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A field study on thermal comfort in naturally-ventilated buildings located in the equatorial climatic region of Cameroon

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ABSTRACT

The purpose of this research is to create a thermal comfort database in three climatic regions in Cameroon. This will help to define guidelines for constructing more comfortable buildings in Cameroon. There is not enough data regarding comfort in residential environment in the intertropical sub Saharan Africa. Thus experimental and subjective results of hygrometric thermal comfort conducted in 290 buildings located in three cities of the equatorial climatic zone of Cameroon is presented. An adaptive approach according to ASHRAE 55/2004, ISO 7730 and 10551 was adopted. A specific questionnaire has been elaborated for the investigation. 710 questionnaires in the dry season and 410 in the rainy season were distributed to inhabitants and filled while different experimental values of indoor parameters were measured. The comfortable temperature ranges for the three cities was found between 22 °C and 29 °C. The 61.24% of voters found acceptable their thermal habitat, the 13.72% considered it neutral.

Contents

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1. Introduction

Thermal comfort in living environment is very important not only for health, but also for occupants as far as productivity is concerned. In fact, comfort conditions significantly influence rest or working efficiency for it affects production and social costs. Therefore, comfort conditions are essential for the well-being, productivity and efficiency of inhabitants [1,2]. Thermal comfort heavily depends not only on environmental factors but also on physical, physiological and psychological aspects. Within the same environment, having the same characteristics and same type of climate, thermal sensation and preferences are different since it depends on individuals [3]. Satisfaction with the thermal environment is complex and subjective responses are very variable. There is not often link between experimental and subjective results. The comparison between PMV from questionnaire and PMV from measurement presents very low correlation [4,5]. In most cases, the relative humidity has a constant interval, while temperature for comfort conditions present very wide ranges. As results, international standards involve a variety of ranges of comfort. In American Society of Heating, Refrigerating and Air-Conditioning Engineers (AHRAE) [6] for example, the comfort temperature is between 23 °C and 26 °C, while the humidity is between 30% and 60%. In CIBSE [7], the comfort temperature is between 22 °C and 24 °C and humidity between 30% and 60%. In ISO 7730 [8], PMV is between −0.5 and 0.5 for PPD <10% while indoor air speed $v_a < 0.25$ m/s. In different cities studied, the comfort temperature was between 22 °C and 28 °C and humidity between 48% and 74%. These standards are almost exclusively based on theoretical analyses of human heat exchange [9] and laboratory studies by means of climatic chambers. There have been extensive studied to evaluate thermal comfort using test chambers, but the laboratory studies offer static and consistent conditions for measurement which were not possible in the field studies. Different climatic regions, such as tropics, may require different levels of comfort parameter mandated in the standards. Many field studies have been carried out in different continents (Europe, Asia, America, Africa, etc.), but very little in residential environment in the intertropical sub Saharan Africa [10–13].

The field studies conducted by Ogbonna and Harris [14], Busch [15], Kwok [16], Nicol and Humphreys [17], Khoo and Wong [18], Henry and Wong [19], showed the importance of the adaptive approach in the study of thermal comfort. Oluwafemi et al. [20], carried out a study in homes in Bauchi, Nigeria, and showed that thermal comfort depends on the adaptation of the occupants in their residence. Nasrollahi et al. [21] conducted a survey of comfort in six Iranians office buildings and showed a perfect harmony between index obtained by measurement and results of questionnaires. Wagner and Roberto [22] investigated on thermal comfort in the hot−humid Brazilian area. They found that in naturally-ventilated environments, 79% of voters opted for change, while the percentage was 55% in ventilated environments. During a study in Pakistan and Bangkok, Surapong et al. [23] found that thermoneutral temperatures ventilated and naturally-ventilated rooms were respectively 28 °C and 25 °C. Alison and Chungyoon [24] showed that occupants of naturally-ventilated rooms fully express their preference and thermal sensation. During the 214 days of study, Miyazawa [25] demonstrated that during the different stages of sleep, the temperature range of thermal neutrality is between 19 °C and 25 °C. Zambrano et al. [26] showed that in Rio de Janeiro, it is possible to create a comfortable environment within a building. Hans et al. [27] found the models to design a system that reduces energy consumption and generates thermal comfort, after a study in three Chinese cities.

The analyzed area is the North-Cameroon (Sudanese and sudano-Sahelian regions). The overall purpose of the research is to create an important database of thermal comfort in the three climatic regions of Cameroon to define guidelines for the construction of more comfortable buildings in Cameroon. Thermal comfort in three cities of the three climate zones of the equatorial region has been studied and the new adaptive approach has been applied to establish various correlations between the collected data.

2. Methodology

2.1. Analyzed cities

Cameroon is divided into three climatic zones including the Sudanese, the sudano-Sahelian, and the equatorial regions. Cameroon is characterized by an equatorial climate with two main seasons of equal amplitudes: a long rainy season from mid-March to mid-November (8 months) and a short dry season from mid-November to mid-March (4 months). The study was conducted in the equatorial cities of Nkongsamba, Douala and Bafang. Fig. 1 shows the 3 cities concerned by the field investigation.

The city of Nkongsamgba is located in the Moungo division, about 140 km from Douala, the economic capital of Cameroon, on the western slopes of Manengouba Mountain (2396 m) and the foothills of Nlonako Mountain (1822 m). Its average altitude is 900 m above the sea level, and is geographically located between 4°54′ to 5°10′N in latitude and 9°30′ to 10°00′E in longitude. The average temperatures are between 16 °C and 25 °C and approximately 2400 mm of rainfall are recorded per year, while the relative humidity is around 80% and the wind velocity from 1.4 m/s to 2.5 m/s.

Douala is the economic capital of Cameroon, the main business center and one of the largest cities in the country. The city is located along the Atlantic Ocean, between 4°03′N and 9°42′E. With an area of nearly 210 km^2, the climate of Douala is equatorial: it is characterized by temperatures between 18 °C and 34 °C, and heavy precipitation, especially during the rainy season from June to October. Air is almost constantly saturated with moisture: 99% relative humidity during the rainy season, but 80% in the dry season. Therefore there is a “relative” dry season, from October to May.

The city of Bafang is located in the West region, particularly in the Haut Kam division at 1100 m altitude. It is located between 5° to 5°15′N in latitude and 10° to 10°11′E in longitude. Its population was estimated at approximately 29,300 occupants in 2010. It covers a land area of approximately 80 km^2. Its climate is that of the subequatorial monsoon type with two seasons including one rainy season from March to October and one dry season from November to February. There are two different micro climates depending on the altitude. These micro climates are: warm and humid in lowland, moist cool and attenuated, when the altitude is between 800 m and 1100 m. Its temperature sometimes reaches 34 °C in the dry season.

