Brazilian Journal of Development

Thermal comfort assessment in a naturally ventilated university dormitory in tropical climate zone

Avaliação do conforto térmico em uma moradia universitária naturalmente ventilada em clima tropical

DOI:10.34117/bjdv6n7-145

Recebimento dos originais: 04/06/2020
Aceitação para publicação: 08/07/2020

Adriana Rodrigues Pereira
Mestre em Engenharia Civil pelo Centro Federal de Educação Tecnológica de Minas Gerais (CEFET-MG)
Instituição: Centro Federal de Educação Tecnológica de Minas Gerais (CEFET-MG)
Endereço profissional: Av. Amazonas, 7675 - Nova Gameleira, Belo Horizonte - MG, 30510-000
E-mail: adrianaengcivil@hotmail.com

Simone Queiroz da Silveira Hirashima
Doutora em Arquitetura e Urbanismo pela Universidade de São Paulo (USP)
Instituição: Centro Federal de Educação Tecnológica de Minas Gerais (CEFET-MG)
Endereço profissional: Av. Amazonas, 7675 - Nova Gameleira, Belo Horizonte - MG, 30510-000
E-mail: simonehirashima@cefetmg.br

Raquel Diniz Oliveira
Doutora em Engenharia de Estruturas pela Universidade Federal de Minas Gerais (UFMG)
Instituição: Centro Federal de Educação Tecnológica de Minas Gerais (CEFET-MG)
Endereço profissional: Av. Amazonas, 7675 - Nova Gameleira, Belo Horizonte - MG, 30510-000
E-mail: raqueldiniz@cefetmg.br

ABSTRACT
This research investigated the occupants’ thermal comfort in a naturally ventilated university dormitory. A field study was conducted in tropical climate zone in Brazil. To carry out the thermal comfort evaluation the bedroom that presents the worst thermal behavior was analyzed. Climatic variables, such as air temperature, air speed and relative humidity, were measured while occupants answered online questionnaires about subjective thermal perception. The method used involves: a) climatic field measurements simultaneously with application of questionnaires to users; b) data analysis in which thermal comfort was evaluated by the indices PMV and operative temperature; c) comparing the indices results and the perceptions of occupants. Linear regression analysis showed that the neutral operative temperature was 23.79 °C. For the adaptive model, the neutral temperature obtained was 25.22 °C. The lower and upper limits, for 80% acceptability, were determined as 21.72 °C and 28.72 °C, respectively. The data obtained for adaptive thermal comfort approach showed a correspondence with the users’ thermal sensation. There was no adherence between the occupants’ responses and the PMV approach, demonstrating the low prediction accuracy of the PMV–PPD model in a tropical climate zone. Occupants noticed their surrounding thermal environment warmer than the PMV predicted.

Keywords: Thermal comfort, Natural ventilation, Adaptive model, Static model.
RESUMO
Esta pesquisa investigou o conforto térmico dos ocupantes em um dormitório universitário com ventilação natural. Um estudo de campo foi realizado na zona climática tropical do Brasil. Para realizar a avaliação do conforto térmico, foi analisado o quarto que apresenta o pior comportamento térmico. Variáveis climáticas, como temperatura do ar, velocidade do ar e umidade relativa, foram medidas enquanto os ocupantes respondiam a questionários on-line sobre percepção térmica subjetiva. O método utilizado envolve: a) medições de campos climáticos simultaneamente com a aplicação de questionários aos usuários; b) análise dos dados em que o conforto térmico foi avaliado pelos índices PMV e temperatura operacional; c) comparar os resultados dos índices e as percepções dos ocupantes. A análise de regressão linear mostrou que a temperatura operatória neutra era 23,79 °C. Para o modelo adaptativo, a temperatura neutra obtida foi de 25,22 °C. Os limites inferior e superior, para 80% de aceitabilidade, foram determinados como 21,72 °C e 28,72 °C, respectivamente. Os dados obtidos para a abordagem de conforto térmico adaptativo mostraram uma correspondência com a sensação térmica dos usuários. Não houve aderência entre as respostas dos ocupantes e a abordagem PMV, demonstrando a baixa precisão de previsão do modelo PMV-PPD em uma zona climática tropical. Os ocupantes notaram o ambiente térmico circundante mais quente do que o PMV previa.

Palavras-chave: Conforto térmico, Ventilação natural, Modelo adaptativo, Modelo estático.

1 INTRODUCTION
People spend more than 80% time indoors [1]. Thus, thermal comfort plays a very important role in the built environment due to this long time spent indoors.

Thermal comfort is defined as “the condition of mind that expresses satisfaction with the thermal environment”, according to ASHRAE STANDARD 55–2017 [2]. Thermal comfort, accomplish by a thermal body balance, depends on human aspects (i.e., physical activities and clothing patterns) and indoor climatic variables (i.e., air temperature, mean radiant temperature, air velocity, and relative humidity) that is influenced by the local microclimate and building envelope [3].

There are some models to evaluate thermal comfort problems that can be divided into two main approaches: studies applying a rational thermal comfort (RTC) model, such as the predicted mean vote (PMV) model [4], and studies applying an adaptive thermal comfort (ATC) model, such as the operative temperature model [5].

In the 70’s, Fanger [4] proposed The Predicted Mean Vote – Percentage Predicted Dissatisfied (PMV – PPD) indice, which is based on heat balance studies between the human body and the environment. This static model considers indoor environmental parameters and occupant’s activity level and clothing.

The international standards ASHRAE STANDARD 55–2017 [2] and ISO 7730-2005 [6] address the static model as a methodology for assessing thermal comfort in buildings. However,
since this model was developed within environmental chambers, it does not consider some parameters such as the occupant's acclimatization, and demographic and psychological variables [7]. Some studies show differences between the thermal comfort predicted by the PMV and the actual thermal sensations of occupants, mainly in naturally ventilated buildings [8,9]. In this context, the adaptive model emerged as an alternative to the heat balance approach for thermal comfort evaluation [5].

