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Determination of Comfort Conditions Using the PMV, Set and PDD Thermal Comfort Indexes in Ivory Coast

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Abstract

This work falls within the context of reducing energy consumption in Côte d'Ivoire. As the building sector is one of the energy consumers worldwide, it could be a major source of energy savings. A major source of energy savings. With this in mind thermal comfort in buildings in Côte d'Ivoire (Abidjan) in order to determine (Abidjan) to determine thermal comfort conditions. To carry out study, measurement campaigns were carried out in various buildings. These measured parameters were used to calculate comfort indices such as PMV, PDD, SET and operating temperature. A correlation was then made between the PMV index and the operating temperature, then between the SET and the operating temperature to determine the thermoneutrality temperature and the different thermal comfort thermal comfort ranges. The PMV gave a thermoneutrality temperature of 24.87˚C in the rainy season and a thermoneutrality temperature of 25.15˚C during the dry season. In addition, the SET gave comfort ranges, with values ranging from 23.23˚C to 25.70˚C in the rainy season and 23.35˚C to 26.08˚C in the dry season. In addition, the acceptability predicted by the PDD showed that in the rainy season, the premises were more acceptable than in the dry season.

Keywords

Operating Temperature, Thermoneutrality, Thermal Comfort, Acceptability, Energy

1. Introduction

Historically, the first comfort was certainly the possibility of having an enclosed and covered area (Gharbi & Merakchi, 2015). This definition has evolved over time and today it is defined as the degree of discomfort or well-being produced by the characteristics of the indoor environment of a building (Mazari, 2012). Thermal comfort is of vital importance in the quest for well-being and productivity among occupants, as well as in the management of energy resources. Indeed, numerous studies with contradictory results have highlighted the increase in response time and errors or omissions when exposed to heat (Parsons, 2007). In addition, the urban sector, particularly urban systems, accounts for more than 75% of global energy consumption (Mansouri et al., 2019). In France, for example, the residential sector accounts for 65% of consumption (Le, 2008). For better management of the energy used to maintain thermal comfort and the well-being of occupants, knowledge of thermal comfort conditions is necessary. In various countries, thermoneutrality temperatures and thermal comfort ranges have been determined. In Egypt, Amgad Farghal and Andreas Wagner determined a thermoneutrality temperature of 25.4˚C in hot weather in naturally ventilated university teaching spaces (Farghal & Wagner, 2008), as did Tunisia, where the comfort zone was set between 16˚C and 26.5˚C (Al-ajmi & Loveday, 2010). However, the thermoneutral temperature determined in Libya is 31.1˚C and a comfort range of 30.8˚C to 32.5˚C (Taki et al., 1999). These differences in determined neutral temperature show that thermal comfort is specific to a given region. The determination of these thermal comfort conditions is governed by a multitude of thermal comfort indices and standards. The standard effective temperature (SET), the perceived temperature (PT), the physiologically equivalent temperature (PET) and the PMV index are used to assess thermal comfort in enclosed environments (Fanger et al., 1974). All these thermal indices include important meteorological and thermo-physiological parameters (Matzarakis et al., 2010). In Côte d'Ivoire, some work has been carried out on thermal comfort in dwellings (Kouassi et al., 2023), which determined thermal comfort conditions in the district of Abidjan. They showed that naturally ventilated buildings in the city of Abidjan could be comfortable by applying the bioclimatic recommendations determined for the city of Abidjan. However, the thermoneutrality temperature values in homes in Abidjan are not known. Consequently, it is impossible to regulate temperature fluctuations in dwellings. The aim of this study is therefore to determine the thermoneutrality temperature in Côte d'Ivoire.

To achieve this objective, a measurement campaign will be carried out in the homes of local residents. During this campaign, the physical parameters of thermal comfort will be measured, and the thermal comfort conditions will be determined using the PMV and SET indices.

2. Material and Methods

2.1. Material

A number of devices were used to carry out this work. These were devices for measuring the physical parameters of comfort.

The 405i and 405 thermometers were used to determine temperature and air speed inside homes. The Testo 605i Thermo anemometer was used to determine humidity and air temperature. The black globe thermometer was used to read the black globe temperature (Tg) and humidity. The infrared thermometer was used to determine the surface temperature of walls and floors. All these instruments are accurate to within 0.03˚C.

2.2. Methods

To estimate the values of the physical parameters corresponding to thermal comfort in naturally ventilated dwellings in the city of Abidjan, data were collected in 350 dwellings in residential areas. The data was collected between 8 a.m. and 9 p.m. in both the wet and dry seasons.