2.2. Experimental campaign

Both the experimental and subjective campaigns were conducted during the dry and rainy seasons. In order to study variation of comfort condition as function of the building construction typology, three types of buildings were analyzed. As shown in Table 1, 290 buildings were investigated including 140 buildings in modern style built with bond-stones (Fig. 2), 84 buildings in traditional style built with boards (Fig. 3) and 66 in traditional style with mud (Fig. 4). All the studied buildings were naturally ventilated, except some modern houses in Douala during the long dry season. Concerning solar radiation which influences the quality of indoor air, buildings with the same orientation were selected. The choice of buildings corresponds to several criteria, concerning structure, typology as well as external environment. But the essential criteria was the availability and the desire of people to participate to the investigation. Also the inertia of the building influenced the selection. In each habitat, two persons had the right to vote. The selected traditional habitats were older than 11 years, built mainly using local materials and occasionally using provisional materials. Their heights varied between 1.9 m and 4.1 m. Most of these buildings were rectangular or circular, and their roots were formed like cone and, sometimes, covered with old rusted metal sheets. These types of habitats were mostly located in the peripheral quarters of the town. Some of these habitats included sheet fences or provisional materials around them. Other habitats were opened to facilitate the lighting of the indoor by the sunlight in day time. These buildings had small verandas that were used for rest and protection against sun and rain. The roofs of the buildings were built with a slope of 45° and more, to protect from the outdoor climate and ameliorate the indoor air quality. Some of the roofs are constructed by wooden beams and clay tile coverings on the exterior side. The windows have wood frames characterized by 2–3 cm of thickness

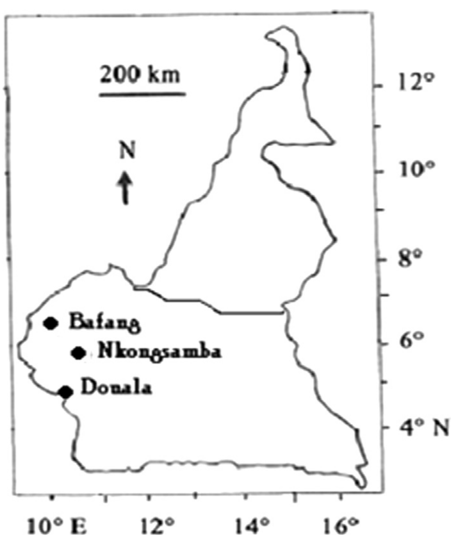

Fig. 1. Plan of Cameroon with the identification of the 3 cites where the field campaign was conducted.

Table 1
Main characteristics of the analyzed buildings.

Type of buildings	Modern	Traditional	
Type of construction	Bond-stone	Board	Earth
Thickness (cm)	7–15	2–3	5–12
Density (kg/m^3)	1329–1644	450–600	1491–1950
Thermal conductivity (W/m °C)	0.65–0.71	0.21–0.45	0.75–1.15
Thermal diffusivity (10^{-7} m^2/s)	3.71–3.85	–	3.80–4.85
Specific heat (kJ/kg)	0.96–1.01	1.02–1.4	0.87–1.05
Height (m)	3–5	2.12–4.10	1.90–3.80
Floor area(m2)	35–49	21–55	22–45
Volume (m^3)	140–245	43–220	44–180
Window exposition	S–SW	E–ES	E–ES

Fig. 2. Example of analyzed modern style building made by brick.

Fig. 3. Example of analyzed traditional style building made by board.

Fig. 4. Example of analyzed traditional style building made by earth.

and most of the openings are oriented to the south. The height or the length of the majority doors was less than 1.8 m. The walls are plastered with clay and lime painted.

On the other hand, the modern buildings were constructed rather recently (from a minimum 0 to a maximum of 47 years), had different shapes and built by imported materials. All the modern buildings presented big fences against thieves. Although the an esthetical layout of these habitats was very impressive, the air quality air was not considered acceptable by the occupants, especially in the dry season, when the occupants had to use the ventilation system to improve the quality of the indoor air. Some thermo physical properties of the different analyzed buildings are provided in Table 1, in accordance with other studies [28–30].

All the values of outdoor temperature, wind speed, relative humidity, and precipitation were collected from the national weather station in Douala, while the indoor wind speed, indoor relative humidity, and indoor temperature were measured respectively by an omnidirectional anemometer, an hygrometer (with the accuracy ±1%) and a probe thermometer (±0.1 °C). The characteristics of the used measurement systems are reported in Table 2.

Measurements were carried out every 30 min, the probes were positioned at 1.1 m height from the ground level, in strict accordance with the prescriptions ASHRAE Standard 55 [6], and ISO 7730 [8]. The devices were installed from 7:30 am, and the data collection started at 8:30 am, so as to enable each probe to adapt to the environment. All the data were collected regularly until 6 pm. These measurements provide four of the six parameters established by ISO 7730 [8] including air velocity, relative humidity, ambient temperature and average radiant temperature. These parameters were then used to calculate the PMV and PPD according to Fanger's model and ISO 7730 [8]. The PMV index suggested by Fanger predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale. Subjects exposed to the climate chambers are asked to give their opinions according to the ASHRAE seven-point scale of thermal sensation(+3(hot), +2(warm), +1(slightly warm), 0(neutral), −1 (slightly cool), −2(cool), −3(cold)).

PMV is determined by simulation following the relations established by Fanger [8]:

$$PMV = [0.303\exp(-0.036M) + 0.028] \times L = a \times L \quad (1)$$

where L is the thermal load on the body, defined as the difference between internal heat production and heat loss to the environment, and a the sensitivity coefficient. PPD (predicted percentage of dissatisfied), is the percentage of all those who have declared uncomfortable environment in voting an index of preference variable from −3 to +3. ASHRAE proposed reference values between the PMV and PPD by outlined the assumptions on the rates of Fanger's PMV and PPD.

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

Fig. 5 shows the evolution of PPD on the basis of PMV.

This would indicate that for a PMV=0, PPD=5%. For PPD=10%, corresponds to a PMV between −0.5 and +0.5. The average radiant temperature (T_r) used to calculate PMV was estimated using the following regression model as function of the measured air temperature (T_a) proposed by Nagano [31]:

$$T_r = 0.99T_a - 0.01, \quad R^2 = 0.99 \quad (3)$$

Table 2
characteristics of the measurement system.

Measurement system	Operative range	Accuracy
Omnidirectional anemometer	0.1–2.5 m/s	–
Hygrometer	0 to 100%	±1%
Digital thermometer	−100 to 100 °C	±0.1 °C

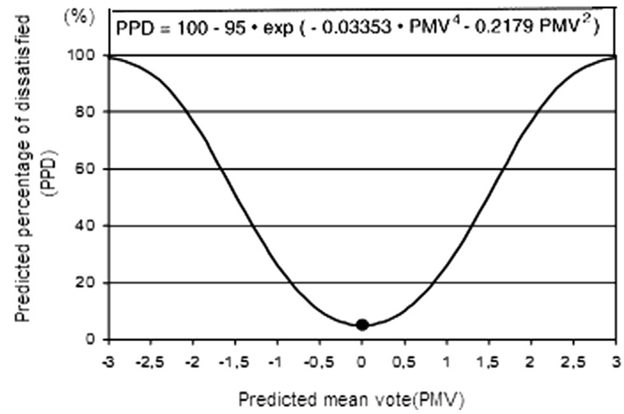

Fig. 5. Evolution of PPD on the basis of PMV.

The international comfort standards such as ASHRAE standards and the International Standards Organization (ISO) are almost exclusively based on theoretical analyses of human heat exchange [9] performed in mid-latitude climatic regions. They were based primarily on mathematical models developed by Fanger on the basis of studies from special climate-controlled chamber experiments. Moreover, these standards are suitable for static, uniformly thermal conditions and are based on the hypothesis that regardless of race, age and sex; human beings are thought to feel comfortable in a narrow, well-defined range of thermal conditions [6,8].