The main concept of the adaptive approach is that users, when subjected to situations of discomfort, can adapt themselves to the environment, slightly widening the perception of comfort conditions. Occupants interacts with its environment, as well as adapt it in agreement to their preferences. The thermal comfort in buildings is related to an adaptation that occurs in three different areas: psychological, behavioral and physiological [10]. ASHRAE Standard 55-2017 [2] presents a method for evaluating thermal comfort according to the adaptive model, for naturally ventilated buildings.

To evaluate the indoor thermal comfort, several studies were conducted based on adaptive and static approaches.

Amin et al. [11] evaluated the influence of occupants’ thermal history on indoor thermal preference in a student dormitory in the UK. The results indicated that the average indoor temperature preference of occupants from warm climates was 2.3°C higher than those from cool climates.

Wu et al. [12] analyzed the thermal comfort in naturally ventilated dormitory buildings in China, considering the adaptive model approach. Questionnaires were used to evaluate the subjective occupants’ thermal perception and climatic variables were measured simultaneously. In this study, the users’ adaptive behaviors of clothing and air velocity modifications were closely correlated to indoor operative temperatures.

Although several thermal comfort studies have been conducted considering different building envelopes, locations and climates, each study was unique in terms of occupants’ sample due to the thermal adaptation. Thus, more studies should be developed considering different climates and building types to promote an accurate database for designing optimal thermal environments.

The Brazilians standards NBR 15575 [13] and NBR 15220 [14] establish envelope criteria, according to eight bioclimatic zones, to assess buildings’ thermal performance. However, the standards do not address occupants’ thermal comfort. Thus, it is important to develop thermal comfort studies for Brazil realities.
Considering the context presented, this study analyzed the occupants’ thermal comfort and thermal perception in bedrooms of a university dormitory in Brazil. The main objectives of the present study are as follows:

1) To evaluate thermal comfort for occupants by using the adaptive and PMV models, according to ASHRAE STANDARD 55–2017 [2].
2) To evaluate the perception and thermal preference of the occupants through questionnaires applied simultaneously with the measurement of climatic variables.
3) To compare the occupants’ answers to the results obtained with the adaptive and PMV models.

2 MATERIAL AND METHODS

This paper evaluates the occupant’s thermal comfort in a university dormitory in Belo Horizonte, Brazil. The method adopted to evaluate the university dormitory occupants’ thermal perception implies two different approaches: quantitative and objective, based on the measurement of climatic variables following EN ISO 7730-2005 [6], and qualitative and subjective, based on a questionnaire following EN ISO 10551/1995 [15].

In the present case study, the adaptive and the static thermal indices were used to quantify the thermal comfort. Then, the results were compared with users’ perception.

2.1 CASE STUDY

The case study is a university dormitory located in Belo Horizonte, Brazil (latitude: 19°55'14.99"S; longitude: 43°56'16.01"W, altitude 858m). Belo Horizonte is classified as Cwa according to the climatic classification of Köppen-Geiger [16].

The bedrooms are distributed in two naturally ventilated buildings (Figure 1) that presents windows facing the Northwest and Southeast facade.

Figure 1. University dormitory master plan. Without scale. Adapted from DPFP [17].
The penthouse apartment floor plan is presented in Figure 2. Table 1 presents the layers of the university dormitory’s envelope.

Table 1. Layers of building envelope.

| Component  | Material                | Thickness (m) |
|------------|-------------------------|---------------|
| Outer wall | Mortar                  | 0.025         |
|            | Concrete block          | 0.1           |
|            | Plaster                 | 0.005         |
| Inner wall | Mortar                  | 0.025         |
|            | Concrete block          | 0.1           |
|            | Mortar                  | 0.025         |
| Floor      | Porcelain tile          | 0.01          |
|            | Mortar                  | 0.025         |
|            | Concrete                | 0.1           |
|            | Plaster                 | 0.005         |
| Ceiling    | Mortar                  | 0.025         |
|            | Expanded polystyrene    | 0.002         |
|            | Extruded polystyrene    | 0.025         |
|            | Asphalt membrane        | 0.007         |
|            | Concrete                | 0.1           |
|            | Plaster                 | 0.005         |

The present paper analyzed one bedroom, highlighted in Figure 3. The bedroom was selected because it is the worst situation considering the thermal comfort criteria: is located on the last floor, its opening is oriented to the Northwest facade and has three walls exposed to sunstroke.
2.2 PILOT STUDY

To validate and adjust the methodology proposed initially, a pilot study was carried out on 04/27/18. On that date, the building was under construction. Thus, the pilot study began at 4:00 p.m. due to the end of employees’ shift. During the pilot study was observed the incidence of direct solar radiation inside the room (Figure 4). Thus, in addition to a thermal stress meter, we decided to use in this research a thermo-hygrometer protected by a radiant barrier to evaluate the thermal comfort for cases where occupants are in the shade or exposed to sunstroke.

During the pilot study, the way that the questionnaires would be applied was also defined. Initially, the questionnaires would be answered on paper. However, the application of online questionnaire through the eSurv online platform was implemented [19]. The e-Surv platform is a free online tool that has been shown to be effective for the application of questionnaires in this research. The use of online research platforms, according to Evans and Mathur [20], eliminates transcription errors, makes preliminary analyzes before the end of data collect, simplifies export and
analysis of data, among others. The participants used a personal smartphone to complete the survey. The data was recorded by the platform and exported into spreadsheets.

