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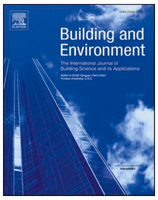

Evaluation of thermal comfort in an office building in the humid tropical climate of Benin

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ABSTRACT

Benin, like most West African countries, is confronted with the lack of indoor thermal comfort standards adapted to the realities of the region. This situation leads to the adoption of Western comfort standards, the consequences of which can be seen in the discomfort of building occupants and above all in significant energy losses. This justifies the need to identify, among the many comfort models developed in the literature, those that are better adapted to the evaluation of thermal comfort in buildings in Benin. Thus, after a literature review on the subject, two comfort models were found to be relevant for the assessment of thermal comfort in air-conditioned buildings in hot and humid regions. These are the adaptive models of López-Pérez and al. and Indraganti and al. The application of these two models on an air-conditioned office building located in the city of Cotonou in southern Benin, resulted in comfort temperatures of $26.1^{\circ}C$and $26^{\circ}C$respectively. These values, very close to the average neutral temperature of the occupants ($26.1^{\circ}C$), reveal the effectiveness of these adaptive models in assessing thermal comfort in the said building. Moreover, the application of Fanger's static model (PMV) and hybrid models ($aPMV$ and PMV_{new}) has shown that the $PMV$and $aPMV$of Yao and al. underestimate the adaptability of the occupants to relatively high comfort temperatures while the $PMV_{new}$of Olissan and al. overestimates this adaptability.

1. Introduction

The major role of a building is to ensure a pleasant indoor climate that is not overly dependent on outdoor conditions. Apart from aesthetics, a building will be judged primarily on the thermal comfort it provides to its occupants. According to ASHRAE-55, thermal comfort can be defined as a state of mind in which people express satisfaction with their thermal environment [1]. It has a direct impact on the health and productivity of building occupants. A low level of thermal comfort generally leads to a loss of productivity, poor health and low thermal satisfaction of the occupants [2,3]. In a study on the influence of thermal comfort on student performance, Cui and al. showed that student learning rates were lower in thermally uncomfortable environments [4]. Thus, the study of thermal comfort is crucial, not only to ensure people's well-being, but also to reduce the energy expenditure attributable to the proper operation of buildings. As evidence, Mui and al. argue that the assessment of indoor thermal comfort is crucial for improving the energy efficiency of buildings [5].

The importance of indoor thermal comfort assessment has been demonstrated by the record increase in the number of publications in this field. Unfortunately, very few comfort studies have been devoted to tropical regions. Of the 17,688 documents consulted by Rodriguez and D'Alessandro, only 2.3% are devoted to thermal comfort in tropical regions [6]. However, according to a report by the Australian James Cook University, nearly 50% of the world's population will reside in the tropics by 2050 [7]. This region of the world will therefore be faced with a spectacular increase in the density of buildings, accompanied by an explosion in energy needs for air conditioning [7]. In addition to the energy wastage currently observed in air-conditioned buildings, the widespread lack of research on indoor thermal comfort in this part of the world will further contribute to global warming.

In West Africa, and more precisely in Benin, in the absence of comfort standards specific to the region, Western standards are applied for air-conditioning buildings. However, according to Olissan and al. the inhabitants of this region are used to higher comfort temperatures and relative humidities than those observed in air-conditioned buildings [8]. Moreover, a study conducted by Toe and Kubota reveals that people's

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Nomenclature

SET	Standard Effective Température
PMV	Predicted Mean Vote
PPD	Percentage People Dissatisfied
$PMVe$	extended PMV model
T_a	air temperature ($^\circ C$)
T_{mr}	mean radiant temperature ($^\circ C$)
RH	Relative humidity (%)
V_a	(m/s)
M	metabolic rate (met)
I_{cl}	clothing insulation (clo)
$CPMV$	Corrected Predicted Mean Vote
f_{cl}	clothing surface area factor
T_{cl}	clothing surface temperature ($^\circ C$)
R_1	long-wave radiation heat transfer between human and surroundings (W/m^2)
R_2	human solar radiation heat load per body surface area (W/m^2)
$aPMV$	Adaptive Predicted Mean Vote
TSV	Thermal Sensation Vote
ACE	Adaptive Comfort Equation
T_c	comfort temperature ($^\circ C$)
T_{rm}	running mean outdoor temperature ($^\circ C$)
PMV_{new}	New model of PMV
ΔPMV	Corrective coefficient
AC	Air-Conditioning
NV	Naturally Ventilated
λ	adaptive coefficient

adaptive capacity and indoor comfort temperatures vary according to the climatic conditions of the area in question [9]. The choice of comfort models adapted to Benin's climatic and socio-cultural specifications is therefore of major importance for achieving sustainable development objectives.

Our study is devoted to identifying, among the many indoor thermal comfort models developed in the literature, those that are most relevant for assessing thermal comfort in air-conditioned buildings in Benin. The methodology adopted for this purpose can be summarised as an in-depth bibliographical synthesis of existing models and the use of the most relevant models to assess thermal comfort in an office building.

2. Thermal comfort assessment

According to Fanger, thermal comfort can be assessed on the basis of six main parameters, four of which are related to the environment and the other two to people. These environmental parameters are air temperature, mean radiant temperature, relative humidity and air velocity. The people-related parameters are metabolism and clothing [3]. But beyond these variables, the thermal perception of an environment can be influenced by physiological, psychological and sociological variables [10]. B. Moujalled reports that, according to Parsons, the study of thermal comfort must be conducted by considering its different physical, physiological and psychological aspects in order to take into account the interrelationships between the thermal conditions of the environment, physiological responses and psychological phenomena [10]. The physical aspect of thermal comfort takes into account the different heat transfers between man and his environment, with the aim of maintaining the body's internal temperature around 37$^\circ C$. This permanent search for the thermal equilibrium of the human body is achieved through thermoregulation, which is nothing else than the set of conscious and unconscious mechanisms that regulate the temperature of the human body. This is the physiological aspect of thermal comfort. As for the psychological aspect, it analyzes the psychological responses resulting from the interaction between the physical characteristics of the environment and perception by the individuals.