2.3. Subjective analysis through questionnaires

Opinions and feelings of individuals were obtained by a careful analysis of questionnaires. A specific questionnaire was developed according to UNI EN ISO 7730 [8] and UNI EN ISO 10551 [32]. Questionnaires were distributed twice a day: in the morning, from 8 to 12 am and in the afternoon, from 2 to 6 pm. Among the two seasons, a total of 1200 questionnaires were collected, representing about two-fifth (2/5) of the copies distributed. The number of questionnaires filled depended on the geographical area, 284 copies in the equatorial area of Cameroon (Nkongsamgba), 680 in the coastal area (Douala) and 236 in the coastal zone in sub-equatorial monsoon (Bafang).

The questionnaires, as developed in the previous works of the authors [4,5,10], had been subdivided into three main parts:

- Part 1: Personal data (age, sex, height, weight, type of residence and construction age of the building).
- Part 2: Thermal aspects (ruling on the thermal environment).
- Part 3: Personal micro climate control.

The questionnaires were written in English and French language, which are the official languages of the country. The language preferences of the occupants were considered while distributing these questionnaires to them.

The following parameters were assessed from the questionnaires:

- Predicted average vote (PMV);
- Thermal satisfaction index (TSI) [%], is the ratio of persons satisfied or persons who expressed a judgment (it is evaluated as the percentage of persons who have answered "light annoyance, comfortable, heavy annoyance" to the question "what is your thermal sensation?");
- Thermal wish index (TWI) [%], is the ratio of persons who do not want to change/persons who expressed a judgment (it is

evaluated as the percentage of persons who have answered “too cool, too warm, as now”, to the question “how would you like to feel?”);

- Thermal acceptability index (TAI) [%], is the ratio of persons who considered acceptable/persons who expressed a judgment (it is evaluated as the percentage of persons who have answered “yes, it is acceptable” to the question “On the basis of your personal preferences, how would you consider the room temperature acceptable or unacceptable?”);
- Thermal tolerability index (TTI) [%], is the ratio of persons who can tolerate it/persons who expressed a judgment (it is evaluated as the percentage of persons who have answered “tolerable, intolerable” to the question “how do you consider this room?”);
- Acceptable air movement index (AAMI) [%], the ratio of persons who expressed a positive judgment/persons who expressed the judgment (it is evaluated as the percentage of persons who have answered “acceptable, not acceptable, slightly acceptable” to the question “how do you feel about the air flow in this moment?”);
- Acceptable vertical thermal gradient index (AVTGI) [%], is the ratio of persons who expressed a positive judgment/ persons who expressed a judgment (it is evaluated as the percentage of persons who have answered “acceptable, not acceptable, slightly acceptable” to the question “how do you consider the temperature difference between head and ankle?”);
- Environmental control satisfaction index (ECSI) [%], is the ratio of persons who expressed a positive judgment/persons who expressed a judgment (it is evaluated as the percentage of persons who have answered “very satisfied, not satisfied, slightly satisfied”, to the question “How do you feel about the possibility of controlling thermal comfort?”);
- wish vertical thermal gradient index (WVTGI) [%], is the ratio of persons who did not want to change/persons who expressed a judgment (it is evaluated as the percentage of persons who have answered “lower than now, higher than now, exactly as it is ” to the question “would you prefer a temperature difference of temperature between head and ankle”). The results obtained often show an excellent agreement with the corresponding literature reviewed [33,34].

3. Results and discussions

Approximately 6000 habitats were visited during the two great seasons of study, 3000 questionnaires were distributed, only 1200 were collected, of which, more precisely, 54% in modern habitats and 46% in traditional habitats. Statistics of the subjects of residential occupants and personal thermal variables from questionnaires are reported in Tables 3 and 4. The majority of voters were women (55%), the average age was 29 and the average height

Table 3
Statistics of the subjects of residential occupants.

City	Douala		Bafang		Nkongsamba		Total
Type of residence	Modern	Traditional	Modern	Traditional	Modern	Traditional	Both types
Sample size	368	312	90	146	190	94	1200
Gender							
Male	201	123	15	55	88	60	542
Female	167	189	75	91	102	34	658
Age (year)							
Maximum	70	41	52	83	56	88	88
Minimum	08	09	11	13	12	13	08
Mean	30	18	32	28	28	37	29
Standard deviation	5.91	0.42	0.79	3.37	0.78	3.52	3.04
Height (m)							
Maximum	1.98	1.82	1.77	1.87	1.88	1.95	1.98
Minimum	1.21	1.15	1.40	1.35	1.35	1.30	1.15
Mean	1.55	1.32	1.51	1.38	1.60	1.57	1.53
Standard deviation	0.15	0.09	0.07	0.12	0.08	0.10	0.12
Type of construction							
In bond-stone	198	240	55	05	134	24	656
In board	94	72	00	00	56	68	290
In earth	76	00	35	141	00	02	254
Construction age							
Maximum	25	60	47	70	28	78	78
Minimum	01	17	18	11	01	25	00
Mean	08	26	21	27	15	36	21.5
Standard deviation	1.92	2.09	4.03	3.29	5.02	1.67	2.34
Metabolic rate (W/m^2)							
Maximum	69.6	69.6	69.6	72	72	72	72
Minimum	58	58	58	58	58	58	58
Mean	58	58	58	68.5	58	69	62
Standard deviation	1.54	2.10	1.02	1.45	0.83	1.3	1.69
Weight (kg)							
Maximum	102	125	125	115	104	92	125
Minimum	51	39	40	52	44	44	39
Mean	67	65	69	72	63	59	67
Standard deviation	7.32	11.02	10.18	16.5	8.07	7.76	10.12
Clothing (clo)							
Maximum	1.50	1.32	1.30	1.20	1.5	1.39	1.50
Minimum	0.29	0.52	0.44	0.23	0.6	0.40	0.23
Mean	0.80	0.93	0.67	0.70	0.83	0.84	0.84
Standard deviation	0.32	0.37	0.43	0.23	0.09	0.49	0.38

was 1.53 m, the prevalent type of construction was bond stone and the average constructing age was around 20 years. The weights range was between 39 kg and 125 kg. Table 5 presents the summary of measured environmental data recorded during the survey in the three cites: it can be observed that the temperature is higher in coast zone (Douala) than in mountainous zone (Bafang). The inhabitants in the modern buildings were younger and more capable of answering the questionnaires.

3.1. Subjective approach

3.1.1. Clothing thermal insulation values

Fig. 6 shows clothing thermal insulation values as function of the outdoor temperature. Individual clothing articles indicated in the survey responses were converted into their respective thermal insulation values using the garment values according to ASHRAE Standard 55 [6]. The range of thermal insulation was between 0.5 clo and 1.4 clo for an outside average temperature ranging from 16 °C to 30 °C. An average value of 0.7 clo was obtained during the dry season and 0.9 clo during the rainy season. Obviously, thermal insulation decreases as outdoor temperature increases. Among individuals under 25 years old, the average clothing insulation value during the dry season was 0.5 clo, while for those above 50 years, the average value was 1.05 clo. These results are in conformity with those obtained by Moujalled et al. [35] who found a strong dependence of the thermal insulation on climatic seasons.

3.1.2. Metabolic rates

Metabolic rates were calculated from the descriptions of the activity of individuals in various questionnaires, according to ISO 7730 [8]. In this study, activity levels varied from 1 met to 1.3 met and there is an average value equal to 1 met in modern habitats in compared with 1.1 met in the traditional one. Fig. 7 confirms that human activity slightly decreases with an increasing operative temperature.

3.1.3. Predicted mean vote (PMV) from questionnaire

Fig. 8 shows the dependence of the predicted mean vote from questionnaire according to the operative temperature (T_0), where a good linear relationship ($R^2=0.794$) was found:

$$PMV = 0.439T_0 - 10.79, \quad R^2 = 0.794 \tag{4}$$

The thermal neutral temperature is obtained for PMV = 0. The average value for the three cities of the thermal neutral temperature was 24.58 °C.