2.3 DATA COLLECTION

To carry out the evaluations, the measurements of the climatic variables and the application of questionnaires were carried out simultaneously. According to Kuchen [21], this type of analysis allows to detect data that influence on the thermal comfort of the user and allows simultaneous evaluation of them.

The measurements of the environmental variables were carried out in October 2018. This month was chosen due to the fact that the university dormitory was under construction in the first half of 2018. In addition, a representative month to collect the environmental data was chosen. According to the latest historical weather data (1981-2010) [22], October is one of the hottest months of the second semester and has an average temperature (22.6ºC) higher than the average annual temperature (21.8ºC).

2.4 MEASUREMENTS OF THE CLIMATIC VARIABLES

The climatic variables measured correspond to those set by ASHRAE STANDARD 55–2017 [2] (clothing insulation, metabolic rate, air temperature radiant temperature, humidity and air speed).

Air temperature and relative humidity were collected simultaneously in the analyzed bedroom and outdoors.

This data was obtained through thermo-hygrometers and a thermal stress meter, both with datalogger. The air velocity was measured through an anemometer.

The equipment was installed with sensors 1.10m from floor level, as recommended by ISO 7726/1998 [23].

The equipment’s’ characteristics are presented in Table 2.

| Equipment                  | Variable                                      | Brand/ Model                  | Precision | Range          | Resolution | Location       |
|----------------------------|-----------------------------------------------|-------------------------------|-----------|----------------|------------|----------------|
| Thermal stress meter       | Globe temperature, dry bulb temperature and humidity | Instrument Therm TGD-300     | ±0.5°C    | -5ºC to 60ºC   | 0.1ºC      | Indoor         |
| Anemometer                 | Air speed                                     | Instrument Therm AD-250      | ±3%       | 0.4 to 30 m/s  | 0.1 m/s    | Indoor         |
| Thermohygrometer datalogger | Dry bulb temperature and humidity             | Onset Computer Corporation/ Hobo U12 | ±0.35ºC | -20ºC to 70ºC | 0.03ºC     | Indoor and outdoor |
ISO 7726/1998 [23] recommends that temperature sensors should be protected from the effects of thermal radiation from heated or cooled surfaces. Thus, shelters were used to protect the thermo-hygrometers used in this research.

The thermo-hygrometer located outdoor was protected from solar radiation by a shelter, made of PVC, fixed to a tripod (Figure 5). The development of the PVC shelter followed the recommendations presented by Hirashima [24].

| Equipment   | Variable            | Brand/ Model                  | Precision | Range          | Resolution | Location |
|-------------|---------------------|-------------------------------|-----------|----------------|------------|----------|
| Temperature sensor | Globe temperature   | National Semiconductor/ LM35 | ±0.5°C    | -55°C to 150°C | 0.5°C      | Outdoor  |

![Figure 5. Data logger HOBO outside the building.](image)

Regarding the location of the equipment in floor design plan, ISO 7726/1998 [23] has no recommendations. However, ASHRAE STANDARD 55–2017 [2] recommends that the equipment has to be located at a representative point of the dispersion of the users in the environment or located in the center, with a minimum distance of 1 meter from each internal wall.

Studies carried out by Barbosa, Weiller and Lamberts [25] indicated that the specification of the measurement in the center of the environment can be replaced by the measurement close to the facades exposed to the lowest insolation, since the temperature data obtained in both cases were similar.

Since the bedroom where the measurements were taken is exposed to sunstroke during part of the day, to avoid direct sunlight in the thermal stress meter, the equipment was positioned closer to an internal wall.

In addition, a thermo-hygrometer was positioned in the area exposed to direct sunlight to evaluate comfort for both scenarios.
Inside the bedroom, a shelter made with PET bottle coated with aluminum foil was used to protect the thermo-hygrometer (Figure 6). According to a study conducted by Barbosa, Lamberts and Guths [26], in which different types of radiation barriers were evaluated to measure indoor air temperatures, the PET bottle shelter presented the lowest standard deviations. The PET shelter was fixed to the ceiling of the bedroom by means of a string, with sensors 1.10m from floor level.

Figure 6. HOBO data logger and thermal stress meter location in the bedroom.

Figure 7 shows shown the location of the equipment in floorplan during the field study.

Figure 7. Layout of the equipment in floorplan inside the bedroom. Without scale.

The stabilization time considered for the 150mm globe thermometer was 30 minutes, as suggested by ISO 7726/1998 [23].

The data loggers were programmed using the software Boxcar Pro 4-Onset. The data were registered every 5 minutes in 10/22/2018, from 09:30am to 18:30pm. Prior to the fieldwork, the equipment was calibrated.
2.5 QUESTIONNAIRE SURVEYS

A questionnaire was developed to collect subjective data from the occupants for thermal comfort evaluation in the university dormitory. The questionnaire (Figure 8) focused on the comfort, acceptance, and thermal preference of users. Complementarily, anthropometric (age, weight and gender), clothing, demographic and activity level data was included.

The questionnaires applied to the occupants were based on ISO 10551/1995 [15] and other questionnaires applied in previous research [24,27,28].

To evaluate the thermal perception, the occupants were asked to rate thermal conditions between −3 (very cold) and +3 (very hot) on the ASHRAE STANDARD 55–2017 [2] thermal sensation scale. Participants had no prior knowledge of this survey.