2.2.1. Data Acquisition

Data was acquired using various devices for measuring the physical parameters of thermal comfort, such as the Testo 405i, the Testo 405, the Testo 605i and the black globe thermometer. During this survey phase, parameters such as temperature, humidity and air speed were measured as well as the black globe temperature. In addition, human-related parameters such as clothing resistance and activity were determined using **Table 1** and **Table 2**.

Table 1. Clothing resistance values (ISO, 1993).

thermal insulation of different items of clothing (clo)							
Woman	medium	light	thick	Man	medium	light	thick
underwear, stockings	0.04	0.04	0.06	underwear, stockings	0.03	0.04	0.04
underwear, top	0.01	0.05	0.14	underwear, top	0.06	0.08	0.08
T-shirt	0.08	0.1	0.12	T-shirt	0.1	0.12	0.12
bustier	0.06	0.06	0.13	polo shirt	0.17	0.17	0.17
short-sleeved blouse	0.12	0.19	0.25	short-sleeved blouse	0.19	0.25	0.25
long-sleeved blouse	0.21	0.25	0.34	long-sleeved blouse	0.21	0.29	0.33
trousers	0.17	0.22	0.28	trousers	0.18	0.24	0.28
shorts	0.08	0.11	0.11	shorts	0.08	0.11	0.11
dress	0.23	0.29	0.29	waistcoat	0.13	0.23	0.29
skirt	0.14	0.18	0.18	pul	0.25	0.36	0.54
jumper	0.25	0.36	0.36	jacket	0.36	0.4	0.44
jacket	0.24	0.69	0.39	tie			
socks	0.02	0.03	0.03	socks	0.02	0.03	0.06
shoes	0.02	0.03	0.03	shoes	0.02	0.03	0.05

Table 2. Table of metabolic values according to activities.

ACTIVITE	W/m²	Met
Resting, lying down	45	0.8
Sitting at rest	58	1
Light activity, sitting (office, school)	70	1.2
Light activity, standing (laboratory, light industry)	95	1.6
Medium activity, standing (machine work)	115	2.0
Sustained activity (heavy machine work)	175	3.0

The clothing resistance of each person surveyed is equal to the sum of the clothing resistance of each item of clothing worn by the respondents (Olissan et al., 2012). It is given by Equation (1).

$$I_{cl} = \sum I_{cl\,u,i} \quad (1)$$

where I_{cl} is the resistance of the whole garment

$I_{cl\,u,i}$ is the resistance of each component i of the garment.

A person's metabolic activity is a function of their activity.

2.2.2. Data Processing

The various comfort indices, i.e. PMV, PDD, SET and operating temperature, have been calculated. The PMV is calculated using Equation (2). A PMV of ±3 gives a PPD of 100% (total dissatisfaction) (Parsons, 2002). This calculation was made by importing the physical parameters of hygrothermal comfort from the berkeley.edu website, using the equations proposed by the standard (ISO, 1993).

$$\begin{aligned}\text{PMV} = &\left[0.303\mathrm{e}^{-(0.036M)} + 0.028\right](M - W) \\ &-3.05\times10^{-3}\left[5733 - 6.995(M - W - P_a)\right] - 0.0014M(34 - t_a) \\ &-3.96\times10^{-8} f_{cl}\left[(t_{cl} + 273) - (t_r + 273)^4\right] - f_{cl}h_c(t_{cl} - t_a)\end{aligned} \quad (2)$$

$$\begin{aligned}t_{cl} = 35.7 - 0.028(M - W) - 0.155 i_{cl}&\left[3.96\times10^{-8} f_{cl}\left\{(t_{cl} + 273)^4\right.\right. \\ &\left.\left.-(t_r + 273)^4\right\} + f_{cl}h_{cl}(t_{cl} - t_a)\right]\end{aligned} \quad (3)$$

$$h_c = \begin{cases} 2.38(t_{cl} - t_a)^{25} & \text{pour } 2.38(t_{cl} - t_a)^{0.25} > 12.1\sqrt{Var} \\ 12.1\sqrt{Var} & \text{pour } 2.38(t_{cl} - t_a)^{0.25} < 12.1\sqrt{Var} \end{cases} \quad (4)$$

$$f_{cl} = \begin{cases} 1.00 + 0.2 I_{cl} & \text{pour } I_{cl} < 0.5 \text{ clo} \\ 1.05 + 0.1 I_{cl} & \text{pour } I_{cl} > 0.5 \text{ clo} \end{cases} \quad (5)$$

PMV = predicted average vote

M = Metabolism, W/m^2 (1 met = 58.15 W/m^2)