3.1.4. Thermal acceptability (TAI), thermal preference (TWI)

Even if subject to the same climate and in the same geographical area, thermal acceptability and thermal preference vary from person to person. They depend on the physics, physiology, psychology and other aspects. In Figs. 9 and 10, respectively, the percentage among the three cities of thermal acceptability (TAI) and the percentage thermal preference (TWI) versus PMV are presented.

In Fig. 9 it appears that during the dry season (a), an average of 16.82% of occupants voted for a neutral with 10.53% in modern living habitat against 23.1% in traditional. 66.7% of the voters found their environment comfortable, while 76.5% found it acceptable. In the rainy season, (Fig. 9b) more voters found their environment slightly cool (35.35% in modern habitats and 3.03% in traditional habitats). In both types of buildings approximately, 2.8% found it slightly warm, 13% very hot, 2% cold during the rainy season. The results obtained by Noël and Rene [10] in North Cameroon have proved that 52.5% of occupants found them acceptable residence

Table 4
Personal thermal variables from questionnaires (1: rainy season, 2: dry season).

City	Douala		Bafang		Nkongsamba		Total
Type of residence	Modern	Traditional	Modern	Traditional	Modern	Traditional	Both types
TSI (%)							
1	64.9	60.3	51.0	49.0	68.1	48.5	68.1
2	58.7	66.5	56.3	43.7	57.4	73.5	66.5
Mean							
TWI (%)							
1	62.1	62.1	70.6	62.8	60.4	51.8	70.6
2	73.0	69.4	73.0	59.4	79.6	89.6	89.6
Mean							
TAI (%)							
1	64.5	47.6	83.3	79.6	73.6	63.6	83.3
2	78.6	58.9	91.8	74.8	37.4	28.6	91.8
Mean							
TTI (%)							
1	79.4	66.8	70.6	72.0	64.8	75.0	79.4
2	38.9	56.2	81.5	64.2	54.3	79.3	81.5
Mean							
AAMI (%)							
1	85.9	79.3	88.9	84.5	74.7	66.1	88.9
2	70.7	67.8	76.8	81.6	49.0	53.4	81.6
Mean							
AVTGI (%)							
1	6.8	18.4	98.3	89.6	58.2	37.8	98.3
2	23.2	51.2	39.6	47.8	18.8	69.3	69.3
Mean (%)							
ECSI (%)							
1	28.9	24.3	25.3	35.0	26.4	37.2	53.5
2	47.2	31.0	56.1	17.1	97.4	82.8	97.4
Mean							
WVTGI (%)							
1	77.5	65.4	89.0	49.0	45.0	48.3	89.0
2	43.1	51.3	43.7	52.6	33.6	52.0	66.7

Table 5
Physical measured data.

City	Douala		Bafang		Nkongsamba		Total
Type of residence	Modern	Traditional	Modern	Traditional	Modern	Traditional	Both types
Tout (°C)							
Maximum	32.9	33.4	30.2	29.6	31.7	30.1	33.4
Minimum	16.9	17.3	15.2	14.8	17.7	17.3	14.8
Mean	25.5	26.2	22.1	19.8	23.5	22.3	23.6
Standard deviation	3.07	2.87	1.45	2.34	2.72	1.53	2.85
T_{in} (°C)							
Maximum	29.9	31.8	27.2	28.1	30.6	29.7	31.8
Minimum	20.3	19.7	15.3	16.5	17.0	16.5	15.3
Mean	25.3	25.9	21.4	20.8	24.6	23.9	23.6
Standard deviation	1.54	2.17	0.98	1.13	1.74	2.56	1.86
V_{out} (m/s)							
Maximum	1.2	1.1	1.6	1.9	2.1	1.5	2.1
Minimum	0.8	0.9	0.6	0.6	1.1	1.0	1.0
Mean	1.0	1.0	0.9	1.0	1.4	1.1	2.0
Standard deviation	0.1	0.05	0.1	0.2	0.51	0.3	0.89
V_{in} (m/s)							
Maximum	0.15	0.21	0.16	0.19	0.23	0.17	0.23
Minimum	0.04	0.05	0.02	0.02	0.05	0.02	0.02
Mean	0.1	0.11	0.08	0.09	0.1	0.09	0.07
Standard deviation	0.05	0.06	0.03	0.04	0.04	0.05	0.05
RH_{out} (%)							
Maximum	98	99	97	95	83	80	99
Minimum	50	49	42	38	43	39	38
Mean	75	62	77.6	69.3	63	58.9	64.5
Standard deviation	3.6	4.53	4.2	5.3	3.8	3.3	4.0
RH_{in} (%)							
Maximum	74	72	79	65	67	66	79
Minimum	53	49	38	41	42	45	38
Mean	55.8	58.3	51.3	54.0	49.9	50.3	48.2
Standard deviation	2.9	3.1	4.3	2.5	2.4	2.9	3.7

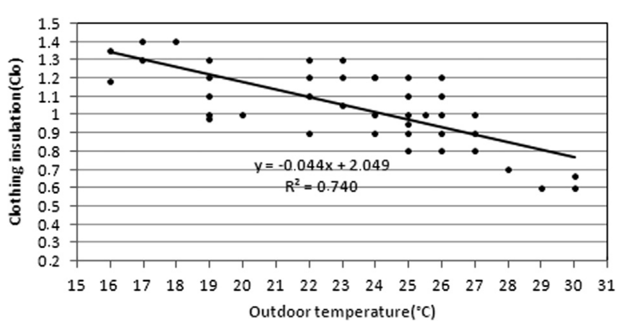

Fig. 6. Thermal clothing insulation values as function of the outdoor temperature.

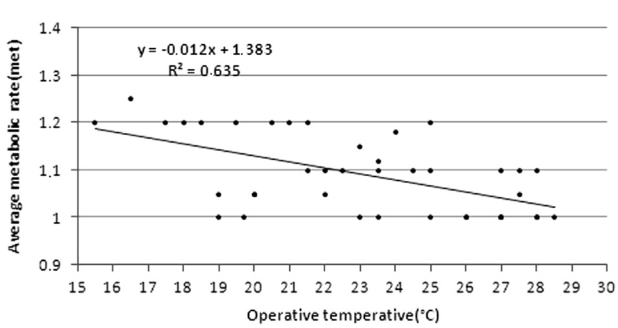

Fig. 7. Average metabolic values as function of indoor operative temperature.

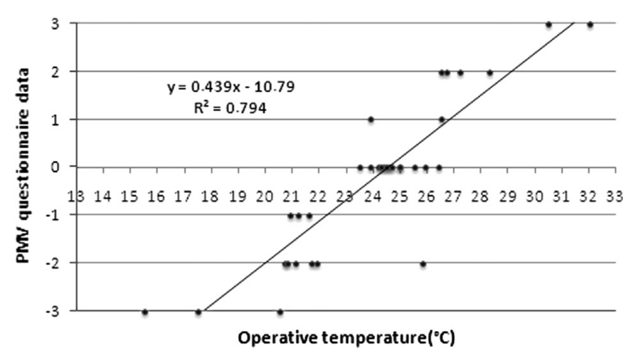

Fig. 8. Mean thermal sensation votes values as function of operative temperature.