Table 3 presents the scales used in the questionnaire surveys. Scale values were used to convert qualitative data into quantitative values.

| Age: ________ | Height: ________ |
|--------------|----------------|
| Weight: ________ | Ethnicity: ________ |
| Place of birth: ________ |
| In which cities have you lived and for how long? ________ |
| Horizonte? ________ |

4) Taking into account only your personal preference, do you accept or reject the thermal conditions of this environment?
   a) Accept
   b) Reject

5) This environment, in your opinion, regarding temperature, is it:
   a) Perfectly tolerable
   b) Easily tolerable
   c) Difficult to tolerate
   d) Intolerable

6) You are a person who usually feels:
   a) Very cold
   b) Very hot
   c) Neutral

7) Considering the wind, how do you prefer?
   a) Weaker
   b) How it is
   c) Stronger
   d) I do not know

8) Considering the temperature, how do you prefer?
   a) Weaker
   b) How it is
   c) Stronger
   d) I do not know

9) Considering the humidity, how do you prefer?
   a) Drier
   b) How it is
   c) Wetter
   d) I do not know
Table 3. Scales used in this study to record subject’s response.

| Scale Values | Thermal sensation | Thermal perception | Thermal preference | Thermal acceptance |
|--------------|-------------------|--------------------|--------------------|--------------------|
| -3           | Cold              | -                  | Much cooler        | -                  |
| -2           | Cool              | -                  | Cooler             | -                  |
| -1           | Slightly cool     | A little comfortable | Slightly cooler  | Unacceptable       |
| 0            | Neutral           | Comfortable        | No change          | Acceptable         |
| 1            | Slightly warm     | Uncomfortable      | Slightly warmer    | -                  |
| 2            | Warm              | Very uncomfortable | Warmer             | -                  |
| 3            | Hot               | -                  | Much warmer        | -                  |

The field research was previously approved by the National Commission of Ethics in Research – CONEP [29]. At the beginning of each survey, a general presentation was made to the interviewees and their approval was requested. The presentation was realized to explain the procedures and the scope of the study as well as to answer any questions about the research.

Interviewees were randomly selected within another university dormitory to carry out the questionnaire survey. To ensure that the respondents had enough time to experience the thermal environment within the bedroom, a short-term acclimatization time of, at least, 15 minutes was set. ASHRAE STANDARD 55–2017 [2] states that the standard can be applied for indoor comfort studies if the occupants remain in the environment for at least 15 minutes.

After the acclimatization, the questionnaires were applied. Each questionnaire lasted, on average, 5 minutes.

Regarding the long-term acclimatization, occupants were categorized as acclimatized if they lived in Belo Horizonte for more than six months. Occupants who reported living in Belo Horizonte for less than six months had their questionnaires disregard.

38 users were interviewed on 10/22/2018 (Figure 9), from 09:30am to 6h30pm (considering local time, without daylight saving time). The questionnaires were applied to a maximum of two individuals per time due to the limitation of space. Thus, the maximum occupation of the bedroom during the interviews was of three individuals (researcher and participants).

It is interesting to observe in Figure 9 the difference for clothing insulation between occupants that answered the questionnaire at the same time. This corroborates the individual difference concerning thermal comfort.
2.6 SAMPLE

The population (386) is considered to be the people living in the analyzed building. The sample size was calculated according to Renckly [30], as shown in Equation 1.

\[ n = \frac{0.25NZ^2}{d^2(N-1) + (0.25Z^2)} \]  

Eq. (1)

where \( n \) is the sample size required, \( N \) is the number of building users, \( Z \) is the number of standard deviation units of the sampling distribution corresponding to the desired confidence level and \( d \) is the precision level.

A sample of 37 users was obtained considering the number of building users (\( N \)) equal to 386, a confidence level of 80% for a confidence coefficient (\( Z \)) of 1.28, and the precision level (\( d \)) of 0.1.

26 women and 2 men were interviewed. Table 4 presents the profile of occupants.

| Variables          | Min. | Mean  | Max.  | Amplitude | SD  |
|--------------------|------|-------|-------|------------|-----|
| Age                | 19   | 22.61 | 29    | 22.61      | 2.63|
| Height (cm)        | 160  | 169.95| 189   | 169.95     | 6.80|
| Weight (kg)        | 49   | 67.84 | 113   | 67.84      | 15.54|
| Clothing (clo)     | 0.30 | 0.50  | 0.70  | 0.50       | 0.08|
| Metabolism (met)   | 1.00 | 1.06  | 1.60  | 1.06       | 0.15|

2.7 STATIC MODEL

To calculate thermal comfort using the static model, climatic data (e.g., air temperature, air humidity, wind speed, and mean radiant temperature) and personal variables (e.g., activity and clothing level) were used.
The static model is defined by the PMV index based on the thermal comfort equation defined by Fanger [31]. This index represents the mean thermal sensation vote on a seven-point scale, between −3 (cold) and +3 (hot). Thermal comfort is achieved when the PMV index is between −0.5 and 0.5 and, in this case, is considered to be thermally neutral. An indoor environment is considered thermally comfortable when it is thermally neutral for 95% of people. The predicted percentage of dissatisfied (PPD) is obtained as shown in Equation 2.

\[
PPD = 100 - 95 x e^{-0.3353 \times PMV^4 - 0.2179 \times PMV^2}
\]

To calculate the PMV and PPD indices, the online calculator CBE Thermal Comfort Tool [32] was used. The tool is based on the equations presented in Annex D of ISO 7730-2005 [6]. The input data used in the calculator were: average radiant temperature, dry bulb temperature, air velocity, relative humidity, metabolic rate and clothing insulation.

To determine the metabolic rate and the insulation of clothing, were used values presented in Annexes B and C of ISO 7730-2005 [6], respectively. The metabolic rate ranged from 1.0 to 1.6 MET and clothing isolation ranged from 0.3 to 0.7 clo. These variables were collected through the questionnaire filled out by the research participants.

2.8 ADAPTIVE MODEL

The adaptive thermal comfort model evaluation followed the recommendations of ASHRAE STANDARD 55–2017 [2] for naturally ventilated buildings.

