	28.9

Table 4
The PMVe and PPDe values inside the hostel for different floors

Floor level	Prediction index	Month		
		January	February	March
Ground floor	PMVe	0.68	0.77	0.79
	PPDe (%)	22.2	26.63	27.34
Second floor	PMVe	0.82	0.83	0.86
	PPDe (%)	29.2	29.74	30.65
All floors	PMVe	0.76	0.82	0.82
	PPDe (%)	26.61	29.02	28.91

Fig. 3 provides the profile of the corresponding PMVe values plotted against local time. From this figure, the characteristics of PMVe index can be observed. For the three months short-term survey, PMVe index approximately fluctuated from +0.38 to +1.22, however, the percentage of PMVe values falling into comfort zone limits was 87% out of the whole data. It was observed from this figure that there was an increasing trend in the PMVe values directly influenced by the outdoor conditions with time from morning to afternoon on these days. Based on this figure also, the worst thermal conditions occurred in the afternoon. This indicated that outdoor conditions among other factors played a role in influencing the PMVe values. It is therefore important for the architects to pay more attention to the effects of sun-earth angular rotation on the indoor thermal environment in the early stages of design process. However, those vote distributions have reflected that PMVe predicted comfortable thermal environment in hostel building during this period. Comparing the PMVe values calculated on the basis of coefficient proposed by Fanger and Toftum [26] with findings from those obtained by Zhang et al. [24] and d`Ambrosio Alfano et al. [27] a good agreement has been found. The expectancy value employ in this investigation (e = 0.5) seems to be in good agreement with Fanger and Toftum’s findings who proposed a value 0.5 for naturally ventilated buildings placed in climatic areas with warm condition all year or most of the year and there are few air-conditioned buildings (the climate here investigated) during the summer. The observed phenomena seem to strengthen the opportunity to extend the PMV approach also to naturally ventilated environments as investigated hostel building because the philosophy forming the base of the expectancy combines very well the best of Fanger`s theory with the need to take into account some adaptation **[35, 36, 37].** The profile of numerical PPDe index calculated from Eqn. (10) is presented in Fig. 4. PPDe index approximately fluctuated from 8.7% to 46%, however, the percentage of PPDe values falling into comfort zone limits was about 36% out of the whole data. There was also an increasing trend in the PPDe values directly influenced by the outdoor conditions with time from morning to afternoon on these days.