W = external work met equal to zero for most metabolisms

I_{cl} = thermal resistance of clothing clo (1 clo =0.155 m^2 k/w)

t_a = air temperature, ˚C

t_r = mean radiant temperature, ˚C

Var = relative air speed, m/s

P_a = water vapour pressure, Pa

h_c = convective heat transfer coefficient, W/m^{2}K

t_{cl} = surface temperature of clothing, ˚C

The prediction of the percentage of dissatisfied people (PDD) is calculated using Equation (6)

$$\text{PDD} = 100 - 95\exp\left[-\left(0.03353\cdot\text{PMV}^4 + 0.2179\cdot\text{PMV}^2\right)\right] \quad (6)$$

SET is linearly related to mean body temperature between 23˚C and 41˚C SET is given by Equations (7)-(9) (Auliciems & Szokolay, 1997).

$$\text{SET} = 34.95 T_b - 1247.6 \quad (7)$$

Below 23˚C the relationship becomes

$$\text{SET} = 26.13(36.4T_b)0.8 \quad (8)$$

And above 41˚C

$$\text{SET} = 41 + 5.58(T - 36.9)0.8 \quad (9)$$

where T_b = average human body temperature

The operating temperature was determined using Equation (10)

$$T_{OP} = \alpha T_a + (1-\alpha) T_{mr} \quad (10)$$

α is a coefficient dependent solely on air speed;

T_a is the air temperature;

T_{mr} is the mean radiant temperature.

2.2.3. Determination of Thermoneutrality Temperatures

The thermoneutrality temperature was determined in two different ways:

- This temperature was determined using a linear correlation between the comfort indices, the PMV index and the operating temperature. A regression line is obtained, and the equation for this line is used to determine the thermoneutrality temperature. It corresponds to the operating temperature for a PMV of (0).

- The thermoneutrality temperture is determined using a linear correlation between the SET and the operating temperature. The equation of the straight line obtained is used to calculate the thermoneutrality temperature according to the SET. This neutral temperature corresponds to the value of the operating temperature for a SET between (22.2 - 25.6) (Moujalled, 2007).

2.2.4. Determining the Percentage of People Satisfied or Thermal Acceptability

The PDD index was used to determine the percentage of people satisfied (AT). This index is used to predict the percentage of people dissatisfied with a thermal environment. The percentage of satisfied people or thermal acceptability was calculated according to Equation (11).

$$\text{AT} = 100 - \text{PDD} \quad (11)$$

3. Results and Discussion

3.1. Determination of the Comfort Temperature According to the Calculated PMV

Figure 1(a) shows the result of the linear regression between the operating temperature and the PMV index for the case of naturally ventilated buildings during the rainy season. The PMV is strongly correlated with the operating temperature. The coefficient of determination is ($R^2 = 0.92$). The equation of the regression line is PMV = 0.3571Top − 8.88 with a slope of 0.36. By replacing the PMV by the value 0, an operating temperature of 24.87˚C is found. This temperature corresponds to the thermoneutrality temperature according to the PMV. The 90% and 80% acceptability intervals correspond to sensations between ±0.5 and ±0.85 (Moujalled, 2007). Thus the thermal comfort temperature according to the

European standard is between (23.44˚C and 26.27˚C) for an acceptability of 90% and between (22.49˚C and 27.25˚C) for an acceptability of 80%.

Figure 1(b) shows the result of the linear regression of the operating temperature and the PMV index for naturally ventilated buildings during the dry season. The equation deduced from the regression is PMV = 0.289Top − 7.2678. The operating temperature is strongly correlated with the PMV calculated during the dry season. The regression line has a coefficient of determination (R^2 = 0.8378). This line has a slope of 0.289, which is less than the slope for the rainy season (0.36). This means that people are less sensitive to variations in operating temperature in the rainy season than in the dry season. This observation was also made by Moujalled, who found a slope of 0.21 in summer and 0.29 in winter (Moujalled, 2007). These values are also close to those obtained by De Dear, who found an average slope of 0.27/˚C for naturally ventilated buildings (De Dear et al. 1998)