The adaptive index used in this research, developed by De Dear and Brager [33], was the neutral temperature (Tₙ), obtained through Equation 3:

\[
Tₙ = 0.31 Tₑ + 17.8
\]

where Tₑ is the mean monthly temperature, that was obtained by data collected from the nearest meteorological station, less than 3 km away from the university dormitory (Belo Horizonte - Pampulha - A521), available on INMET website [34].

During the fieldwork, the data collected for air speed did not exceed the maximum limit of 0.1 m/s.
The mean radiant temperature ($T_{\text{mrt}}$), considering the natural convection environment, was obtained according to Equation 5:

$$T_{\text{mrt}} = \left(\left(T_g + 273\right)^4 + 0.25 \cdot \frac{10^8}{\varepsilon} \cdot \left(\frac{T_g - T_a}{d}\right)^{0.25} \cdot (T_g - T_a)\right)^{\frac{1}{4}}$$

Where $T_g$ is the indoor globe temperature (°C), $T_a$ is the dry bulb temperature (°C) and ‘$\varepsilon$’ and ‘$D$’ are the emissivity and the diameter (m) of the black globe, respectively.

Since the air movement in the bedroom was fairly negligible (< 0.1m/s), the bedroom operative temperature was calculated as shown in Equation 6.

$$T_o = \frac{(T_{\text{mrt}}+T_a)}{2}$$

Thermal comfort within the limit of 80% acceptability (variations of 3.5°C from the calculated neutral temperature) was used.

2.9 USERS’ PERCEPTION

To compare the results obtained for the static model indices (PMV and PPD) and the occupants’ actual thermal comfort, two indices were used: Actual Mean Vote (AMV) and Actual Percentage of Dissatisfied (APD).

AMV is obtained through responses from users regarding the thermal sensation. As in the PMV index, responses are distributed on a seven-point scale, between −3 (cold) and +3 (hot). Individuals who voted +1, 0 or −1 are considered thermally comfortable.

The APD index can be obtained by means of Equation 7:

$$\text{APD} = 100 - 95 \cdot x \exp\left(0.03353 \cdot \text{AMV}^4 \cdot 0.2179 \cdot \text{AMV}^2\right)$$

3 RESULTS AND DISCUSSION

3.1 OUTDOOR AND INDOOR THERMAL ENVIRONMENT

During the field study period, outdoor air temperature ranged from 22.68°C to 33.24°C and the outdoor relative humidity varied between 36.66% and 59.46%. Indoor air temperature ranged from 22.4°C to 27.4°C and indoor relative humidity oscillated between 48.18% and 62.92%.

The overview of relative humidity and air temperature recorded is show in Figure 10.

Table 5 presents the statistics for outdoor and indoor climatic variables on 10/22/2018.
Figure 10. Indoor and outdoor air temperatures during fieldwork.

![Graph showing indoor and outdoor air temperatures during fieldwork.](image)

Table 5. The distribution of indoor environment.

| Variables                      | Min.  | Mean | Max.  | Amplitude | SD  |
|-------------------------------|-------|------|-------|-----------|-----|
| Air temperature (°C)          | 22.40 | 24.92| 27.40 | 5.00      | 1.23|
| Relative humidity (%)         | 48.18 | 54.19| 62.92 | 14.76     | 4.27|
| Globe temperature (°C)        | 22.60 | 25.16| 27.70 | 5.10      | 1.42|
| Mean radiant temperature (°C) | 22.58 | 25.23| 28.21 | 5.63      | 1.50|
| Operative temperature (°C)    | 22.59 | 25.08| 27.03 | 4.71      | 1.35|

**Indoor**

**Outdoor**

Air temperature (°C) 22.68 28.95 33.24 10.55 2.91
Relative humidity (%) 36.66 45.85 59.46 22.80 6.10

Figure 11 shows the relationship between the outdoor and indoor environment concerning air temperatures and relative humidity. There was a moderate positive correlation between indoor and outdoor temperatures ($R^2=0.64$), in disagreement with other studies [7,35–37]. The same happened to relative humidity ($R^2=0.55$). Otherwise stated, in the records for this case study, there was no strong relationship found between the indoor and outdoor environment data, considering air temperature and relative humidity.
Neutral temperature is commonly obtained by linear regression method [12]. The linear regression of actual thermal sensation plotted against indoor operative temperature was used to determine the neutral temperature.

The neutral operative temperature in the bedroom of the case study was 23.79°C. This temperature was a bit different from the neutral temperature obtained by Gonçalves [38] for Belo Horizonte (23.01°C), demonstrating conformity between the studies.

3.2 USERS’ PERCEPTION

Figure 12 summarizes the answers obtained during the assessment through judgment scales.

In general terms, all the occupants perceived the space to be outside the critical conditions (−3 and 3) and 89.47% found it to be within the comfort conditions (-1, 0 and 1) (Figure 12, graph A). All the occupants claimed to be within the comfort range (0 and 1), being comfortable the most popular answer with 65.79% of votes (Figure 12, graph C). This shows that, during the sampled period and at different times of the day, most of the occupants felt comfortable. A difference of more than 30% emerged between the results of perception and sensation votes, which assessed the thermal sensation of the same group of people, was noticed.

Figure 12 (graph B), illustrates the distribution of the thermal preference votes during the application of questionnaires. It shows that 47.37% of the occupants preferred that the thermal environment of the bedroom remain the same (no change); 10.53% preferred it to be a little warmer; 34.21% preferred it to be a little cooler and 7.89% preferred it to be colder. In other terms, occupants preferred the thermal environment in the bedroom to stay the same or change slightly.
Figure 12 (graph D), shows the distribution of the thermal acceptance votes during the survey. 97.37% of the occupants rated the climatic environment of the bedroom as acceptable, as opposed to 2.63% of occupants who evaluated as unacceptable. The results show a high thermal compliance of the occupants in the bedroom.

