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Comparative Assessment of The Thermal Comfort in Naturally Evolving Buildings in Hot and Dry Sahelian Climate: Case of The City of Ouagadougou in Burkina Faso

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ABSTRACT
Thermal comfort/stress depends on the balance of thermal energy on the human body. This balance is influenced by physical activity, clothing, and environmental parameters such as hygrothermal conditions of the ambiance and hygrothermal performances of the shelter's envelope. To better consider the bioclimatic conception of buildings in a hot and dry climatic context, thermal comfort assessment tools allow to decide on the feelings of the occupants of naturally evolving buildings. This paper assesses the thermal perception using three methods, namely the thermal sensation of vote (TSV), the Predicted Mean Vote (PMVe) and the tool specially developed for the hot and dry climate: case of Burkina Faso (CAT_BF). To do this, a survey was carried out on the thermal perception of the occupants of naturally evolving housing. At the same time, the thermal parameters were measured made it possible to obtain values of physical parameters such as air temperature, radiant temperature, relative humidity, air speed and quantities related to the individual such as metabolism and clothing level. The studies are based on the thermal sensations of individuals in the 720 dwellings at 2iE Kamboinsé, a locality located in Ouagadougou in central Burkina Faso, over which they had full control of the interior atmosphere. As the PMVe method was developed for conditioned buildings, a corrective factor (e) was used to adapt it to the atmosphere of buildings in free evolution. The thermal comfort assessment tool based on the adaptive model is adapted to freely evolving buildings in Burkina Faso. The study shows that TSV gives 52% of thermal comfort, while the PMVe predicts 52.7% comfort index; against the 52.5% predicted by the CAT_BF. The results indicate that the PMVe method with the expectation factor of 0.5; as well as the CAT_BF approximately predict the real perception of the thermal comfort of the occupants of the naturally evolution buildings.

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Introduction

Context of the study

The thermal comfort is the feeling of well-being felt when exposed to an indoor or outdoor environment. The interaction between man and his environment has therefore been highlighted and has long been the subject of numerous studies [1-5].

The construction sector is responsible for more than 50% of global electricity consumption, 32% of energy emissions and 12% of fresh water consumption [6]. It consumes more than 3 billion tons of raw materials per year. Extreme heat and lack of access to cooling currently threaten the health and safety of more than 1.2 billion people worldwide (UN-Habitat, 2020). As temperatures rise, cooling demand is expected to triple by 2050. Modern conventional materials used in construction are also important factors in energy consumption [7]. Modern construction uses materials such as cement and steel which are not always adapted to the hot and dry climatic conditions of many regions such as Burkina Faso. This increases the thermal discomfort of non-air-conditioned buildings and the electricity consumption due to the use of mechanical air conditioning systems for thermal comfort [2, 8-10].

Studies have shown that the analytical model for calculating the PMV index predicts a good thermal sensation in mechanically conditioned buildings; but it unfortunately predicts a warmer thermal sensation than that of felt by the occupants in buildings with natural ventilation [11].

Therefore, Fanger and Toftum[12] proposed a corrective factor called the expectation factor to reduce or even eliminate this difference, between the measured and the

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actual PMV indices. The choice of the corrective factor is made according to the study area, but despite corrective measures to reduce the above difference, this so-called stable PMV method remains questionable [13-15]. Thus, a comfort assessment tool was developed for the hot and dry climatic zone, based on the adaptive model at 80% thermal acceptability, and allowed to characterize the outdoor comfort of three climatic regions of Burkina Faso and the comfort of habitats [5],

The present study aims to assess the thermal comfort in climate environments of occupants of naturally evolving buildings in hot and dry climates. The objective is to use the basic tools of the thermal sensation of votes (SVT) and compare with the PMVe index and the comfort assessment tool developed for the hot and dry climatic zone of Burkina Faso (CAT_BF) to highlight their ability to predict the thermal comfort. Therefore, section 2 will present the methodology used in the present study; including the presentation of the devices used to measure the thermal parameters during the survey, the procedures used to assess the thermal comfort by thermal sensations of votes, the PMV method and the CAT_BF. Section 3 will present and discuss the results.