(58% in Ngaoundere and 47% in Kousseri). In Fig. 10, it appears that during dry season, 66.3% of occupants have voted "no change" for their environment in traditional buildings, whereas 58.2% of occupants want "more cool" in modern habitats. In rainy season, 52.9% of inhabitants voting again "no change" as thermal preference in traditional habitats while 58.9% of occupants were voting "more warm" in modern habitats. An analysis of these different results show that thermal sensation and thermal preference varied according to type of building and also according to season. This conclusion confirm the results found in the last works [4,5,10,36].

3.2. *Objective approach*

3.2.1. *Predicted mean vote (PMV) from instrumental data*

In Fig. 11, it could be seen that there is a linear correlation between the PMV and indoor air temperature. The PMV ranges varied from −2.03 to 2.1 for indoor air temperatures ranging from 16 °C to 31 °C. There is a good correlation (R^2=0.916) between PMV and indoor air temperature. From Fig. 10, the following

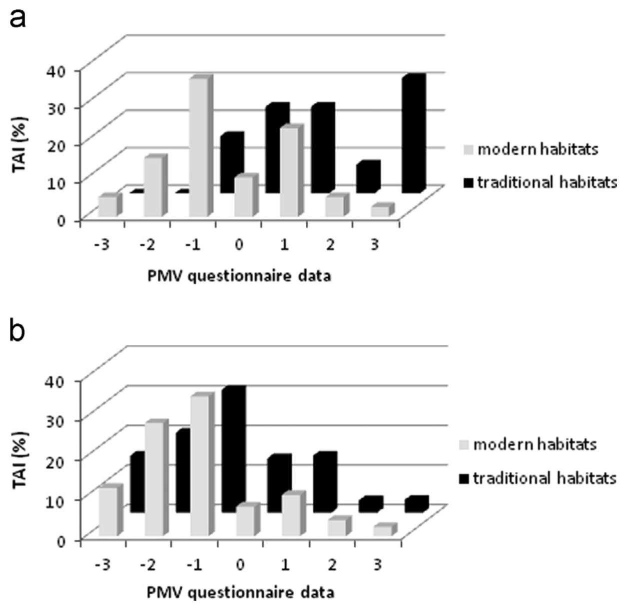

Fig. 9. Thermal acceptability index during the dry (a) and rainy (b) season.

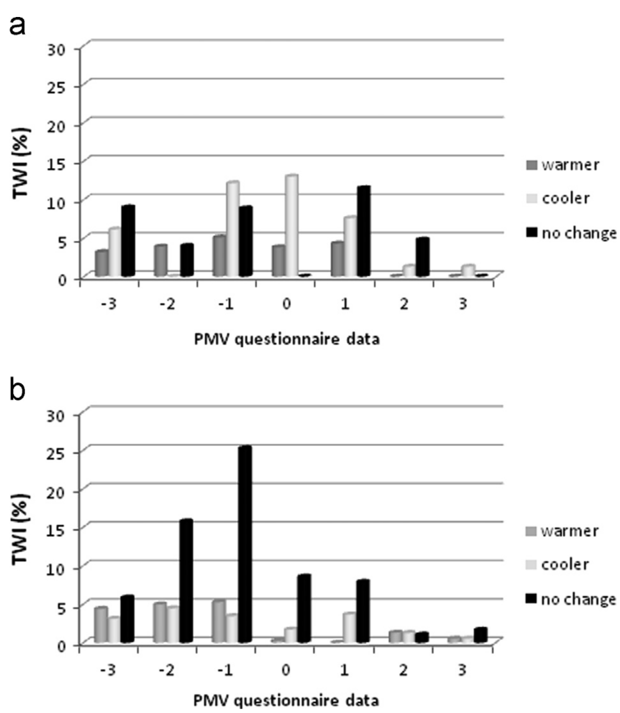

Fig. 10. Thermal wish index during the dry (a) and rainy (b) season.

correlation for PMV was found:

$$PMV = 0.279T_a – 6.422, \quad R^2 = 0.916 \tag{5}$$

Table 6 reports the results of the correlations between PMV and indoor temperature for values of clothing thermal insulation of 1 clo and metabolism of 70 W/m^2, as function of different ranges of humidity levels and air velocity.

3.2.2. Temperature of neutrality

The average temperature of neutrality is 26.5 °C in coastal areas with an average value of 23.02 °C in the studied area. When compared to some previous studies, the temperature difference obtained was 4.38 °C from the result obtained by AG Kwok [16] in classrooms in Hawaii, United States (temperature of neutrality = 27.4 °C); a difference

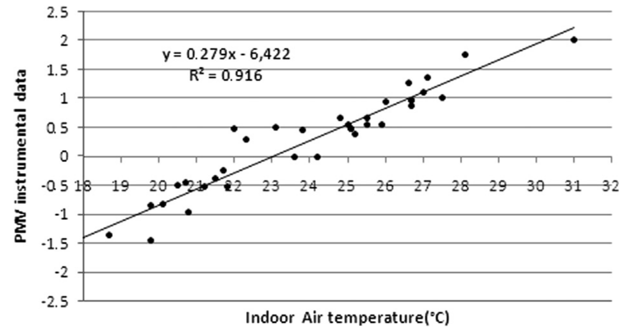

Fig. 11. PMV values as function of indoor air temperature.

Table 6
Relations between PMV and indoor temperature for values of clothing thermal insulation of 1 clo and metabolism of 70 W/m^2.

	Air velocity (m/s)	Indoor temperature (°C)	PMV equation	R^2
40% ≤ RH ≤ 50%	0.05	25–30	$PMV = 0.235T_a - 5.029$	0.917
	0.10	25–30	$PMV = 0.195T_a - 4.062$	0.974
	0.15	20–25	$PMV = 0.166T_a - 3.598$	0.812
	0.20	20–25	$PMV = 0.218T_a - 4.768$	0.981
	0.25	15–20	$PMV = 0.270T_a - 5.723$	0.945
50% ≤ RH ≤ 60%	0.05	25–30	$PMV = 0.229T_a - 4.832$	0.948
	0.10	25–30	$PMV = 0.226T_a - 5.922$	0.983
	0.15	20–25	$PMV = 0.246T_a - 5.340$	0.988
	0.20	20–25	$PMV = 0.194T_a - 4.190$	0.981
	0.25	15–20	$PMV = 0.270T_a - 5.723$	0.945
60% ≤ RH ≤ 70%	0.05	15–20	$PMV = 0.231T_a - 4.789$	0.997
	0.10	20–25	$PMV = 0.227T_a - 4.800$	0.987
	0.15	20–25	$PMV = 0.245T_a - 5.220$	0.995
	0.20	25–30	$PMV = 0.254T_a - 0.543$	0.679
	0.25	25–30	$PMV = 0.200T_a - 4.130$	0.991
70% ≤ RH ≤ 80%	0.05	15–20	$PMV = 0.261T_a - 5.243$	0.968
	0.10	20–25	$PMV = 0.254T_a - 5.315$	0.993
	0.15	20–25	$PMV = 0.219T_a - 4.569$	0.993
	0.20	25–30	$PMV = 0.233T_a - 4.870$	0.997
	0.25	25–30	$PMV = 0.263T_a - 5.618$	0.683

of 5.78 °C was found from that obtained by NH Wong et al. [18] in Singapore (temperature of neutrality = 28.8 °C); 3.28 °C from that obtained by Ogbonna and Harris [14] in Jos, Nigeria (temperature of neutrality = (6.3 °C); and 2.88 °C from that obtained by Ibrahim Hussein [37] in Malaysia (temperature of neutrality = 25.9 °C). This confirms that the thermal neutral temperature varies from place to place.