The evaluation of thermal comfort in recent years has been mainly motivated by the need for energy efficiency in the building sector, without compromising the long-term health and well-being of the occupants [11]. Several indices and models have therefore been developed to best express the thermal feeling of building occupants. They can be classified into three categories: static models, adaptive models and hybrid models.

2.1. Static models

Static models are approaches to assessing indoor thermal comfort or predicting the thermal sensation of people based on the human heat balance. They take into account only the heat exchanges between man and his immediate environment. The two main models developed in this sense are the Standard Effective Temperature (SET) model proposed by Gagge and al [12] and the Predicted Mean Vote (PMV) model developed by Fanger [13]; the latter being the most widely used in the literature.

The PMV (Predicted Mean Vote) is an empirical model for the assessment of thermal comfort that predicts the average response of a large group of people to their thermal environment. This model is based on the conventional theory of the heat balance between the human body and the environment in which it is located. It was developed by Fanger based on extensive American and European laboratory experiments conducted in a well-controlled environment. This steady-state thermal comfort model has been adopted by international standards such as ISO 7730 [14], ASHRAE Standard 55 [1] and the European standard EN15251 [15] for the assessment of indoor thermal comfort conditions. The PMV index is depending on the 6 variables mentioned hereinabove.

$$PMV = f(T_a,\ T_{mr},\ RH,\ V_a,\ M, I_{cl}) \tag{1}$$

where $T_a$is indoor air temperature ($^\circ C$), $T_{mr}$is mean radiant temperature ($^\circ C$), $RH$is relative humidity (%), $V_a$is air velocity (m/s), $M$is metabolism (met) and I_{cl} is clothing (clo).

Depending on the PMV, the percentage of people dissatisfied with the thermal conditions of the room in which they are located may be determined by Eq. (2).

$$PPD = 100 - 95\ \exp\left[-\left(0.335PMV^4 + 0.2179PMV^2\right)\right] \tag{2}$$

where PPD is the Predicted Percentage Dissatisfied (in %).

To extend its application to free-running (naturally ventilated) buildings, improvements were made to the original PMV model. For example, Fanger and Toftum proposed an extended PMV model by incorporating an expectation factor "e" into the calculation of the basic PMV [16]. This factor was proposed in order to correct the observed discrepancies between the calculated PMV and the actual feeling of the occupants of naturally ventilated buildings (discrepancies caused by the occupants' expectations and adaptability). The expectation factor "e" varies approximately between 0.5and 1and was determined based on the analysis of a database of 3, 200 field survey results from four cities with different climates: Bangkok, Brisbane, Athens and Singapore [17]. The extended $PMV$is calculated using Eq. (3).

$$PMVe = e \times PMV \tag{3}$$

Faced with the flowering of increasingly glazed buildings in response to aesthetic and daylighting requirements, Huang Z. and al. propose the use of the CPMV model to assess thermal comfort in these types of buildings. The CPMV is a model for assessing thermal comfort in

Table 1
Thermal comfort equation in air-conditioned buildings.

Source	Function mode	Comfort equation	Survey climate
López-Pérez and al. [22]	AC	$T_c = 0.13T_{rm} + 22.7$	Hot–humid climate of Mexico
Indraganti and Boussaa [28]	AC	$T_c = 0.049T_{rm} + 22.5$	Warm desert climate of Qatar
Indraganti and al. [29]	AC	$T_c = 0.15T_{rm} + 22.1$	Hot–humid climates of India
CIBSE [30]	AC	$T_c = 0.09T_{rm} + 22.6$	–
Humphreys and Nicol [31]	AC	$T_c = 23.9 + 0.295(T_{rm} - 22)\exp(-[(T_{rm} - 22)/(24\sqrt{2})]^2)$	–

*AC: Air Conditioned; T_c: comfort temperature; T_{rm}: running mean outdoor temperature.

buildings with large glazed surfaces that integrates short-distance radiation factors (solar radiation) into the calculation of the CPMV [18]. It is calculated using Eq. (4).

$$CPMV = [0.303 \times \exp(-0.036M) + 0.0275] \times \{M - W - 3.05[5.733 - 0.007(M - W) - P_a] - 0.42(M - W - 58.15) - 1.73 \times 10^{-2} \times M(5.867 - P_a) - 0.0014M(34 - T_a) - R_1 + R_2 - f_{cl}h_c(T_{cl} - T_a)\} \quad (4)$$

where $CPMV$is the Corrected Predicted Mean Vote, $PMV$is the Predicted Mean Vote.

$R_2$is the human solar radiation heat load per body surface area (W/m^2), $R_1$is the long-wave radiation heat transfer between human and surroundings (W/m^2), $f_{cl}$is the clothing surface area factor, $T_{cl}$is the clothing surface temperature ($^\circ C$) and $T_{mr}$is the mean radiant temperature ($^\circ C$).

In this case, the percentage of dissatisfied people is determined by:

$$PPD = 100 - 95\exp\left[-\left(0.3353CPMV^4 + 0.2179CPMV^2\right)\right] \quad (5)$$

Despite the different improvements in PMV, there are still discrepancies between the prediction results obtained and the actual thermal sensation of the occupants [19–22]. Humphreys and Nicol have shown, in their study on the validity of PMV for predicting comfort votes in thermal environments, that PMV showed marked and systematic differences with the actual average vote, both for naturally ventilated and air-conditioned spaces [23]. Deuble and de Dear have highlighted the inadequacies between the thermal sensation vote of the occupants of an office building in mixed operation mode and the PMV [24]. A study carried out by Z. Zhao and al. in an air-conditioned office building in Qatar shows that the PMV overestimates the comfort level when the actual thermal sensation of the occupant is higher than a slight coolness (-1), while it underestimates the comfort level when the actual thermal sensation of the occupant is slightly warm or even warmer [20]. In general, the observed differences between PMV and TSV in buildings can be justified by uncertainties about the metabolism and resistance of clothing, the psychological aspect of comfort and the adaptability of the occupants. Thus, to overcome the shortcomings of PMV, a new approach has been proposed: adaptive models.