Area of the study

Burkina Faso is a landlocked Sahelian country located in West Africa with an area of 274,200 km². It is located between 9°20' and 15°05' N and 2°20' E and 5°30' W. Figure 1 presents climatic zone of Burkina Faso. In the north of the country, the climate is hot desertic type. This area l covers a small part of the territory represents the Sahelian climate zone. It is characterized by an average annual rainfall of less than 600 mm. The rainy season is short and lasts less than 4 months. A large interannual and spatiotemporal variability of rainfall is observed with strong diurnal and annual thermal amplitudes. The center of the country is marked by a hot semi-arid climate, also called the Sudano-Sahelian zone, this part is characterized by an average annual rainfall of between 600 and 900 mm. The rainy season lasts approximately 5 months. The diurnal and annual amplitudes are less significant than in the northern part. The southern part of the country is covered by a humid and dry tropical type climate, also called the Sudanian climate zone, it is characterized by an average annual rainfall higher than 900 mm. The rainy season lasts between 6 to 7 months [16].

Ouagadougou is in central Burkina Faso with an estimated population of over 2.8 million inhabitants, the highest temperatures range from 36.1 °C to 34.9 °C with a difference of 1.2 °C and minimum temperatures from 23.2 °C to 22.1 °C with an average difference of 1.1 °C. In this area, the climatic data are more lenient compared to that of the Northern region. Figure 2 shows that April is the hottest month with maximum monthly temperature reaching 40.2 °C. January is the coldest month with a minimum monthly temperature of 16.7 °C. April remains the hottest month with an average daytime temperature of 33.7 °C and January the coldest month with an average daytime temperature of 24.9 °C. The observation shows that the maximum temperature amplitude of Ouagadougou is 16.6°C for the month of December and the minimum amplitude is 8.5°C in Ouagadougou.

Figure 3 gives the frequencies of the climatic parameters of Ouagadougou. Figure 3(a) shows that the most frequent daily temperatures are in the range of 26 to 31°C, with a

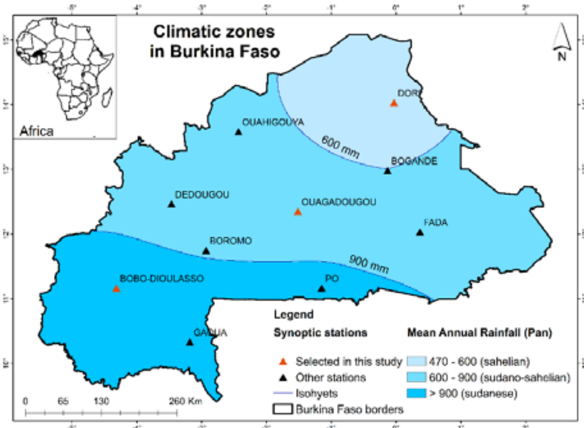

Figure 1: Climatic zones of Burkina Faso. Data obtained from the National Meteorological Agency (ANAM-BF) of Burkina Faso (Ouedraogo et al., 2020).

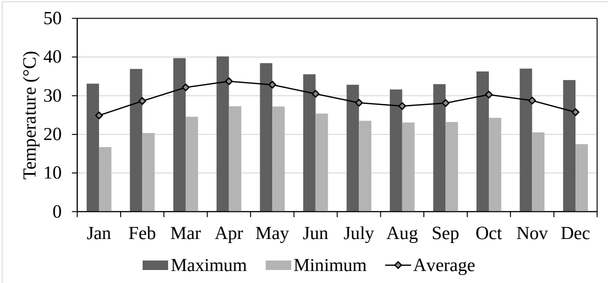

Figure 2: Annual temperatures in the Ouagadougou

frequency of more than 60%. Figure 3(b) shows the most frequent daily relative humidity in the range 25–45% and in the range 80–90%, with a frequency of over 54%. Figure 3(c) shows the most frequent daily wind speeds in the interval 2 to 3.25 m/s, with a frequency of more than 58%. Figure 3(d) shows that the most frequent daily global radiations are in the range 4.5 to 6 kWh/m², with a frequency of more than 68%.

Experimental

Thermal parameter measuring device (HD32.2)

Figure 4 presents the Delta OHM type HD32.3 which is the instrument for measuring the climatic parameters of thermal comfort. The device is equipped with a tripod allowing the sensors to be held at a height of 1.1 m. It has three sensors with SICRAM module allowing it to make several measurements in real time. It is a device that can be programmed directly before recording climate data.