Figure 12. Distribution of votes registered in the questionnaire: A) thermal perception, B) thermal preference, C) thermal sensation, D) thermal acceptance.

3.3 STATIC MODEL

Figure 13 presents the histogram for the PMV index during the interviews. 86.84% of the calculated votes indicated the comfort range (-0.5 ≤ PMV ≤ 0.5); 3% of the calculated votes were within the range considered slightly cold (-1.5 ≤ PMV < -0.5); and 11% of the calculated votes indicated the thermal sensation referring to the slightly warm interval (1.5 ≤ PMV < 0.5).
Figure 13. PMV Histogram of interviews.

The results of the linear regression analysis, as shown in Figure 14, indicate that a weak positive correlation between AMV and PMV model were \( R^2 = 0.48 \). Therefore, the static thermal comfort model was not able to predict the occupants’ thermal sensation for this case study. This result confirms the findings of previous studies [7,39,40], which reported a significant difference between the results of the static model and the actual thermal sensation in naturally ventilated buildings.

Table 6 presents the comparison between the average PMV, PPD, AMV and APD. The average PMV was -0.56 for the morning (discomfort by hot) and 0.26 for the afternoon. The average real perception vote was 0.15 for the morning and 0.16 for the afternoon. The PPD overestimated occupants’ thermal dissatisfaction (APD) in both periods of the day.

The relationship between the means obtained for the PMV to AMV indices in the morning and afternoon periods did not present a large difference. This is due to the fact that, in this case, there is a cancellation of terms during the calculation of the mean, since the positive values compensate for the negative ones. Thus, we decided to perform an analysis of the linear correlation between the PMV and AMV indices.
Figure 15 shows the predicted mean vote and the actual thermal vote reported for each of the interviewees. The results corroborate the conclusion of other studies [41,42], which attribute the difference between PMV and AMV indices to the fact that physiological and psychological factors are not taken into account in the static thermal comfort model.

Humphreys and Nicol [43] attribute the difference between PMV and AMV indices to three factors: individual differences, measurement errors and approximations in the formulation of the equation (some factors that contribute to the thermal comfort are not considered, for example).

The fact that the case study is a university dormitory and the occupants are from several Brazilian locations is also a determining factor for the difference between the indices. Other studies that approached thermal comfort in student dormitories concluded that the thermal history of the occupants influences the thermal sensation vote. Occupants from warmer climates tend to prefer comfort temperatures higher than those from cold climates [11,44].

Table 6. Comparison between the average PMV, PPD, AMV and APD indices for the morning and afternoon.

| Period of the day | Static Model | Real perception |
|------------------|--------------|-----------------|
|                  | PMV | PPD | AMV | APD |
| Morning          | -0.56 | 14% | 0.15 | 5% |
| Afternoon        | 0.26 | 9% | 0.16 | 5% |

Figure 15. PMV x AMV.

Each thermal vote (perception, preference, sensation and acceptance) were plotted independently with the operative temperature. A relationship between perception votes and operative temperature was not found.
Figure 16 reveals that users’ AMV values are generally higher than the corresponding PMV values. In other words, occupants in this case study notice their surrounding thermal environment warmer than that predicted by the static model. Furthermore, between 22.5 – 27.1°C operative temperature intervals, all types of votes were reported. This can be attributed to the variability of individual perception, since the votes on the thermal sensation scale were quite widely distributed. This graphical analysis was chosen because the bedroom operative temperature combines the effect of dry bulb temperature (Ta), mean radiant temperature (Tmrt), and air speed; the operative temperature represents how people feel in an indoor environment [45].

Based on the results shown in Figure 17, it can be concluded that within the tested temperature range (22.5 – 27°C), the heat balance model overpredicts thermal dissatisfaction, as found by Aghniaey et al. [45].

Figure 16. Relationship between operative temperatures and A) Thermal perception; B) Thermal preference.
3.4 ADAPTIVE MODEL

The mean monthly temperature was calculated and then it was possible to obtain the neutral temperature and the lower and upper limits for 80% of acceptability (Table 7).

For the adaptive thermal comfort model, the operative temperature remained within the limit of 80% of acceptability during the monitoring (Figure 18).

Table 7. Neutral temperature and 80% acceptability limits.

| Neutral temperature | 25.22°C |
|---------------------|---------|
| Lower limit         | 21.72°C |
| Upper limit         | 28.72°C |

Considering the three central points of the seven-point scale, (from +1 to -1) as those that provide thermal acceptability, 89.47% of occupants reported to feel comfortable during the survey.

The adaptive model approach predicted the thermal acceptability for occupants satisfactorily during the monitoring in the bedroom. The results confirm the appropriateness of the adaptive model for the evaluation of thermal comfort in naturally ventilated buildings with the same climatic characteristics. The effectiveness of the model is attributed to aspects that are not considered in the static evaluation model, such as the psychological, physiological and behavioral factors.
4 CONCLUSIONS

This study aimed to evaluate the thermal comfort for occupants of a naturally ventilated university dormitory in a tropical climate zone in Brazil. To evaluate thermal comfort, 38 interviewees answered questions regarding sensation, perception and thermal acceptability. Then, users' responses were compared with the results obtained for the static and adaptive thermal comfort models.

Regarding the static model, there were differences between the comfort results obtained by using the Fanger method and the actual mean vote (AMV) of the interviewees. PMV was found to overestimate the students' perceptions. This corroborates the importance of taking into account the subjective assessment of users during the evaluation of thermal comfort. This consideration becomes especially important for the comfort evaluation of a university dormitory. The occupants’ different thermal and cultural history could have an impact on their adaptive behavior.