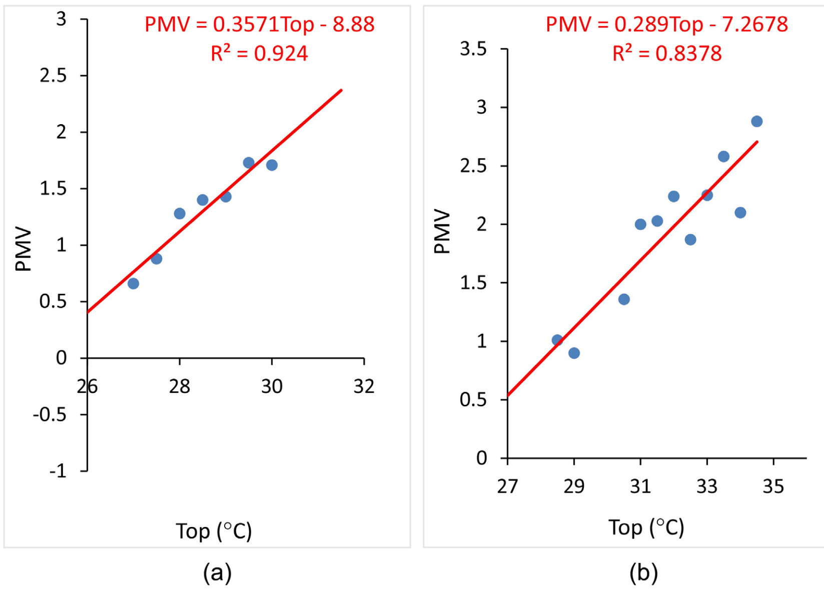

Figure 1. Linear regression of PMV indices on operating temperature. (a) Rainy season; (b) Dry season.

By replacing the PMV by the value 0, which corresponds to a neutral sensation, a thermoneutral temperature of 25.15˚C is obtained. Thus, according to the PMV index, the optimum comfort temperature for naturally ventilated buildings during the dry season in Côte d'Ivoire is 25.15˚C. Taking into account 90% satisfaction, i.e. the PMV interval between −0.5 and 0.5, we obtain a comfort range of (23.41 and 26.87˚C) and between (22.206˚C and 28.089˚C) for a PMV between −1 and +1 for an acceptability of 80%.

These thermoneutrality temperatures, determined according to the PMV calculated as 24.87˚C in the rainy season and 25.15˚C in the dry season, are close to those determined in Egypt by Amgad Farghal and Andreas Wagner, who determined a thermoneutrality temperature of 25.4˚C in the hot season in naturally ventilated university teaching spaces (Farghal & Wagner, 2008). The same is true for Tunisia, where the comfort zone was found to be between 16 and 26.5˚C (Al-ajmi & Loveday, 2010). However, the thermoneutrality temperature in Libya is much higher than that in Côte d'Ivoire. In naturally ventilated buildings, the comfort zone was between 30.8 and 32.5˚C with a neutral temperature equal to 31.6˚C (Taki et al., 1999). This difference could be explained by the fact that the surveys were carried out in the hot season and also by the acclimatisation of the inhabitants of this region. Brager and de Dear argue that in naturally conditioned buildings thermal comfort is more closely linked to natural fluctuations in the outdoor climate (Brager & De Dear, 2001).

3.2. Determining the Comfort Temperature Using the Calculated SET

In order to check whether the indices used in European countries could be used to predict comfort in Côte d'Ivoire, the comfort temperature was determined using the SET (Standard Effective Temperature) comfort index. **Figure 2(a)** shows the result of regressing the operating temperature on the SET thermal comfort index during the rainy season. The equation of the regression line is Top = 0.7276SET + 7.0816. The operative comfort temperature corresponding to a SET value is between 22.2 and 25.6 (Boulinguez et al., 2022). Using the equation of the straight line obtained and replacing the SET value by the bounds of the neutral and acceptable sensation predicted by the SET, the comfort range for the operative temperature is between the values 23.23˚C and 25.70˚C. As in the rainy season, the comfort temperature was also determined using linear regression between the SET comfort index calculated for each individual during the dry season and the operating temperature (**Figure 2(b)**). The regression line obtained has the equation Top = 0.8179SET + 5.1482 and (R^2 = 0.7674). The comfort temperature is therefore between (23.35˚C and 26.08˚C). The comfort temperature values for the rainy period are lower than those for the dry period. This difference in values could be explained by the fact that thermal comfort parameters such as temperature and humidity differ during these two seasons.

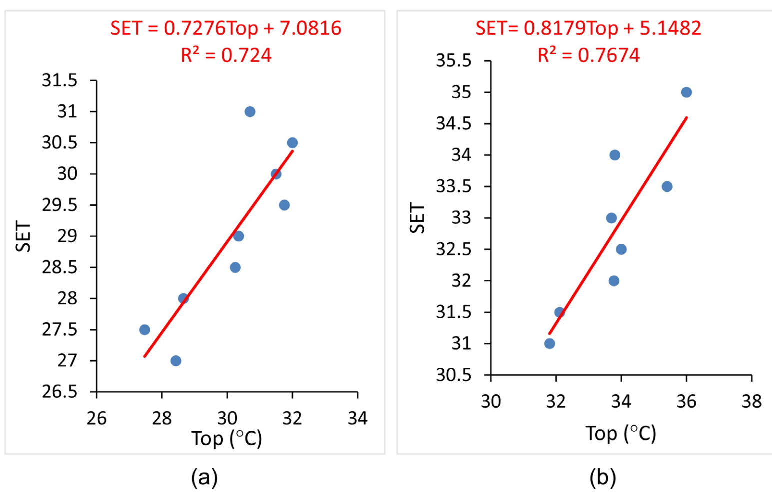

Figure 2. Linear regression of SET indices on operating temperature. (a) Rainy season; (b) Dry season.