2.2. Adaptive models

The adaptive comfort theory was first proposed by de Humphreys and Nicol in the 1970 in response to the enormous increase in the price of oil [25]. The principle of the adaptive approach states that: “if a change occurs in such a way as to cause discomfort, people respond in such a way as to restore comfort” [26]. This search for thermal comfort can result in behavioural, physiological and psychological adjustments. Since the psychological aspect is a complex factor, difficult to integrate in models but essential to the evaluation of thermal comfort, many researchers then turned to field surveys to collect the real thermal feelings of building occupants. The adaptive approach to thermal comfort is therefore based on the results of field surveys. The different models resulting from this approach take into account the thermal sensation votes of the occupants of the building under consideration and the outside temperature of the study area.

Given the specific parameters of the individual and the region in which he or she is located, several adaptive comfort equations have been developed in the literature. These models show better results compared to the well-known Fanger model. The adaptive approach is widely adopted in thermal comfort studies, particularly because of the major role that adaptive models play in reducing energy consumption and greenhouse gas emissions and ease of use. Table 1 presents some adaptive comfort equations for air-conditioned buildings.

The determination of the comfort temperature with the Humphreys and Nicol equation (Table 1) takes into account the average outdoor temperature (T_{rm}). A better estimate of this temperature is determined from the exponentially weighted moving average of the daily mean air temperature [27]. The latter, expressed in ($^\circ C$), is expressed as:

$$T_{rm} = (1 - \alpha)\left(T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} + \ldots\right) \quad (6)$$

where αa constant whose value varies between 0.6and 0.9; T_{od-1}, $T_{od-2}\ldots$ are the average daily temperatures of the days successively preceding the survey ($^\circ C$).

ASHRAE-55 recommends $\alpha = 0,9$for tropical and humid regions [1]. The same standard recommends the use of daily average outdoor temperatures for 7 to 30 consecutive days prior to the survey date for the calculation of the exponentially weighted moving average temperature (T_{rm}).

2.3. Hybrid models

Fanger argues that one of the obvious weaknesses of the adaptive model is that it does not take into account metabolism, clothing and the four classical thermal parameters that have a well-known impact on the human heat balance and thus on thermal sensation [16]. The PMV - PPD takes these 6 parameters into account, but ignores factors such as the outdoor climate, the expectations of the occupants and their psychological adaptability. In spite of this, the Fanger model remains an essential tool in the evaluation of thermal comfort. Moreover, Chen and al. describe it as a theoretical support for the quantification of thermal comfort in buildings [21]. Thus, in order to consider the factors that characterize the adaptive model within the PMV, Yao and al. have developed a new standardized thermal comfort evaluation index: Adaptive Predictive Average Vote ($aPMV$) [17]. The $aPMV$is an adaptive theoretical model for assessing indoor thermal comfort combining the $PMV$and the adaptive model. It is based on the ‘black box’ theory and consider factors such as culture, climate, social, psychological and behavioural adaptations, which have an impact on the senses used to detect thermal comfort [17]. It was developed through a field study of 3,621students in non-air-conditioned conference buildings in the city of Chongqing, China. The $aPMV$is calculated by Eq. (7).

$$aPMV = PMV/(1 + \lambda \times PMV) \quad (7)$$

The adaptive coefficient (λ) is determined by the method of least squares, substituting the comfort survey data in Eq. (7) above and minimizing the squared error between the TSV and APMV. Therefore, Gao and al. propose equation (8) to calculate the value of λ[32].

(a) (b)

Fig. 1. (a) Front view of the study building; (b) Top view [Google Map].

$$\lambda = \left(\sum_{i=1}^{N} 1/TSV_i - \sum_{i=1}^{N} 1/PMV_i \right) / N \tag{8}$$

where N is the number of data sets, TSV_i is the thermal sensation under different thermal environmental conditions obtained using occupant responses, and PMV_i is the average predictable vote estimated using physical measurements.

The $aPMV$ has been adopted by the Chinese National Standard for Assessment of Indoor Thermal Environment in Civil Buildings GB/T 50.785–2012. This standard recommends values of $\lambda = 0.21$ and $\lambda = -0.49$ according to $PMV \geq 0$ and $PMV < 0$, respectively, for hot summer and warm or mild winter regions in China [21].

Chen and al [21] recommend correction of the adaptive factor for use in a climate other than that for which it was developed. According to the authors, inhabitants of cities located in different climatic zones should have different levels of adaptability to thermal sensation. The values of the adaptive factor must therefore be determined according to the study area.

Olissan and al. have also developed a hybrid thermal comfort model combining PMV and the occupants' thermal sensation vote [8]. Called PMV_{new}, this model has been implemented to assess the thermal comfort of the occupants of air-conditioned and naturally ventilated buildings located in the coastal strip of Benin. As this region is subject to a hot and humid climate, the authors estimated the difference between the thermal sensation vote and Fanger's PMV (ΔPMV) by a multilinear regression whose independent variables are the temperature and relative humidity of the indoor air. Thus, the PMV_{new} is calculated by equation (9).

$$PMV_{new} = PMV - \Delta PMV \tag{9}$$

$$\Delta PMV = a.T_a + b.RH \tag{10}$$

where PMV_{new} is the Fanger PMV adapted to the south coastal region of Benin, ΔPMV is the correction factor, T_a is the indoor air temperature ($^\circ C$), RH is the indoor relative humidity (%), a and b are constants from the multilinear regression.

This model was tested in twelve air-conditioned environments in the city of Abomey-Calavi in southern Benin. The results obtained allowed the authors to conclude that the model well represented the thermal feeling of the occupants of the studied environments.

In summary, the above-mentioned static, adaptive and hybrid models have proven themselves for the assessment of thermal comfort in buildings. However, their effectiveness on buildings located in regions other than those in which they were developed remains to be proven. A case study has therefore been carried out to verify this claim.