The first sensor (TP 3275) of the PT 100 thin wire type equipment allows the measurement of the ambient temperature and the temperature of the globe thermometer with a measuring range of - 40 °C to 100 °C, with an accuracy of class 1/3DIN (0.10 to 0.19°C). The second sensor PT 100 type (HP 3217) allows to measure the relative humidity and the wet bulb temperature; with an accuracy of class 1/3DIN. The relative humidity measurement range is 5% to 98%, with an accuracy of ± 2.5%. A third probe (AP 3203) of the NTC 10 kohm type is used to measures air speed. Its measuring range is 0.05 to 5 m/s, with an accuracy of ± 0.05 m/s. This device is equipped with DeltaLog10 software which allow to analyze various environments in real time, whether in the presence or absence of solar radiation.

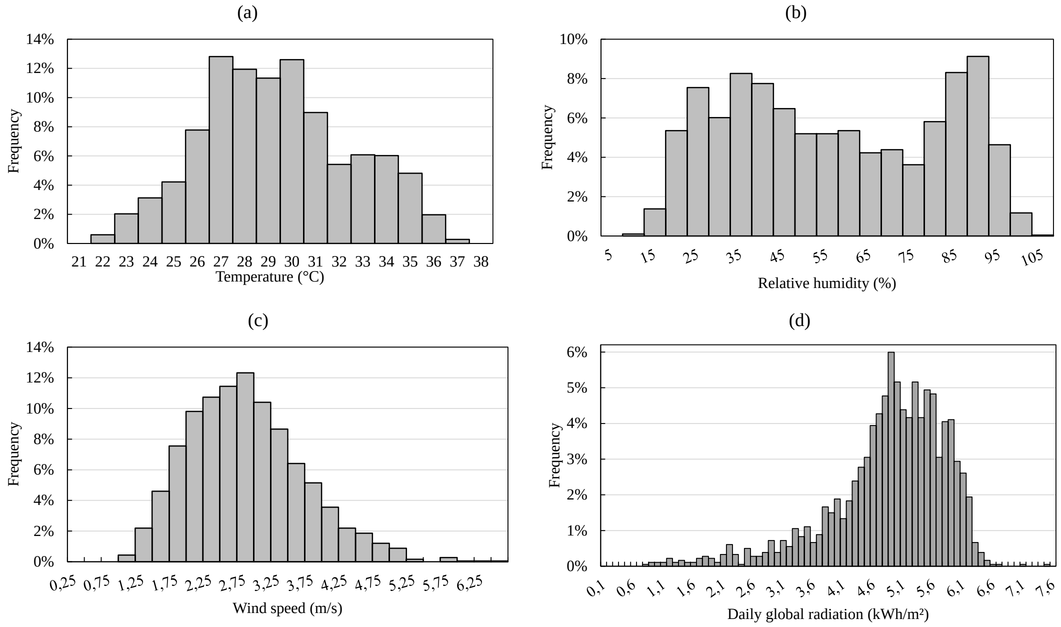

Figure 3: Daily frequencies of Temperatures (a), Relative humidity (b), Wind speed (c), Global radiation (d) of the Ouagadougou region

The software also makes it possible to manage data transfer the the computer, present graphs, calculate thermal comfort indices such as PMV and PPD, WBGT in and WBGT out. Table 1 presents the different sensors with the parameters it measures.