The results of the adaptive model indicated a correspondence between the model thermal acceptability (considering the 80% acceptability limit) and the thermal sensation reported by the occupants. The neutral temperature obtained was 25.22 °C and the lower and upper limits were 21.72 °C and 28.72 °C, respectively. A strong correlation between the outdoor temperature and the thermal sensation vote was expected, although this trend was not observed for this researched universe. This could be explained by the fact that Belo Horizonte is in a transitional climate. The
operative temperature varies greatly throughout the day and the comfort temperature range tends to be higher than elsewhere.

For future works, studies should cover other seasons, in order to obtain a wider evaluation of the thermal comfort and adaptation of the users over the year. It is also advisable to study the behavior of an adaptive thermal comfort model considering a larger sample, that will increase the confidence, decrease the uncertainty and provide greater precision.

Further research is needed in order to assess user preference and behavior in university dormitory, mainly due to the wide variety of user profiles.

It is expected that the results of this paper can help building designers to establish the comfortable indoor conditions for naturally ventilated buildings in a tropical climate.

REFERENCES

[1] N.E. KLEPEIS, W.C. NELSON, W.R. OTT, J.P. ROBINSON, A.M. TSANG, P. SWITZER, J. V BEHAR, S.C. HERN, W.H. ENGELMANN, The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants, J. Expo. Sci. Environ. Epidemiol. 11 (2001) 231–252. doi:10.1038/sj.jea.7500165.

[2] ANSI/ASHARE Standard 55, Thermal Environmental Conditions for Human Occupancy, ASHRAE, Atlanta, GA, 2017.

[3] L.V. De Abreu-haribich, V.L.A. Chaves, M.C.G.O. Brandstetter, Evaluation of strategies that improve the thermal comfort and energy saving of a classroom of an institutional building in a tropical climate, Build. Environ. 135 (2018) 257–268. doi:10.1016/j.buildenv.2018.03.017.

[4] E.W. Shaw, Thermal Comfort: analysis and applications in environmental engineering, by P. O. Fanger. 244 pp. DANISH TECHNICAL PRESS. Copenhagen, Denmark, 1970. Danish Kr. 76, 50, R. Soc. Health J. 92 (1972) 164. doi:10.1177/1466442407209200337.

[5] J.F. Nicol, M.A. Humphreys, Adaptive thermal comfort and sustainable thermal standards for buildings, Energy Build. 34 (2002) 563–572. doi:10.1016/S0378-7788(02)00006-3.

[6] ISO, ISO 7730:2005, INTERNATIONAL STANDARD ISO environment — Analytical determination, Iso. 2005 (2005).

[7] A. García, F. Olivieri, E. Larrumbide, P. Ávila, Thermal comfort assessment in naturally ventilated offices located in a cold tropical climate, Bogotá, Build. Environ. 158 (2019) 237–247. doi:10.1016/j.buildenv.2019.05.013.

[8] Z. Sadat, M. Tahsildoost, M. Hafezi, Thermal comfort in educational buildings: A review
article, Renew. Sustain. Energy Rev. 59 (2016) 895–906. doi:10.1016/j.rser.2016.01.033.

[9] T. Cheung, S. Schiavon, T. Parkinson, P. Li, G. Brager, Analysis of the accuracy on PMV – PPD model using the ASHRAE Global Thermal Comfort Database II, Build. Environ. 153 (2019) 205–217. doi:10.1016/j.buildenv.2019.01.055.

[10] R. De Dear, G. Brager, D. Cooper, Developing an adaptive model of thermal comfort and preference, ASHRAE Trans. 104 (1997) 1–18. https://escholarship.org/uc/item/4qq2p9c6.pdf%5Cnhttp://escholarship.org/uc/item/4qq2p9c6.pdf%5Cnhttp://repositories.cdlib.org/cedr/cbe/ieq/deDear1998_ThermComPref.

[11] R. Amin, D. Teli, P. James, L. Bourikas, The influence of a student’s “home” climate on room temperature and indoor environmental controls use in a modern halls of residence, Energy Build. 119 (2016) 331–339. doi:10.1016/j.enbuild.2016.03.028.

[12] Z. Wu, N. Li, P. Wargocki, J. Peng, J. Li, Energy & Buildings Adaptive thermal comfort in naturally ventilated dormitory buildings in Changsha , China, 186 (2019) 56–70. doi:10.1016/j.enbuild.2019.01.029.

[13] ABNT – Associação Brasileira de Normas Técnicas, NBR 15575 – Desempenho de edifícios habitacionais até cinco pavimentos, ABNT, Rio de Janeiro, 2013.

[14] ABNT – Associação Brasileira de Normas Técnicas, ABNT NBR 15220 - Desempenho térmico de edificações, ABNT, Rio de Janeiro, 2005.

[15] ISO, ISO 10551 - Ergonomics of the thermal environment: Assessment of the influence of the thermal environment using subjective judgement scales Ergonomie, Geneva, 1995.

[16] C. Alcarde Alvares, J. Stape, P. Sentelhas, J. Gonçalves, G. Sparovek, Köppen’s climate classification map for Brazil, 2013. doi:10.1127/0941-2948/2013/0507.

[17] DPFP – Departamento de Planejamento Físico e Projetos, Projeto Executivo: Implantação, (2014).

[18] DPFP, Projeto Executivo: Bloco I – Unidade habitacional: planta geral e paginação de piso, (2014).

[19] eSurv, eSurv - Free Survey Maker, https://esurv.org/ (accessed October 7, 2019).

[20] E.J. R., The value of online surveys, Internet Res. 15 (2005) 195–219. doi:10.1108/10662240510590360.

[21] E. Kuchen, M.N. Fisch, G.E. Gonzalo, G.N. Nozica, Predição do índice de conforto térmico em edifícios de escritório na Alemanha, Ambient. Construído. 11 (2011) 39–53. doi:10.1590/S1678-86212011000300004.