3. Case studies

3.1. Study area

The case study was carried out on an office building located in the city of Cotonou in southern Benin. With a surface area of 79 km^2, the city of Cotonou is located at the intersection of parallels 6°20'and 6°23'North latitude and meridians 2°22'and 2°28'East longitude [33]. It enjoys a tropical Aw climate according to the Köppen-Geiger climate classification [34]. The hottest season of the year covers the period from February to May with an average temperature and humidity of around $30^\circ C$ and 80% respectively. The coolest season is observed in July–August. The average temperature and humidity recorded during this period are around $27^\circ C$ and 83% respectively.

The city of Cotonou is the economic capital of Benin with a population of $2,401,067$ inhabitants, about $1/5$ of the national population [35]. It represents the country's development pole and is home to most private, national and international institutions. This city concentrates a large part of the country's energy needs. As Benin is a very low-industrialized country, most of the energy produced is consumed by office buildings. According to the 2017 report of the Directorate General of Energy Resources, 44.38% of the electricity produced is consumed by office buildings and services [36].

3.2. Presentation of the study building

The building selected for the evaluation of thermal comfort models is the building of the Caisse Nationale de Sécurité Sociale. It is located in the city of Cotonou. The building consists of a nine-storey circular tower and two A and B wings of seven storeys each and of concave shape (Fig. 1). Wing A, with the main entrance and facing north, makes an angle of about 47° with wing B. The building envelope, constructed of cement mortar brick and concrete, has 38% glazed area. The building has mainly an entrance hall on the ground floor, 88 offices and seven meeting rooms, all spread over an area of 6098 m^2. All meeting rooms and offices are air-conditioned. The air-conditioning systems installed in

Table 2
Informations of the participants.

Sex	Number	Age (years)	Height (*cm*)	Weight (*kg*)	Metabolism (*met*)	Clothing resistance (I_{cl})
Female	14	[23 – 47]	[155 – 170]	[50 – 98]	1.2	[0.5 – 0.7]
Male	15	[26 – 47]	[166 – 178]	[61 – 85]	1.2	[0.75 – 0.85]

Fig. 2. (a) Overview of a group office; (b) temperature and humidity sensor; (c) anemometer.

the building are splits. Each office therefore has its own air-conditioning unit. 215 people occupy the building.

3.3. *Comfort survey*

A comfort survey was carried out in order to collect the real feelings of the building's occupants with regard to their thermal environment. It is a level III survey according to Nicol's classification [37]. Moujalled [10] considers this type of survey preferable to explore the thermal quality of an environment, since it allows to collect more information on the indoor thermal environment and on the occupants.

Respondents were asked a series of questions divided into four sections. The first section looked at the anthropometric data of the respondents such as sex, age, height, weight and health status (Table 2). No health problems were identified among the survey participants.

In the second section, the actual thermal sensation of the occupants in relation to their thermal environment was assessed. Thus, questions such as: What is your current feeling about your thermal environment? What is your current thermal preference? What was your activity in the hour before the survey? etc. Answers to the first two questions were recorded on the ASHRAE seven-point scale defined by -3(cold), -2(cool), -1(slightly cool), 0(neutral), $+1$(slightly warm), $+2$(warm), and $+3$(hot). As for the third section, information on the level of activity and clothing of the occupants was provided. A table showing different combinations of clothing according to ISO 7730 [14] was proposed in the questionnaires. The level of clothing of each participant was therefore estimated according to the choice made by each participant taking into account the clothing worn.

Finally, in the fourth and last section, the respondents gave their opinion on the personal control they have over their thermal environment. The average time to complete the questionnaires is 5 min. A total of 205 questionnaires were selected out of the 217 distributed; the 12 rejected questionnaires were filled out incorrectly. 29 volunteers participated in the survey, including 14 women and 15 men (Table 2). The questionnaires were distributed to the occupants on a daily basis and alternately in the morning and afternoon. For similar thermal conditions and levels of activity and clothing, no significant difference was observed between the morning and afternoon thermal sensation votes. This is explained by the long break period (approximately 2.5 h) enjoyed by occupants in the middle of the day. Thus the influence of workload accumulation on the thermal sensation of the participants is considerably limited. The survey took place from June 17 to July 20, 2019.

Parallel to the surveys, temperature, humidity and air velocity measurements were taken in the building's offices. The devices used for this purpose were EasyLog-USB temperature and humidity sensors and an anemometer (Fig. 2) whose characteristics are shown in Table 3. In the offices for personal use, the sensors were placed on each participant's desk and at a good distance from computers and any other heat source that could compromise the reliability of the measurements. In contrast, in the multi-occupancy rooms, the sensors were placed on the desk closest to the center of the room. The climatic atmosphere in this case is considered to be homogeneous. This assumption was made on the basis of a recommendation of ISO 7726 [38]. The latter states that an environment can only be considered "homogeneous" from a bio-climatic point of view if, at a given time, the air temperature, radiation, air velocity and humidity can be considered practically uniform around the subject, i.e. when the deviations between each of these quantities and their spatial mean value calculated as an average of the locations do not

Table 3
Specifications of the instruments.

Parameter measured	Instrument	Accuracy	Internal resolution	Tolerance
Air temperature ($^\circ C$)	EasyLog USB 2+	$\pm 0.55^\circ C$	$0.5^\circ C$	$[-35^\circ C;\ 80^\circ C]$
Relative humidity (%)	EasyLog USB 2+	±0.5%	$0.5\%RH$	[0%; 100%]
air velocity ($m/\ s$)	Digital anemometer	$\pm 2\% + 1d$	$0.1m/s$	$[0.2\ m/s;\ 20\ m/s]$

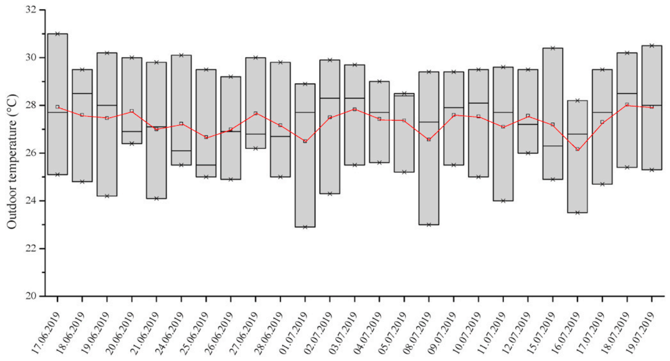

Fig. 3. Outdoor temperature during the investigation period.