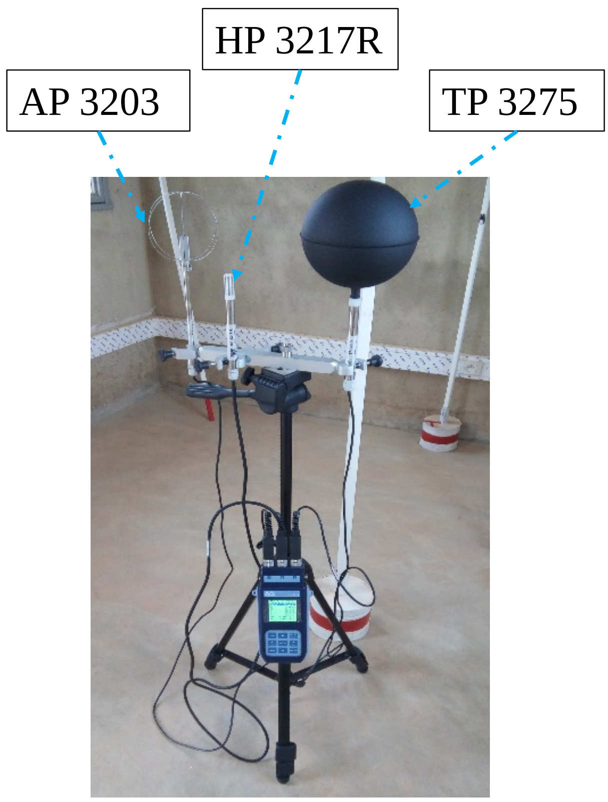

Figure 4: Device for measuring the climatic parameters: Delta OHM HD32.2

Table 1: Climatic parameters measured by the Delta OHM HD32.2 device

Sensors	Symbol	Temperature	Relative humidity	Wind speed
TP3275 or TP3276.2 65	Tg	Globe thermometer temperature	-	-
HP3217R t or HP3217.2	T a, Tr, HR	Ambient temperature/Radiant temperature	Relative humidity	-
AP3203 or AP3203.2	Go	-	-	Air speed

Assessment of the thermal comfort by thermal sensation vote

The surveys took place on the campus of Institute 2iE in Kamboinsé, Ouagadougou in the student hostels (Figure 5). The hostels are one storey buildings blocks with a reinforced concrete structure frame (Figure 5a). The fill masonry is made of compressed inter-locking earth bricks stabilized with cement. The roof is made of metal sheet. Each building block contain two range of rooms, total of 32 rooms per block, oriented back-to-back towards the Southern-Northern direction (Figure 5b). Each room has a ground area of 9.32 m^2 and a total volume of 26.09 m3. Each room is subjected to both cross and vertical natural ventilation facilitated by a central chimney installed in each building block. During the day, the survey consists of simultaneously collecting the climate data and the feelings of individuals' votes, the period of January to March 2019.

As part of this study, the data sheet questionnaires put in place, is presented in the appendix, takes into account several conditions for the collection of data in the field, the sensation of individuals [17-20]. It is made up of several parts: the information on the thermal resistance of clothing; the subjective information such as sensation perception, or thermal sensation voting (TSV) following the ASHRAE seven-point thermal sensation scale ranging from (-3) very cold to (+3) very hot and thermal preference (TP); the objective information on climatic parameters such as air temperature, relative humidity and wind speed,