3.2.3. Percentage of dissatisfaction (PD)

Local thermal comfort was analyzed. For an indoor air quality study, there are a number of empirical equations used by some authors, such as Simonson [38], over the last few years. Indices, like the percentage of dissatisfaction with local thermal comfort, thermal sensation, and indoor air acceptability were determined in terms of some simple parameters, such as dry bulb temperature and relative humidity. Thus, the agreement chosen by the ANSI/ASHRAE and ISO 7730 to establish comfort boundary conditions was about 10% of dissatisfaction. To meet the local thermal comfort produced by the inside air conditions, Toftum et al. [39,40] have studied the response of 38 individuals who were provided with clean air in a closed environment. As a result, the equation for the percentage of local dissatisfaction was developed as shown in Eq. (3).

$$PD = \frac{100}{1 + e^{(-3.58\ +\ 0.18 \times (30 - t)\ +\ 0.14 \times (42.5\ -\ 0.01 p_v)}} \tag{6}$$

The ASHRAE recommends keeping the percentage of local dissatisfaction below 15%, and the percentage of general thermal comfort dissatisfaction below 10%. Ica can be remarked that this PD tends to decrease when the temperature decreases and, consequently, these limiting conditions can be employed to define the optimal conditions for energy saving in the air conditioning systems. Consequently, Fig. 12 shows indoor local thermal comfort conditions in accordance with previous indices. When local thermal comfort was analyzed, it was found that the percentage of dissatisfied persons exceeded 35% in the three cities and, in particular, in Douala, due to its higher average temperature.

3.3. Response of various types of buildings to climatic conditions

3.3.1. Internal environmental parameters

Fig. 13 shows the monthly average distribution of indoor air temperature, from January to December in each city. The temperature range values vary from 20.2 °C to 27.6 °C with an average of 25.6 °C in the coastal zone, 21.1 °C in sub-equatorial monsoon area and 24.3 °C in the equatorial area. From these results, it can be observed that the temperature is higher in the coastal zone than in the mountainous area. Regarding the type of the building, greater temperature fluctuations were found in traditional habitats built with mud rather than in modern breeze blocks ones. The average difference in temperature between modern and traditional habitats in both seasons is 0.6 °C in coastal and sub-equatorial monsoon against 0.7 °C in the equatorial region of Cameroon.

In Fig. 14, it can be noticed that the monthly average indoor relative humidity, from January to December in each city. According to seasons and investigated cities, values of relative humidity are very spread: from 49.0% to 67.2% with an average of 53.1% in the coastal zone (Douala), from 51.0% to 73.5% with an average of 61.9% in the sub-equatorial monsoon area (Bafang) and in equatorial Cameroon (Nkongsamba). The range of humidity obtained is not in accordance with the recommendations (30–60%) of ASHRAE 55/2004.

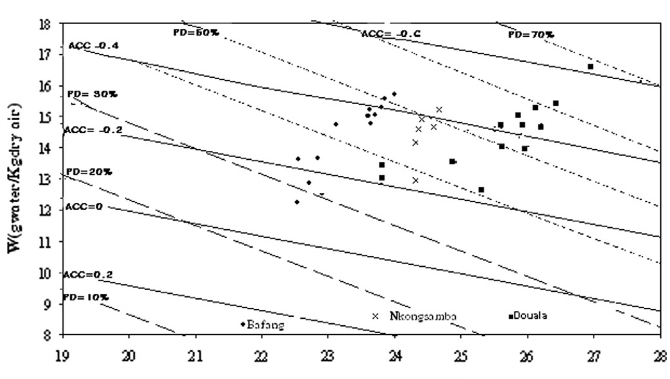

Fig. 12. Local thermal comfort conditions.

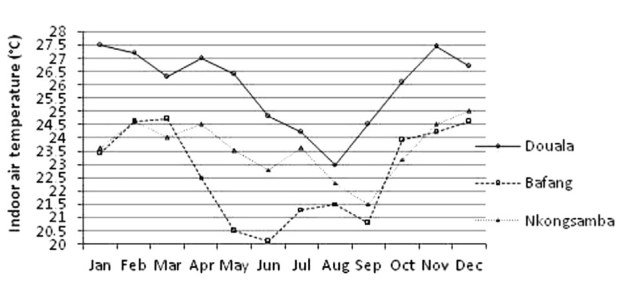

Fig. 13. Indoor monthly air temperature in each city.

Fig. 15 shows monthly variation of the indoor air speed in the different cities studied. During both seasons, the average air speed obtained is of 0.16 m/s for the 3 cities. The highest picks were found in May (0.32 m/s), August (0.31 m/s) and October (0.29 m/s) in the equatorial Cameroon area (Nkongsamba).

3.3.2. External environmental parameters

The outdoor climate has a great influence on indoor thermal comfort. Fig. 16 shows the evolution of the average monthly outside temperature in the dry season (November) and in the rainy season (June) for a period of 21 years, from 1991 to 2011, in all the 3 cities.

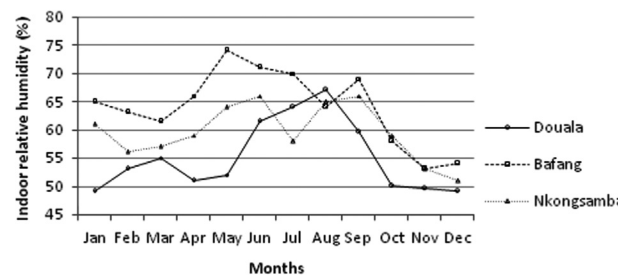

Fig. 14. Indoor monthly relative humidity in each city.

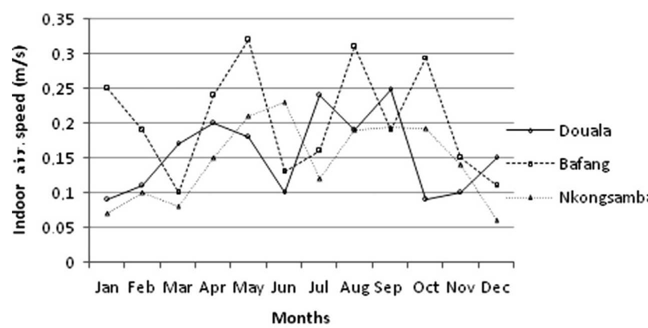

Fig. 15. Indoor monthly air speed in each city.

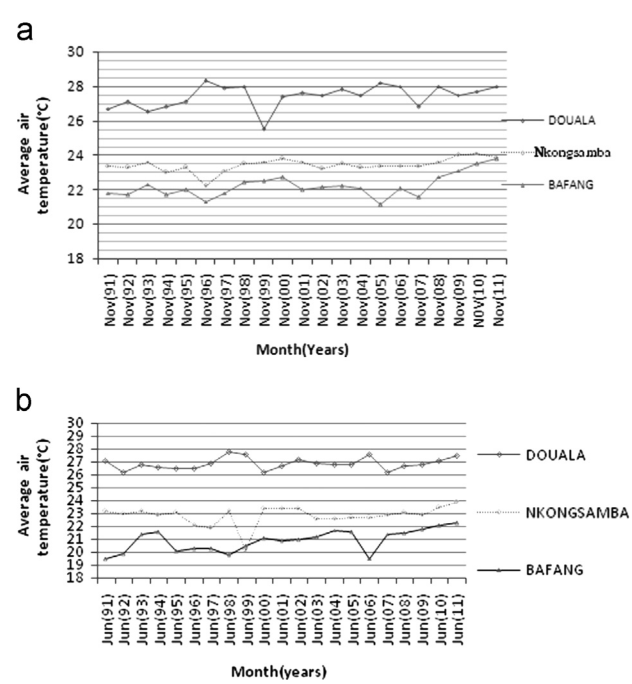

Fig. 16. Mean outdoor temperature for 21 consecutive years during dry season (a) and rainy season (b).