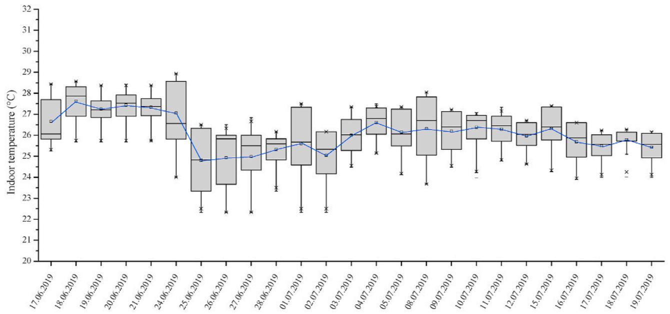

Fig. 4. Indoor temperature during the investigation period.

exceed the values obtained by multiplying the required measurement accuracy by a factor of X. This condition is frequently met in the case of air temperature, air velocity and humidity, but more rarely in the case of radiation [38]. Thus, prior to the surveys, for each multi-occupancy room, temperature and humidity sensors were placed on each desk. The sensor placed on the desk closest to the center of the room was considered the primary sensor. The temperature and humidity measurements were taken over a working day. The differences between the data measured on each desk and those measured by the main sensor were of the order of $1.5^{\circ}C$and $0.2\ kPa$. However, with reference to the ISO 7726 standard, the deviations not to be exceeded, taking into account the devices used in this study, are $1.5^{\circ}C$for the temperatures and $0.3\ kPa$for the humidity. As for the air speed, point measurements have been made and the average deviation obtained is $0.1\ m/s$against a deviation of $0.22\ m/s$according to the same standard. Consequently, the hypothesis of homogeneity of the climatic environment of these premises has been validated.

The temperature and humidity of the premises were recorded continuously throughout the survey period with a 5-min time step. Air velocity was measured as participants completed the questionnaires. The recorded temperatures and humidities ranged from $20.2^{\circ}C$to $29.5^{\circ}C$and 44.4%to 81.6%respectively. Air velocity was estimated at $0.1\ m/s$on average. Outdoor and indoor conditions during this period are shown in Figs. 3 and 4 respectively.

3.4. Thermal comfort models for the study building

As stated above, three categories of models have been implemented for the assessment of thermal comfort in buildings: static, adaptive and hybrid models. The use of any of these models depends mainly on the mode of operation and the region where the buildings to be studied are located. However, since no comfort model has been developed for the humid tropical region of West Africa, it would not be prudent to proceed directly to the choice of a model to assess thermal comfort in the study building. The models presented above will therefore be applied to this study.

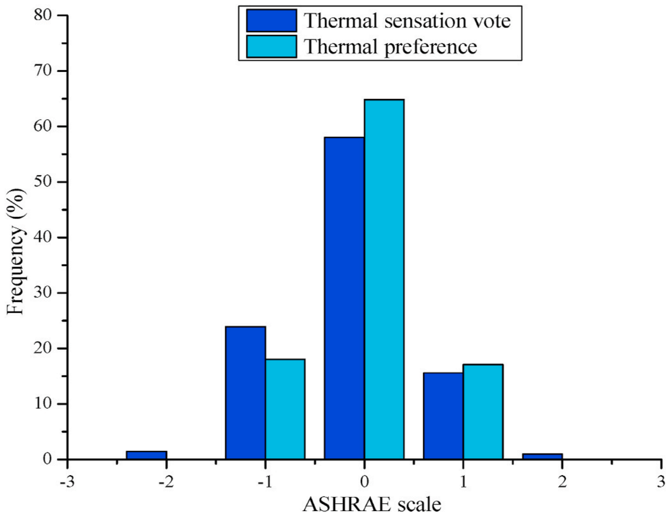

Fig. 5. Distribution of the thermal sensation vote and the thermal preference of the occupants.

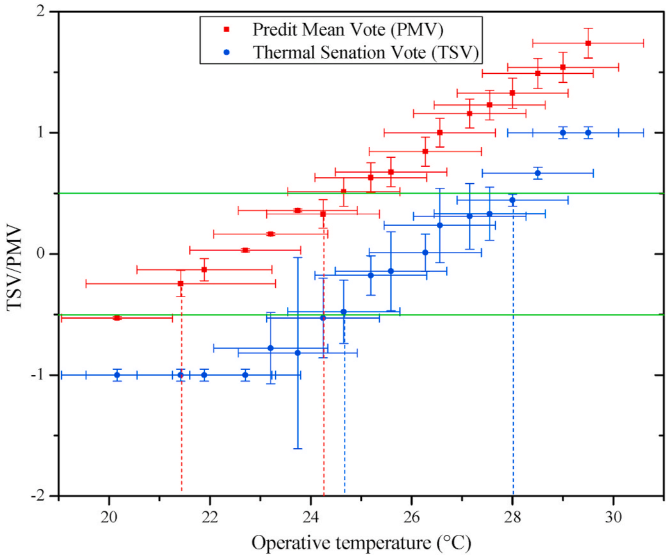

Fig. 6. Thermal sensation voting results as a function of operating temperature.

Thus, the static Fanger model (PMV) was first used. The comfort indices from this model were calculated using the online calculator of the Center for the Built Environment (CBE) [39]. The environmental data (temperature, humidity and air velocity) measured during the survey were entered into the online calculator, as well as the metabolism and clothing level of the participants. As for the extended PMV, it was not applied to the case study because of the way the building operates (air-conditioned building). The same applies to the CPMV because of the non-existence of calculation parameters related to direct solar radiation inside the offices. Indeed, the offices surveyed have curtains and blinds that prevent the transmission of direct solar radiation.