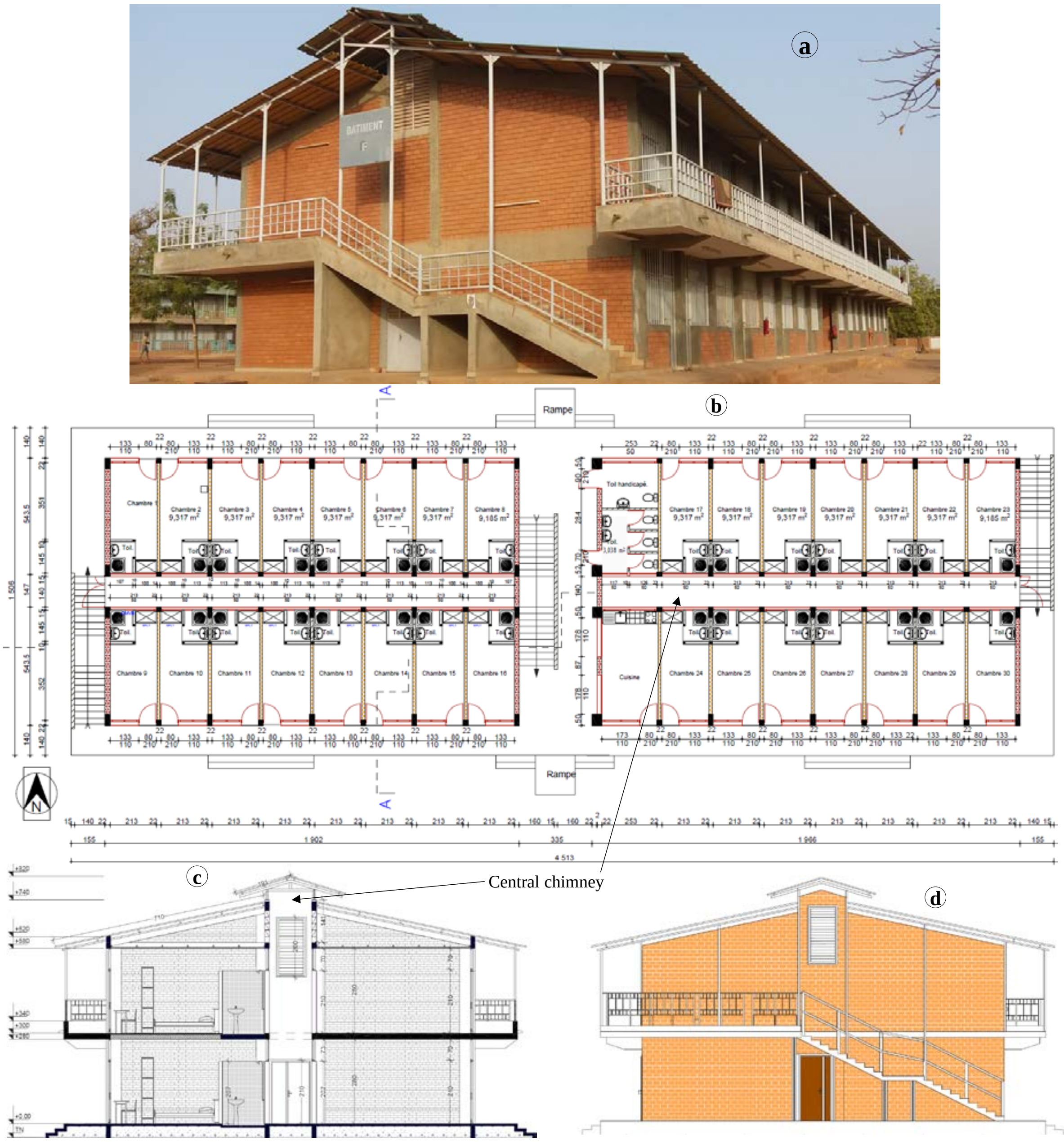

Figure 5: (a) Photo of the hostels of investigated occupants, (b) Plan view of the different of the building block, (c) Sectional view of the building, (d) elevation view of building

which transform stimuli into physiological sensations [21] and metabolic activity which is the production of internal heat in the human body allowing to maintain the temperature around 37°; the climatic parameters measured in the room.

After preparing the Delta OHM device for the thermal comfort measuring device, the data collection immediately followed on occupants, mainly students, in their hostels. The first phase consists of explaining the purpose of the experiment to the respondent as well as the importance of the study and how the investigation will take place. Then, the measuring device is placed close to the occupant, approximately one meter away. For 10 to 15 minutes, the indoor climate parameters of the room are measured while the respondent simultaneously completes the questionnaire. At the end of the investigation, the investigator checks the filling of the questionnaire and takes the device to another occupant to repeat the investigation.

A total of 385 participants were able to answer the questionnaires under conditions their indoor thermal environment. This population size was determined according to equation 1, where n is the minimum sample size to obtain significant results for an event; e is the margin of error generally set at 5%; z is the confidence level; p is the probability of occurrence of the event; N is the size of the target population. Among 385 respondents, 306 were men and 79 were women, aged between 17 to 52, whose height varied between 1.30 and 1.93 m and weight between 42 to 96 kg. The determination of the thermal resistance of the clothing was made according to the standard [22]. The metabolism which is the result of an activity or a particular physical state was determined according to the standard [23].

$$n = \frac{N}{\frac{N \times e^2}{z^2 \times p \times (1-p)} + 1} \quad (1)$$

Assessment of the thermal comfort the predicted index mean votes

The PMV method, based on the thermal balance of the human body, translates the average vote of a person in a given thermal environment. It can be calculated using equation 2 proposed by Fanger [24]. The PMV model is established on the basis of a thermal equilibrium between the human body and the environment considered under stationary conditions [24]. The comfort zone is defined by a combination of the six key climatic parameters of thermal comfort mentioned above. If the calculated PMV value is within the recommended range (-0.5 to +0.5) or (-0.80 to +0.80) depending on thermal acceptability, the conditions are within the comfort zone [25]. The Fanger model is expressed following equations 2-6 and parameters defined in Table 2.