3.3. Determination of the Percentage of People Satisfied

Figure 3(a) shows the prediction of the acceptability of the thermal environment as a function of the operating temperatures encountered in the buildings during the rainy season by the PDD. During this season, for operating temperatures of between 27˚C and 28˚C, the PDD predicts an acceptability of almost 80% in the various premises surveyed. This value falls progressively as the operating temperature rises, reaching a minimum value of 40% acceptability. However, in the dry season, for temperatures ranging from 27.5 to 30, the percentage of people accepting their thermal environment predicted by the PDD (Figure 3(b)) is around 60%. This value also falls as the operating temperature rises, reaching a minimum value of 1.6% for a temperature of 36˚C. These figures show that the dry season is the most uncomfortable time of the year in Abidjan. Moujalled's work on dynamic comfort modelling has revealed an acceptability rate of around 95% in winter and summer premises for temperatures between 23˚C and 24.5˚C. This acceptability decreases steadily as the operating temperature rises. Between 28˚C and 31˚C operating temperature, room acceptability falls below 25%. (Moujalled, 2007).

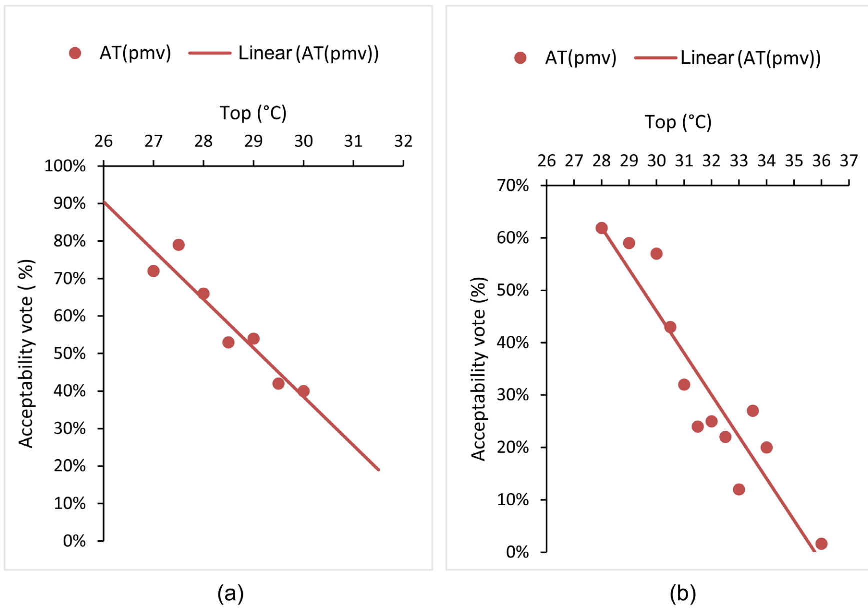

Figure 3. Acceptability of premises according to the PDD. (a) Rainy season; (b) Dry season.

4. Conclusion

Two indices were used to determine thermal comfort conditions in Côte d'Ivoire, specifically in the city of Abidjan, the economic capital of Abidjan, where most homes and offices are located. The first index, the PMV, produced a thermoneutral temperature of 24.87˚C during the rainy season, with a comfort range of 23.44˚C to 26.27˚C. For an acceptability of 90% and a comfort range of (22.49˚C to 27.25˚C) for an acceptability of 80%. In addition, the SET comfort index gave comfort ranges similar to those of the PMV. During the rainy season, the comfort range predicted by the SET was between 23.23˚C and 25.70˚C and between

23.35˚C and 26.08˚C during the rainy season. In addition, during these periods, the PDD showed that the premises were more comfortable in the rainy season than in the dry season. In fact, in the rainy season, acceptability reached a maximum value of 80% and a minimum of 40%, whereas in the dry season, it reached a maximum of 60% and a minimum of 1.4%. In view of these results, heat is the main source of discomfort. It would therefore be wise to limit external heat gain in the various houses to be built, by shielding the largest façades from direct sunlight. Good ventilation of the premises could also help to reduce internal temperatures through convection.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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