With respect to adaptive models, Mishra and Ramgopal state that many of these equations often do not predict comfort zones that are very different from each other [11]. Nevertheless, for optimization of building energy efficiency, it makes sense to use CEA that reflects the actual thermal sensation of the occupants. For this purpose, the ECAs in Table 1 were all used in order to highlight those that are the most suitable for our study. The running mean outdoor temperature (T_{rm}) used for this purpose was obtained from equation (6) by taking the weighted average of

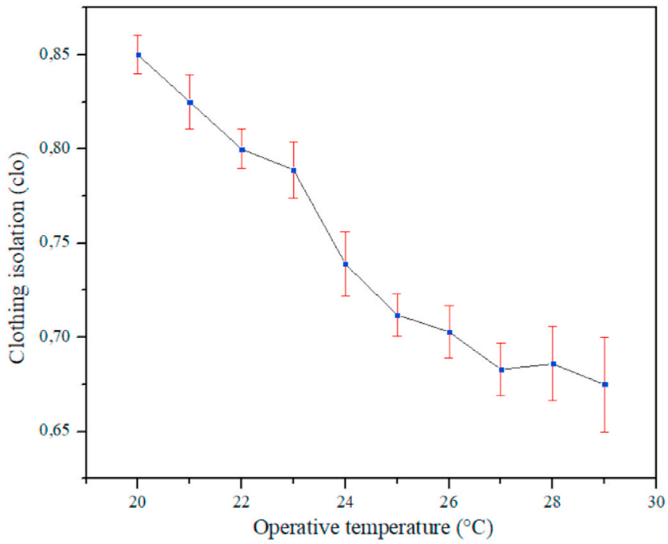

Fig. 7. Clothing resistance of the occupants as a function of the indoor temperature.

outdoor temperatures for the 30 days preceding the survey.

Finally, the application of the hybrid models that are the adaptive PMV (*aPMV*) of Yao and al. and the $PMV_{new}$of Olissan and al. to this case study required the voting of the thermal sensation of the occupants. The responses obtained were used to determine the adaptive coefficient (λ) of the *aPMV*and the regression coefficients of the PMV_{new}.

4. Results and discussion

4.1. Occupants' thermal sensation and preference

The set of occupants' thermal sensation votes in relation to their thermal environment and their preference is shown in Fig. 5. Fig. 6 presents the average thermal sensation vote of the occupants as a function of the average operating temperatures grouped by 0.5°Camplitude class. Given the lack of consensus on the choice of a specific comfort range in the literature, the comfort range resulting from the thermal sensation votes has been assimilated to that of Fanger with reference to the comparative study by Chen and al. [21], i.e. $[-0.5; 0.5]$. Thus, the comfort temperature ranges from 24.8°Cto 28°C. Within this range, 47.8%of the responses show a neutral feeling of the participants in relation to their thermal environment, compared to 10.7%who feel slightly cool and 11.2% who feel slightly warm. For temperatures below 24.8°C, 13.2%of respondents felt slightly cool, while 7.3%felt neither cold nor hot. Above 28°C, only 3.4%of participants felt comfortable in their environment, while 3.9%felt slightly warm.

However, since the thermal sensation vote does not always correspond to a state of comfort or discomfort, respondents were given a preference vote. The results reveal that 4.2%of people in the neutral zone prefer to feel slightly warmer, compared to 57.1%of those who do not want any change. A total of80.2% respondents prefer an environment with an operating temperature of 24.8°Cor higher, with an average clothing level of 0.7 *clo*and a metabolism of 1.2 *met*. This acceptability of relatively high comfort temperatures can be justified by the thermal history of the participants. Since all respondents have lived in southern Benin for at least 8 years, they are acclimatized to the hot and humid climate of the region. A study conducted by Mina and al. in the United Kingdom on 3452students revealed significant differences in the subjective thermal comfort of people with a warmer thermal history and those with a climatic history similar to that of the United Kingdom [40]. Through this study, the authors showed the influence of long-term thermal history on thermal sensation, comfort zone, acceptability, preferences and comfort temperature. This thus confirms the preference of the respondents in this study.

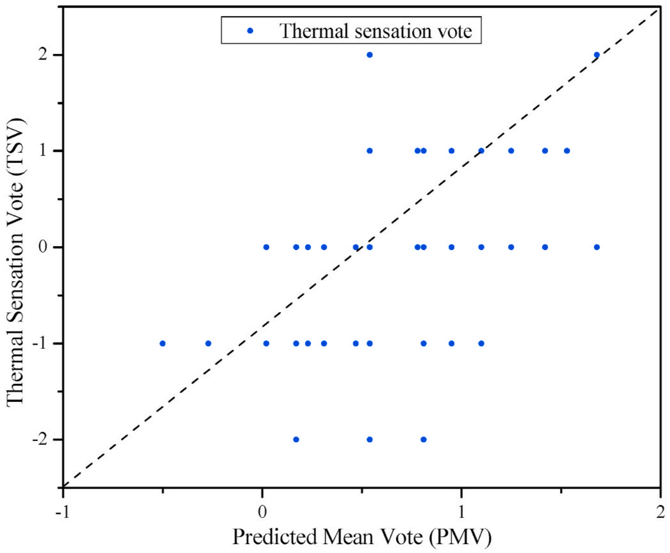

Fig. 8. Representation of TSV as a function of PMV.

4.2. Adaptation of the occupants to their thermal environment

The adaptation mode most adopted by the occupants is the action on the air conditioning system. In fact, occupants can turn their air conditioners on or off as they feel like it. This control is much more noticeable in personal offices. On the other hand, in collective offices, the control of air conditioners is limited. Occupants are often forced to adapt to the imposed thermal environment. In these offices, clothing adjustments are much more noticeable. Since the air conditioners are permanently on in these offices, the occupants often use tracksuits to restore their thermal comfort. The plot of a curve of the clothing level in relation to indoor temperatures shows a change in clothing as the operating temperature decreases (Fig. 7). The linear regression of this curve makes it possible to affirm that the occupants dress according to the indoor temperature of their office ($R^2 = 0.87$).