$$PMV = \left[0.303 \times \exp(-0.036 \times M) + 0.028\right] \times L$$

$$avec$$

$$L = \begin{Bmatrix} (M-W) - 3.05\times10^{-3} \times \left[5733 - 6.99 \times (M-W) - p_a\right] - 0.42 \times \left[(M-W) - 58.15\right] - 1.7\times10^{-5} \times M \times (5867 - p_a) \\ -0.0014 \times M \times (34 - t_a) - 3.96\times10^{-8} \times f_{cl} \times \left[(t_{cl}+273)^4 - (\bar{t}_r + 273)^4\right] - f_{cl} \times h_c \times (t_{cl} - t_a) \end{Bmatrix} \quad (2)$$

$$PPD = 100 - 95 \times \exp\left(-0.03353 \times PMV^4 - 0.2179 \times PMV^2\right) \quad (3)$$

$$t_{cl} = 35.7 - 0.028 \times (M-W) - I_{cl} \times \left\{3.96\times10^{-8} \cdot f_{cl} \cdot \left[(t_{cl}+273)^4 - (\bar{t}_r+273)^4\right] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\right\} \quad (4)$$

$$h_c = \begin{Bmatrix} 2.38 \times (t_{cl} - t_a)^{0.25} & 2.38 \times (t_{cl} - t_a)^{0.25} > 12.1 \times \sqrt{v_{ar}} \\ 12.1 \times \sqrt{v_{ar}} & 2.38 \times (t_{cl} - t_a)^{0.25} < 12.1 \times \sqrt{v_{ar}} \end{Bmatrix} \quad (5)$$

$$f_{cl} = \begin{Bmatrix} 1.00 + 1.290 I_{cl} & I_{cl} \le 0.078\ m^2 \cdot K / W \\ 1.05 + 0.645 I_{cl} & I_{cl} > 0.078\ m^2 \cdot K / W \end{Bmatrix} \quad (6)$$

Table 2: Summary of the parameters leading to the calculations of the PMV/PPD index

Parameters determined by iteration	Reading on Abacus	Measurable parameters
Clothing surface temperature (t_{cl})	Metabolism (Met)	Partial Vapor Pressure in Air (Pa), or Relative Humidity (RH)
Convective transfer coefficient (hc)	External work (Met)	Air temperature (t_a)
-	Clothing resistance (Clo)	Average radiant temperature (t_r)
-	-	Air speed (V_{ar})

The expectation or expectation factors (e) presented in table 3, are values between 0.5 to 1 to be multiplied to the measured or calculated PMV index to approach the value corresponding to the real felling of the occupants of naturally evolving spaces. Being in a country with a hot and dry climate, the context Burkina Faso where it is hot almost all year round except for a very short period from December to January; the expectation factor is low; Hence, an expectation factor of 0.5 was applied to the PMV be better express the real perception of the Burkinabe respondent.

Table 3: Estimation of the expectation factors corresponding to expectation levels of occupants in naturally ventilated building with respect to their familiar environment [26]

Duration of the hot period	Position of the building in relation to the air-conditioned buildings	Expectations	Expectation Factor
Hot weather most of the year	Buildings without HVAC in regions with few buildings with HVAC	Weak	0.5
	Buildings without HVAC in regions with some buildings with HVAC	Weak	0.7
Hot summers	Buildings without HVAC in areas with few buildings with HVAC	Moderate	0.7 or 0.8
	Buildings without HVAC in areas with some buildings with HVAC	Moderate	0.8 or 0.9
Brief hot periods during summer	Buildings without HVAC in areas where HVAC is common	High	0.9 or 1

Assessment of the thermal comfort using the comfort assessment tool developed for the hot and dry climatic zone of Burkina Faso

Figure 6 represents the decision support tool proposed by Ouedraogo et al. [5] for the assessment of the thermal comfort of buildings in hot and dry climatic zones of Burkina Faso. It is based on the adaptive method.

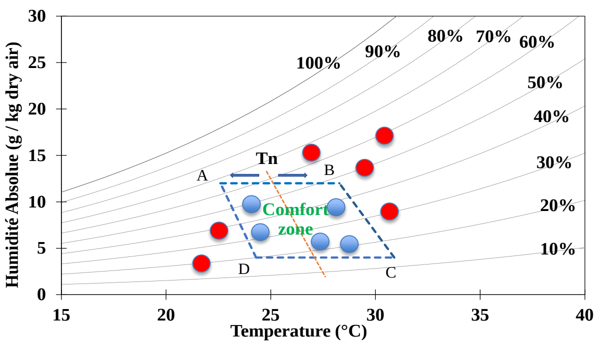

Figure 6: Thermal comfort decision support tool (Ouedraogo et al., 2021)

The lines A-D and B-C delimited the comfort zone by straight lines of equal thermal sensitivity in the vertical direction. The horizontal lines are limited above by absolute humidity equal to 12 g/kgAS for a partial water vapor pressure of 1900 Pa [25], and below by 4g/kgAS for a partial vapor pressure equal to 650 Pa. The cloud of blue points, inside- the boundary A-B-C-D, represents the points of thermal comfort and the red points represents the points of thermal discomfort. Thermal comfort being a subjective perception, the acceptability of 80% was considered in this study with a wider range of 7°C.