The outside temperature is changing at an alarming rate. In the dry season an average increase of 0.5 °C was found in coastal areas, while an average increase of 0.3 °C characterizes the subequatorial and the monsoon zones; in the rainy season, the tendency of increase is of 0–1 °C, with large fluctuations in coastal and sub-equatorial. An evalutaion of others outdoor parameters, shows that the wind speed varies from a minimum value of 0.5 m/s in the city of Doula to a maximum value of 2.3 m/s in November in the city of Nkongsamba and from 0.6 m/s to 2.2 m/s in June. In the Nkongsamba area, wind speed is higher probably due to the presence of mountains. On the other hand, rainfall is more abundant in coastal areas, sometimes up to 900 mm in June 2008, while rainfall decreases of 2.7 mm per year during the rainy season. However, rainfall is becoming more dangerous in the coast, causing higher floods and much destruction. Rainfall increases from the subequatorial zone to the coastal zone of Cameroon.

As confirmed by previous studies [4,5], objective evaluation by means of measurement results is different from that obtained by subjective interpretation thorough questionnaires. In general, individuals who voted indices (+3, +2, −2, −3) find their concession “uncomfortable”. Sensation and thermal preference also depend on the number of years spent in the region. It may be the reason why some individuals, living in homes with an average of more than 25 years and regularly in traditional Cameroonian sub equatorial monsoon are still considering comfortable their habitats. In addition, the different buildings in recent years do not take into account the macro and micro climate, which is the source of discomfort in most case. No architectural policy, that takes into account local materials and different habits or activities of individuals, in these regions is defined. The traditional buildings in sub-sahara Africa, with local materiels are more comfortable than modern buildings built with imported materials. Many systems can be put in place to assure indoor air quality and energy conservation [41] and simplified models to predict thermal comfort conditions in moderate environments were developed [42].

4. Conclusion

In this study, an investigation of hygrometric thermal comfort experimental and subjective results, conducted in 290 buildings located in three cities of the equatorial climatic zone of Cameroon, is presented. A total of 1120 questionnaires were elaborated both in the dry and rainy seasons, while various experimental values of indoor parameters were measured. Moreover, external environmental parameters such as the monthly average of outside temperature, wind speed and precipitation in the dry season (November) and in the rainy season (June) for duration of 21 years, from 1991 to 2011, in all the 3 cities, are reported. Conclusions could be summarized as follow:

- Comfort range varies according to regions and is highly dependent on climate and regional activity.
- Predicted mean vote (PMV) as votes of thermal sensation does not always show a good correlation in natural ventilation buildings.
- Temperature decreases gradually from the coastal to the mountainous area.
- Average temperature of neutrality is 23.02 °C in the subequatorial zone and 26.5 °C in the coastal areas.
- For PMV=0, PPD=8.8% (in area of Cameroon), 10.5% (coastal) and 11% (in sub-equatorial monsoon zone).
- For internal air speeds from 0.02 m/s to 0.25 m/s and humidity from 48% to 74%, the comfort temperature is ranged from 22.39 °C to 28.15 °C and the thermo neutral temperature is 22.52 °C.
- Precipitation decreases with approximately 2.7 mm per year while the temperature is increasing in an alarming way.
- During the rainy season, 65.5% preferred not to change their environment.

In sub-Saharan zone, solar radiations are also elements that contributed to the immediate increase of internal temperature; therefore, it is important for builders to take into account micro-climate considerations in order to define the types of material that can contribute to build comfortable buildings.

Acknowledgements

Authors are grateful to the various authorities of the three cities who gave us access to information about their locality. They also thank the head of the national weather station and all those, near and far, who participated in this research during the field study.

Appendix A. Synthesis of the questionnaire

Note: This questionnaire is anonymous; the results of the statistical evaluation, the analysis and conclusions will be published. Please carefully read each question before answering and do not discuss with your friend who also filled this questionnaire.

*** Thanks you for your co-operation and the time you will have to devote to this questionnaire ***

Part 1: Personal data

(Please tick off the appropriate box)

Age………… Sex : M ☐ **F** ☐ height…………, weight…………

What is the type of house you live in? : Modern☐ Traditional☐

Is it with: mud ☐ wood☐ stone☐ glass ☐

Is it plastered ☐ Paint☐

How long did you live in the town?..

How long you live in your present house?..

How old is your house?..

What is the color of your house?………………………………………………

How many rooms does it have?...

Part 2: Thermal

Questionnaires (please tick off the appropriate box)

1) How do you feel about the temperature in this moment?
Cold ☐ , cool ☐ , Slightly cool ☐ , Neutral☐ , Slightly warm ☐ , warm☐ , Hot ☐

2) How do you find it?
Acceptable☐ Slightly acceptable☐ Not acceptable☐ Slightly not acceptable☐

3) What is your thermal sensation?
Comfort ☐ Light annoyance ☐ Annoyance ☐ Heavy annoyance☐

4) How would you like to feel?
Much too cool ☐ Too cool ☐ A little bit cool ☐ No change ☐ A little bit warm☐ Too warm ☐ Much too warm☐

5) On the basis of your personal preferences, how would you consider the room temperature?
Acceptable ☐ Not acceptable ☐

6) How do you consider this room?
Perfectly tolerable ☐ Slightly hard to tolerate☐ Hard to tolerate☐ Veryhardto tolerate ☐ intolerable☐

7) How do you feel about the air flow in this moment?
Completely not acceptable☐ Not acceptable ☐ Slightly not acceptable ☐ Slightly acceptable ☐ Acceptable☐ Perfectly acceptable☐

8) Would you like to have an air
Smaller than now☐ Exactly how it's now☐ Greater than now☐

9) How do you consider the temperature difference between head and ankle?
Completely not acceptable ☐ Not acceptable ☐ Slightly not acceptable ☐
Slightly acceptable☐
Acceptable ☐ Perfectly acceptable☐

Provide us indication regarding your clothing (e.g. Underwear, woman clothes, trousers, accessories, shirt, pullover etc.)

10) What was your occupation during last hour?

(Please turn over).