In Fig. 7, it can be seen that clothing insulation varies from 0.85 *clo*to 0.74 *clo*when the temperature varies between 20°Cand 24°C. This level of clothing can be considered high for people living in an area where it is hot all year round. This level can be lowered to a maximum of 0.75 *clo*. According to ISO 7730 [14], this value corresponds to a set of clothing consisting of shorts, trousers, shirt, sock and shoe. This action will make it possible to raise the temperature of highly air-conditioned environments by 2to 3°Cand at the same time reduce energy consumption without affecting the comfort of the occupants.

4.3. Evaluation of thermal comfort in the study building

4.3.1. Evaluation by Fanger's PMV

Fig. 8 shows the set of thermal sensation votes as a function of the calculated predicted average votes. The analysis of the latter reveals a difference between the thermal sensation vote (TSV) of the occupants and the Fanger's PMV. Indeed, a similarity between the TSV and the PMV would have given points very close to the diagonal. Also, referring to Fig. 6, we can clearly see a gap between the average occupant thermal sensation vote (TSV) and the PMV indices. This indicates that Fanger's PMV underestimates the adaptability of respondents to relatively high temperatures. This is evidenced by the fact that the comfort interval derived from the survey results is [24.7°C; 28°C]compared to [21.5°C; 24.3°C]when PMV is applied to the study. The uncertainties

Table 4
Statistical analysis of ACE.

Models	López-Pérez and al. [22]	Indraganti and Boussaa [28]	Indraganti and al. [29]	CIBSE [30]	Humphreys and Nicol [31]	Reference
Comfort temperature ($^\circ C$)	26.1	23.8	26	25	25.1	26.1 ± 0.5
Critical Probability of Student's Test	0.7688	$p - value < 2.2e - 16$	0.141	$p - value < 2.2e - 16$	$p - value < 2.2e - 16$	

associated with these values were estimated using the method developed in the Guide to the Expression of Uncertainty in Measurement (GUM) [41]. This guide recommends the combination of Type A uncertainties (statistically related) and Type B uncertainties (related to the equipment and other sources that influence the measurement). Thus, the uncertainties related to the mean operating temperatures (Fig. 6) were obtained by composing the uncertainties resulting from the confidence interval calculated according to Student's Law and the accuracy of the temperature sensors used. For the uncertainties for the PMV, the type A uncertainty was estimated in the same way as for the temperatures. On the other hand, the Type B uncertainty was estimated taking into account the uncertainties related to the temperature, humidity and speed sensors and those related to the clothing and metabolism of the participants. In fact, the realized balance of the sources of influence and the mathematical model of Fanger for the calculation of the PMV allowed us to apply the propagation law composed of the measurement uncertainties with correlated variables, developed in the GUM [41] and used by Can Ekici in his study on the 'Measurement Uncertainty Budget of the PMV Thermal Comfort Equation' [42].

These results reveal the acceptability of the participants for high comfort temperatures and call into question the efficiency of the Fanger model in estimating the comfort of building occupants. This is in line with the assertion of Olissan and al. [8] that people living in the humid tropical region of Benin are adapted to high comfort temperatures and that the Fanger PMV model is not appropriate for assessing thermal comfort in this region. Adopting this model to estimate thermal comfort in this building would therefore result in discomfort, reduced staff productivity and wasted energy due to excessive use of air conditioning systems.

4.3.2. Evaluation by adaptive models

The comfort temperatures obtained by applying the ACE in Table 1 to this study are grouped in Table 4. These different temperatures are compared to a reference temperature: this is the neutral temperature resulting from the average of the operating temperatures measured for TSV = 0. The value of this temperature is 26.1 ± 0.5 °C with a confidence level of 95% according to the normal law. The application of Student's t-test on the temperatures obtained with the five adaptive models allowed to highlight the models of López-Pérez and al [22] and Indraganti and al [29] (Table 4). Indeed, these two models give comfort temperatures statistically equal to the neutral mean temperature with critical probabilities higher than the significance level of the test used (0.05). On the other hand, the Indraganti and Boussaa [28], CIBSE [30] and Humphreys and Nicol [31] models give comfort temperatures statistically different from the neutral temperature with risks lower than $2.2e - 14\%$(Table 4).

In addition to the statistical analyses, a similarity can be observed between the climatic conditions in the regions where the two models chosen were developed and the region where the present study was carried out (Cotonou). Indeed, the adaptive models of López-Pérez and al. and Indraganti and al. were designed respectively for Mexico City and South India, which are subject to a hot and humid climate just like Cotonou.

However, the populations of these three regions have different cultures. This therefore suggests that the thermal history of the participants in this survey has a great influence on their thermal sensation, contrary to the culture whose influence was not noticed.

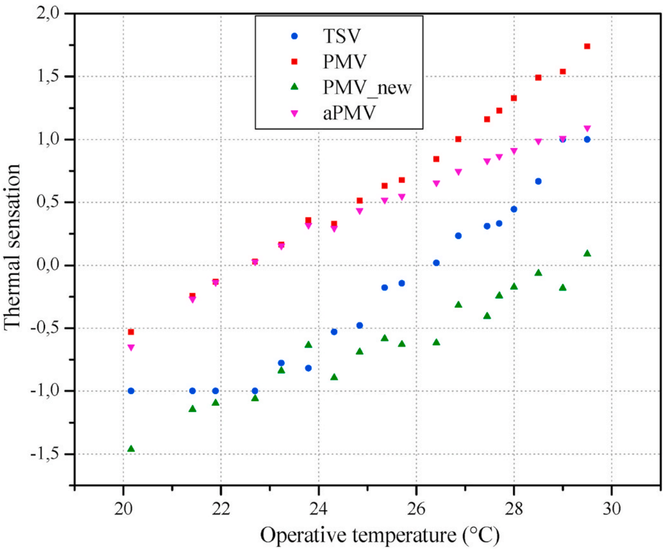

Fig. 9. *TSV*, *PMV*, PMV_{new}, *aPMV*in relation to operative temperature.