Results and Discussion

Thermal comfort assessed from thermal sensations of votes

The survey on the perception of the sensation of thermal comfort of occupants in naturally evolving buildings reveals that 52.0% of respondents reported being satisfied with their thermal environment; i.e. they were feeling the thermal neutrality on ASHRAE judgement scale (Figure 7). The shelters of these occupants have an ambient temperature range between 24.7 to 34.8°C; with a relative humidity in the range of 5 to 70.2%; the wind speed between 0 and 1.75 m/s; the thermal resistance of the clothing between 0.03 and 0.13 Clo; and the metabolism between 41 to 145 Met.

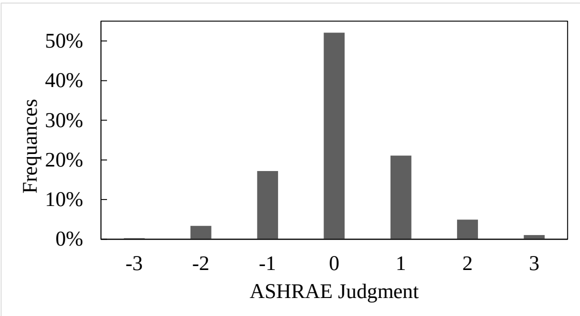

Figure 7: Frequency of thermal judgments on the ASHRAE scale: thermal sensation votes of data from the survey.

The number of respondents who were not satisfied with their thermal conditions is 48.0%; among them, 21 % and 27 % respectively experienced cold and warm discomfort. For those who experience cold discomfort, the temperature ranges between 25 to 34.2°C; with relative humidity of 7.4 to 60.20%; the wind speed between 0 and 1.57 m/s; the thermal resistance of the clothing between 0.03 to 0.12 Clo and the metabolism between 41 to 120 Met. For those who experienced warm discomfort, temperature ranges between 27 to 36.6°C; with relative humidity of 5.5 to 61.50%; the wind speed between 0 and 1.52 m/s; the thermal resistance of the clothing between 0.03 to 0.13 Clo and the metabolism between 41 to 145 Met, despite the possibility of total control indoor climatic conditions by natural ventilation. Table 4 summarizes the climatic parameters characterizing each thermal perceptions, i.e. thermal comfort and thermal discomfort (cold and warm).

Table 4: the ranges of climatic parameters observed on the three types of atmospheres

		Ta (°C)	RH (%)	Va (m/s)	Clo	met
Discomfor-Cold (21%)	Max	34.2	60.20	1.57	0.12	120.00
	Min	25.0	7.40	0.00	0.03	41.00
	Avg	28.9	21.3	0.30	0.07	63.5
Comfort (52%)	Max	34.8	70.20	1.75	0.13	145.00
	Min	24.7	5.00	0.00	0.03	41.00
	Avg	30.0	22.5	0.26	0.07	70.3
Discomfort -Warm (27%)	Max	36.6	61.50	1.52	0.13	145.00
	Min	27.6	5.50	0.00	0.03	41.00
	Avg	32.0	23.9	0.39	0.07	70.4

Thermal comfort assessed from predicted mean votes

Figure 8 presents the results of the PMVe calculated with the six key climatic parameters of thermal comfort and the expectation factor as a function of the operative temperature. The chosen comfort range is ±0.80 with a predicted percentage of thermal dissatisfied people of 20% to further extend the satisfaction zone. 203 people are in the thermal comfort zone; i.e. 52.7 % and 182 people are out of the thermal comfort zone, i.e. 47.3 %. On the contrary, the PMV calculated without the corrective factor gives only 22.3% in the comfort and 77.7% in the discomfort.