A.1. Appendix

Occupation	Last 10 min	Minutes ago	Minutes ago	Minutes ago
Doing office job	☐	☐	☐	☐
Walking in slope	☐	☐	☐	☐
Walking in flat land	☐	☐	☐	☐
Walking in ascent	☐	☐	☐	☐
Resting	☐	☐	☐	☐
Running	☐	☐	☐	☐
Seating	☐	☐	☐	☐
Taking a bath	☐	☐	☐	☐
Driving	☐	☐	☐	☐
Reading	☐	☐	☐	☐
Doing something else	☐	☐	☐	☐
Eating	☐	☐	☐	☐
Washing dishes	☐	☐	☐	☐
Cooking	☐	☐	☐	☐

Part 3: Personal microclimatic control (please tick off the appropriate box)

1) **How can you define the level of control of microclimatic conditions?**

No control☐ Light control☐ Medium control☐ High control☐ Total control☐

2) **How do you feel about the possibility of controlling thermal comfort?**

Satisfied☐ Not satisfied☐

3) **Can you open/close the windows?**

No ☐ Yes ☐

4) **How often do you do this?**

Never ☐ Rarely☐ Sometimes☐ Frequently☐ Always ☐

5) **Can you open/close the external doors?**

No☐ Yes ☐ there is no door☐

6) **Can you open/close the inner doors?**

No☐ Yes ☐ there is no door☐

7) **Can you regulate the thermostat?**

No ☐ Yes ☐ There is no thermostat☐

8) **Can you regulate curtains/rolling shutters?**

No☐ Yes☐ There is none of them☐

References

[1] Taylor P, Fuller RJ, Luther MB. Energy and thermal comfort in a rammed earth office building. Energy Build 2008;40:793–800.
[2] Wagner A, Gossauer E, Moosman C, Gropp Th, Leonhart R. Thermal comfort and workplace occupant satisfaction—results of field studies in German low energy office buildings. Energy Build 2007;39:758–69.
[3] Hensen JLM. On the thermal interaction of building structure and heating and ventilating system. (PhD thesis). Eindhoven: Technische Universiteit Eindhoven; 1991.
[4] Ricciardi P, Buratti C. Thermal comfort in open plan offices in northern Italy: an adaptive approach. Build Environ 2012;56:314–3207.
[5] Buratti C, Ricciardi P. Adaptive analysis of thermal comfort in university classrooms: correlation between experimental data and mathematical models. Build Environ 2009;44:674–87.
[6] ASHRAE Standard 55/2004. Thermal environment conditions for human occupancy. Atlanta, GA, USA; 2004.
[7] CIBSE. Environmental design. London. CIBSE Guide A the Chartered Institution of Building Services Engineers; 1999.
[8] UNI EN ISO 7730. Ergonomics of the thermal environment—analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria; 2006.
[9] Butera F. Principles of thermal comfort. Renewable Sustainable Energy Rev 1998;2:39–66.
[10] Noël D, René T. An investigation into thermal comfort and residential thermal environment in an intertropical sub-Saharan Africa region: field study report during the Harmattan season in Cameroon. Energy Convers Manage 2010;51:1391–7.
[11] Noël D, René T, Donatien N. Thermal comfort: a review paper. Renewable Sustainable Energy Rev 2010;14:2626–40.
[12] Noël D. Contribution to the study of thermal comfort and coupled heat and mass transfer through building components in the Sub-Saharan Africa region. (PhD thesis). Cameroon: University of Yaounde I; 2010.
[13] Noël D, René T, Donatien N. Estimation of some comfort parameters for sleeping environments in dry-tropical sub-Saharan Africa region. Energy Convers Manage 2012;58:110–9.
[14] Ogbonna AC, Harris DJ. Thermal comfort in sub-Saharan Africa: field study report in Jos-Nigeria. Appl Energy 2008;85:1–11.
[15] Busch JF. A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in Thailand. Energy Build 1992;3:235–49.
[16] Kwok AG. Thermal comfort in tropical classrooms. ASHRAE Trans 1998:1031–47.
[17] Nicol JF, Humphreys MA. Adaptive thermal comfort and sustainable thermal standards for buildings. Energy Build 2002;34:563–72.
[18] Wong NH, Khoo SS. Thermal comfort in classrooms in the tropics. Energy Build 2003;35:337–51.
[19] Henry F, Wong NH. Thermal comfort for naturally ventilated houses in Indonesia. Energy Build 2004;36:614–26.
[20] Oluwafemi K, Akande, Adebamowo MA. Indoor thermal comfort for residential buildings in hot–dry climate of Nigeria. Energy Use Build 2010;1(11).
[21] Nasrollahi N, Knight I. Surveyed thermal comfort in Iranian offices. Build Environ 2007;1:10.
[22] Wagner A, Roberto L. Thermal comfort in buildings located in regions of hot and humid climate of Brazil. Energy Build 2005;1:23.
[23] Ch Surapong, Nyi Nyi H. Thermal comfort assessment in two tropical regions and radiant cooling as a passive cooling option. Energy Build 2007;1:17.
[24] Kwok Alison G, Chungyoon Chun. Thermal comfort in Japanese schools. Sol Energy 2003;74:245–52.
[25] Miyazawa M. Seasonal changes of sleep environment at bedtime and on arising. In: The proceeding of the 18th symposium on human-environment system; 1994.
[26] Zambrano L, Malafaia C., Bastos LEG. Thermal comfort evaluation in outdoor space of tropical humid climate. In: PLEA 2006—the 23rd conference on passive and low energy architecture. Geneva, Switzerland; September 2006. p. 6–8.
[27] Han J, Zhang G, Zhang Q, Zhang J, Liu J, Tian L, et al. Field study on occupants' thermal comfort and residential thermal environment in a hot–humid climate of China. Build Environ 2007;42:4043–50.
[28] Meukam P, Jannot Y, Noumowe A, Kofane TC. Thermo physical characteristics of economical building materials. Constr Build Mater 2004;18(6):437–43.
[29] Tsilingiris PT. On the thermal time constant of structural walls. Appl Therm Eng 2004;24(5–6):743–57.
[30] Silvia M, Fernando R, Ignacio C. Study of thermal environment inside rural houses of Navapalos (Spain): the advantages of reuse buildings of high thermal inertia 2010;24:666–76Constr Build Mater 2010;24:666–76.
[31] Nagano K, Mochida T. Experiments on thermal design of ceiling radiant cooling for supine human subjects. Build Environ 2004;39:267–75.
[32] UNI EN ISO 10551. Ergonomia degli ambienti termici—valutazione dell'influenza dell'ambiente termico mediante scale di giudizio soggettivo; 2002.
[33] Taleghani M, Tenpierik M, Kurvers S, Dobbelsteen AV. A review into thermal comfort in buildings. Renewable Sustainable Energy Rev 2013;26:201–15.
[34] Forgiarini R, Ghisi E. What is the most adequate method to assess thermal comfort in hybrid commercial buildings located in hot–humid summer climate. Renewable Sustainable Energy Rev 2014;29:449–62.

[35] Moujalled B, Cantin R, Guarracino G. Comparison on thermal comfort algorithms in naturally ventilated office building. Energy Build Environ 2008;40:2215–23.
[36] Dili AS, Naseer MA, Varghese Z. Thermal comfort study of Kerala traditional residential buildings based on questionnaire survey among occupants of traditional and modern buildings. Energy Build 2010;42:2139–50.
[37] Hussein I, Hazrin M. Field study on thermal comfort in Malaysia. (©EuroJournals Publishing, Inc. 2009). Eur J Sci Res 2009;37(1):134–52 (ISSN 1450-216X).
[38] Simonson CJ, Salonvaara M, Ojanen T. Improving indoor climate and comfort with wooden structures. Espoo: Technical Research Centre of Finland; 2001; 2001.
[39] Toftum J, Jorgensen AS, Fanger PO. Upper limits for indoor air humidity to avoid uncomfortably humid skin. Energy Build 1998;28:1–13.
[40] Toftum J, Jorgensen AS, Fanger PO. Upper limits of air humidity for preventing warm respiratory discomfort. Energy Build 1998;28:15–23.
[41] Dounis AI, Caraiscos C. Advanced control systems engineering for energy and comfort management in a building environment—a review. Renewable Sustainable Energy Rev 2009;13:1246–61.
[42] Buratti C, Ricciardi P, Vergoni M. HVAC systems testing and check: a simplified model to predict thermal comfort conditions in moderate environments. Appl Energy 2013;104:117–27.