4.3.3. Evaluation by hybrid models

The evaluation of thermal comfort with hybrid models allows a greater number of parameters to be taken into account than static and adaptive models. The combination of environmental parameters and thermal sensation votes is an asset in the quest for a more accurate estimate of thermal comfort. However, their systematic application for comfort assessment does not guarantee reliable results. As a proof, the adoption of adaptive PMV for comfort assessment in our study does not reflect the reality of the occupants' thermal feeling (Fig. 9).

Fig. 9 shows the results obtained with the adaptive models of Yao and al. (*aPMV*) [17] and Olissan and al. (PMV_{new}) [8]. Following the recommendation of Chen and al. [21] that the adaptive coefficient (λ) be determined for each region considered, a value of 0.34was obtained for λin our study using Eq. (8). The results obtained with this model show a very small variation between the aPMV and the PMV for thermal sensations below 0.5, thus deviating it from the thermal sensation vote of the occupants. Above this value, a progressive approximation to the thermal sensation vote is observed. The trend of the aPMV curve can be explained by the fact that this model was mainly developed for free running buildings. In a hot and humid climate such as that of Benin, the average temperature in naturally ventilated buildings is often above $28^\circ C$. This justifies the comparison between the aPMV and the TSV when the indoor temperature is around $28^\circ C$. The fact that this model has not yet been adopted in the literature for the evaluation of thermal comfort in air-conditioned buildings reinforces the results found. However, it should be noted that the application of this model by Chen and al. [21] in mixed-mode residences has given good results.

The results from the PMV_{new}model were obtained on the basis of the regression coefficients of the correction factor defined by the authors for the coastal strip of southern Benin. For this purpose, Eq. (9) becomes:

$$PMV_{new} = PMV - (0.13T_a - 0.032RH) \tag{11}$$

Inside the $[-1\ ;\ -0.5]$range the PMV_{new}expresses well the real feeling of the occupants. Beyond this interval, PMV_{new}overestimates

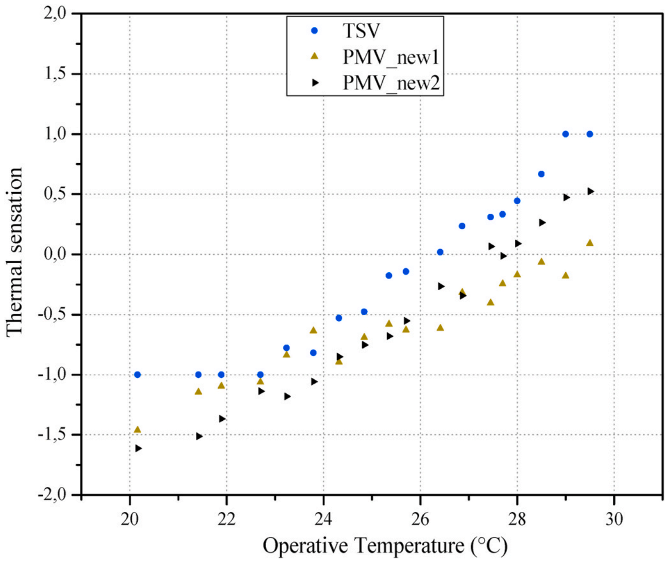

Fig. 10. *TSV*, PMV_{new_1}, PMV_{new_2}in relation to operative temperature.

their capacity to adapt. In view of the results obtained with equation (11), it was therefore decided to determine the regression coefficients from our own survey following the development principle of PMV_{new}.

4.3.3.1. Adapting $\boldsymbol{PMV_{new}}$*to the case study.* The principle of PMV_{new}consists in carrying out a multilinear regression between $\Delta PMV (\Delta PMV = PMV - TSV)$ and the two explanatory variables that are indoor temperature and humidity. Thus Eq. (12) was applied to this case study and the results obtained are shown in Fig. 10.

$$PMV_{new} = PMV - (0.054T_a + 0.041RH) \tag{12}$$

Fisher's overall test of significance on this regression gives a probability ($p = 0.04136$) of less than 0.05. The model is therefore globally significant. At the same time, according to the test of significance of the parameters (Student's test), only the t-student probability of the constant ($p = 0.4261$) is greater than 0.05. This constant is therefore not significant and will be considered as null in the model. Furthermore, the value of the coefficient of determination ($R^2 = 0.3656$) suggests that the regression is not ideally fitted between the variables ΔPMV, $T_a$and RH. This may be explained by the small sample size considered in this study.

Fig. 10 highlights the similarity between the results of the PMV_{new}adapted to our study and the vote of thermal sensation of the occupants. The average difference between the occupants' thermal sensation votes and the results of Eq. (12) is equal to 0.38versus 0.47when Eq. (11)is used. The existence of this discrepancy (0.09) can be explained by the weak correlation found between $\Delta PMV$and the temperature and humidity variables ($R^2 = 0.3656$).

5. Conclusion

At the end of this study, we can retain that Fanger's static model (PMV) is not adapted to the evaluation of thermal comfort in the studied building. The neutral temperature interval obtained with this model is relatively lower than that desired by the people surveyed. The hybrid adaptive PMV model by Yao and al. and the PMV_{new}model by Olissan and al. also have limitations for the assessment of thermal comfort in the building in question. The results of the adaptive PMV are close to those of Fanger's PMV for temperatures below 26°Cwhile PMV_{new}overestimates the adaptive capacity of the occupants to their thermal environment. The adoption of these models will therefore lead to occupant discomfort. On the other hand, the adaptive models of López-Pérez and al. and Indraganti and al. are more appropriate for the assessment of thermal comfort in the study building. The relevance of the results obtained leads to the conclusion that these models are well suited to assess thermal comfort in the study building. However, their generalization for the evaluation of thermal comfort in air-conditioned buildings located in the humid tropical region of Benin would not be prudent. Further studies covering a larger population are therefore needed to confirm the effectiveness of the two adaptive comfort models in this region.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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