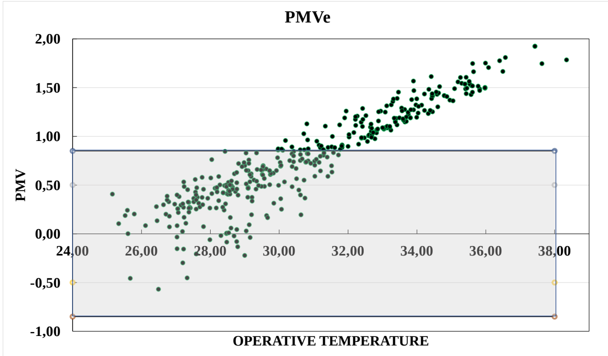

Figure 8: PMVe comfort index defined in the comfort zone defined by Fanger

Thermal comfort assessed from the tool CAT_BF

Figure 9 presents the results of the assessment of the thermal comfort from the tool developed for the hot and dry climate of Burkina Faso (CAT_BF). It shows that 52.5% of all respondents are in the comfort zone. The remain 47.5% are in uncomfortable zone; either hot and dry incomfort or hot and humid.

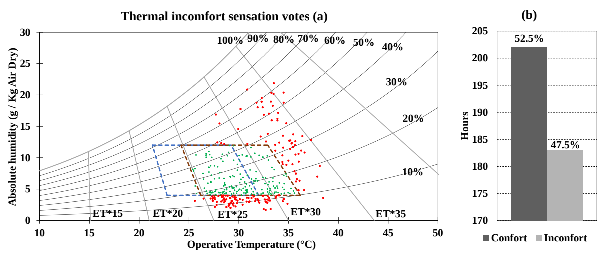

Figure 9: (a) Sensation of thermal comfort of occupants satisfied with their environment predicted using the tool developed for the hot and dry climate of Burkina Faso (CAT_BF); (b) prediction in percentage of votes

Discussions

The results from the surveys on occupants of naturally evolving buildings show that, out of the 385 respondents, 52% feel the thermal comfortable; while 48% feel the thermal discomfort. When the same data from the survey were used to determine the PMVe index corrected with the expectation factor of 0.5; the results show that 52.7% are in thermal comfort and 47.3% remain in discomfort. When the tool developed for hot and dry climate of Burkina Faso was used to check the survey data, 52.5% feels the thermal comfort and 47.5% feel thermal discomfort. Given that the real thermal sensation of the respondents was chosen as the basis for the comparison of the results, it can be seen that the two methods PMVe and CAT_BF predict the same thermal sensation of comfort as the actual perception of the respondents occupying a naturally evolving of building. This was not the case for PMV, without the corrective factor. The PMVe slightly diverged by only +1.3 % and -1.6% respectively for predicting the thermal comfort and discomfort from the really perception; while the PMV diverged more than -57.1 % and +61.9 %. It would still be necessary to have the exact estimate of the ratio of air-conditioned buildings compared to the naturally evolving buildings in the study area for a better estimate of the corrective factor. The CAT_BF also diverged by only +0.97% and -0.64% respectively for predicting the thermal comfort and discomfort from the really perception. The CAT_BF was already designed, ready and easy to use to directly predict the comfort. It does not depend on certain conditions such as the correction factor depending on the environment.

Conclusions

To evaluate thermal comfort in a context of hot and dry climate, the study comparatively relied on three comfort evaluation methods, namely the thermal sensation votes (TSV), the corrected predicted mean votes (PMVe) and the thermal comfort assessment tool Burkina Faso (CAT_BF). The comparison of these results consisted of placing the figurative points of the thermal environments of the respondents on the diagram including the comfort zone defined by the tool, the comfort zone defined by the index (PMVe) with the results of the respondents' voting feelings. The sensation of votes on real site gives 52 % cases of thermal comfort, and 48% of people in thermal discomfort. The PMVe calculated with the expectation factor of 0.5 predicts 52.7% cases of thermal comfort, and 47.3% cases of thermal discomfort. The CAT_BF shows that 52.5 % of these people would be in thermal comfort and therefore 47.5 % of these people would be in discomfort. At the end of this study, we can say that the thermal comfort predicted by the PMVe and CAT_BF are closer to the really perceptions of the respondents occupying naturally ventilated buildings, with divergence of less than ±1.6 %. Additional studies would make it possible to link the difference between the measured and the predicted thermal comfort (zone) and the overheating in the buildings. Additional studies should make proposals for bioclimatic strategies, particularly passive strategies, which would allow to improve the thermal comfort in naturally ventilated building.

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