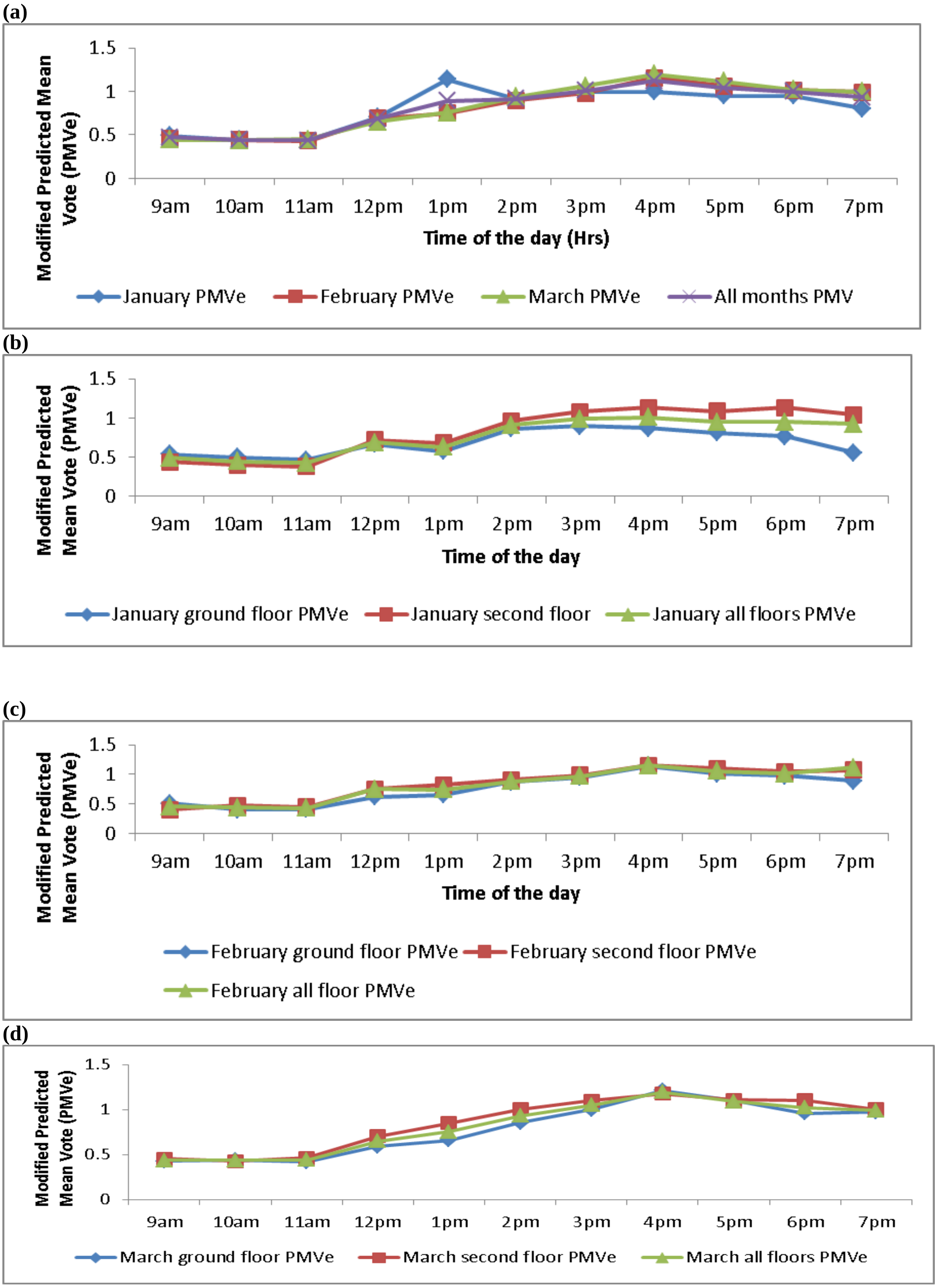

Fig 3: PMVe values with time of the days (a) different months (b) different floor level

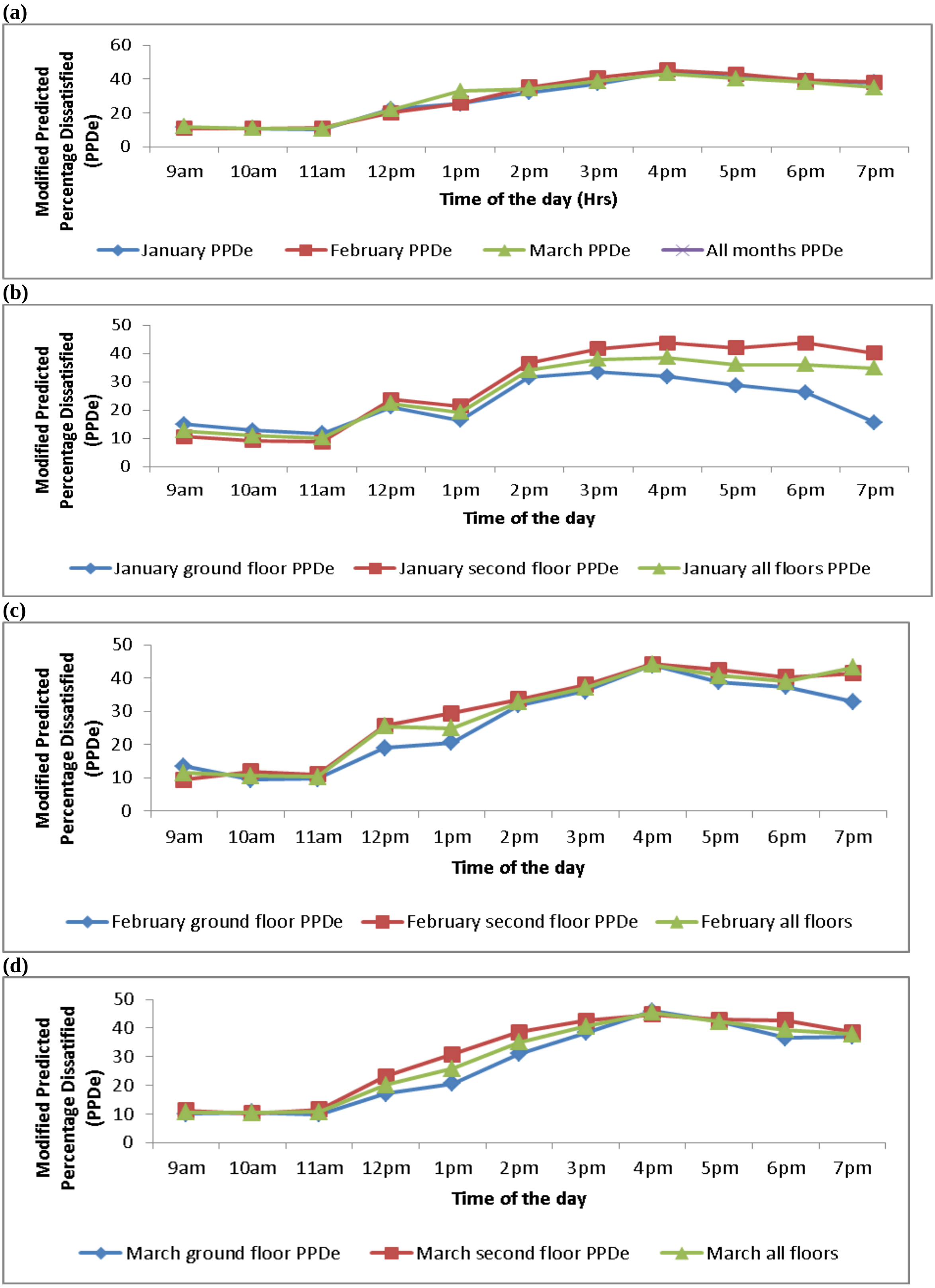

Fig. 4: Time series of PPDe values versus time of day (a) different months (b) different floor level

4.3. PD from questionnaire survey

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%. Comparison between the PD index obtained from questionnaires survey and the numerical PPDe values calculated from Eq. (12) is also presented in Table 5. ASHRAE Standard 55 [12] 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. It was found that there was minimum difference between the actual dissatisfaction rate and the numerical PPDe index across the different months. While the numerical PPDe index showed that 28.9% of respondents were predicted to have stated a thermal dissatisfaction with their environment, on the other hand, the PD value obtained from questionnaire survey on the average was about 20%. This showed that, generally, the value of numerical PPDe index based on Eqn. (12) was on the average 8% higher than that which was obtained from actual sensation vote of the respondents. Statistical Z-test showed again that there was little significant difference between the respondents` opinions (questionnaire survey results) and the numerical PPDe values ($p < 0.005$). This is a validation of the results of d`Ambrosio Alfano et al. [27]**.** Comparing with Brazilian study reported by Van Hoof [38**]** higher PPDe value of 47.5% was obtained. On the contrary, Hwang and Chen [39] reported a range of 3-14% according to the age of interviewed. Wong et al. [40] obtained under neutral conditions in summer a PD of 20% in a tropical climate, whereas Fato et al [41] in a Mediterranean Climate obtained a value of 11%. A so high value of the PPDe could be related to an incorrect choice of the value of the clothing insulation in subtropical climates during the summer.

Table 5

Comparison of PD from questionnaire with Fanger`s PPD index

Indices	January	February	March	All months
Calculated PPD index	28.32	29.54	29.16	28.9
PD (questionnaire survey)	9	14.1	18	13.9

5.0. Conclusion

A dry season field measurement was performed in a naturally ventilated hostel building in Obafemi Awolowo University, Ile-Ife, Nigeria. According to the recorded and stored data, the PMVe and PPDe indices were calculated by using iterative procedure. The following observations were drawn from this study. On the basis of PMVe index, the indoor thermal environment on these days was basically comfortable to the occupants. There is no noticeable difference between PMV values across all the different months. However, the results showed the PMVe values on second floor are higher than the ground floor. In terms of different times of the day, the poorest thermal conditions occurred in the afternoon due to increased solar radiation. the PD values based on the questionnaires are generally lower than the numerical PPDe index values in the hostel. On the basis of data reported in this study the PMVe model appears well fitted for naturally ventilated hostel buildings if the right expectancy factor is applied

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