[22] BRAZIL, Brazilian climatological normals 1981-2010, Inst. Nac. Meteorol. - INMET.
[23] I. ISO, ISO 7726 - Ergonomics of the thermal environment, instruments for measuring physical quantities, Geneva, 1998.

[24] S.Q. da S. Hirashima, Calibração do índice de conforto térmico temperatura fisiológica equivalente (PET) para espaços abertos do Município de Belo Horizonte, MG, (2010) 225.

[25] M.J. Barbosa, G.C.B. Weiller, R. Lamberts, Disposição dos equipamentos para medição da temperatura do ar em edificações, Ambient. Construído. (2007) 89–108.

[26] M.J. Barbosa, R. Lamberts, S. Guths, Uso de barreiras de radiação para minimizar o erro no registro das temperaturas do ar em edificações, Ambient. Construído. (2008) 117–136.

[27] M.A. FARIA, Avaliação das condições de conforto térmico nas salas de aula do campus Morro do Cruzeiro da UFOP, Universidade Federal de Ouro Preto, 2013.

[28] L.M. Monteiro, Modelos preditivos de conforto térmico: quantificação de relações entre variáveis microclimáticas e de sensação térmica para avaliação e projeto de espaços abertos, (2008). doi:10.11606/T.16.2008.tde-25032010-142206.

[29] BRAZIL, Plataforma Brasil. Ministério da Saúde - Comissão Nacional de Ética em Pesquisa. http://plataformabrasil.saude.gov.br (accessed October 18, 2018).

[30] T.R. Renckly, Air University Sampling and Surveying Handbook: Guidelines for Planning, Organizing, and Conducting Surveys, Alabama, 1996.

[31] P.O. Fanger, Thermal comfort: analysis and applications in environmental engineering, R.E. Krieger Pub. Co, Copenhagen, 1970.

[32] H. Tyler, S. Stefano, P. Alberto, C. Toby, M. Dustin, S. Kyle, CBE Thermal Comfort Tool, Cent. Built Environ. Univ. Calif. Berkeley. (2017). http://www.cbe.berkeley.edu/ (accessed November 15, 2018).

[33] R.J. de Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55, Energy Build. 34 (2002) 549–561. doi:10.1016/S0378-7788(02)00005-1.

[34] BRAZIL, Estação Meteorológica de Observação de Superfície Automática, Inst. Nac. Meteorol. INMET. http://www.inmet.gov.br/portal/index.php?r=estacoes/estacoesAutomaticas.

[35] S. Thapa, A. Kr, G. Kr, Thermal comfort in naturally ventilated office buildings in cold and cloudy climate of Darjeeling, India – An adaptive approach, Energy Build. 160 (2018) 44–60. doi:10.1016/j.enbuild.2017.12.026.
[36] R. Kc, H.B. Rijal, M. Shukuya, K. Yoshida, An in-situ study on occupants’ behaviors for adaptive thermal comfort in a Japanese HEMS condominium, 19 (2018) 402–411. doi:10.1016/j.jobe.2018.05.013.

[37] A.K. Mishra, M. Ramgopal, Thermal comfort in undergraduate laboratories A field study in, Build. Environ. 71 (2014) 223–232. doi:10.1016/j.buildenv.2013.10.006.

[38] W. de B. GONÇALVES, R.M. VALLE, E.S. GARCIA, Estudo de índices de conforto térmico para aplicação em Belo Horizonte - MG, com base em pesquisa de população universitária, ENCAC 2001 - VI Encontro Nac. Conforto No Ambient. Construído e III Encontro Latino-Americano Conforto No Ambient. Construído. (2001) 1–8.

[39] M.K. Nematchoua, R. Tchinda, P. Ricciardi, N. Djongyang, A field study on thermal comfort in naturally ventilated buildings located in the equatorial climatic region of Cameroon, Renew. Sustain. Energy Rev. 39 (2014) 381–393. doi:10.1016/j.rser.2014.07.010.

[40] S. Siu, Y. Lau, J. Zhang, Y. Tao, A comparative study of thermal comfort in learning spaces using three different ventilation strategies on a tropical university campus, Build. Environ. 148 (2019) 579–599. doi:10.1016/j.buildenv.2018.11.032.

[41] A. Jindal, Thermal comfort study in naturally ventilated school classrooms in composite climate of India, Build. Environ. 142 (2018) 34–46. doi:10.1016/j.buildenv.2018.05.051.

[42] A. Ioannou, L. Itard, In-situ and real time measurements of thermal comfort and its determinants in thirty residential dwellings in the Netherlands, Energy Build. 139 (2020) 487–505. doi:10.1016/j.enbuild.2017.01.050.

[43] M.A. Humphreys, J.F. Nicol, The validity of ISO PMV for predicting comfort votes in everyday thermal environments, Energy Build. 34 (2002) 667–684. doi:10.1016/S0378-7788(02)00018-X.

[44] Y. He, N. Li, J. Peng, W. Zhang, Y. Li, Field study on adaptive comfort in air conditioned dormitories of university with hot-humid climate in summer, Energy Build. 119 (2016) 1–12. doi:10.1016/j.enbuild.2016.03.020.

[45] S. Aghniaey, T.M. Lawrence, T.N. Sharpton, S.P. Douglass, T. Oliver, M. Sutter, Thermal comfort evaluation in campus classrooms during room temperature adjustment corresponding to demand response, Build. Environ. 148 (2019) 488–497. doi:10.1016/j.buildenv.2018.11.013.

[46] T.H. Karyono, Bandung Thermal Comfort Study: Assessing the Applicability of an Adaptive Model in Indonesia, Archit. Sci. Rev. 51 (2008) 60–65. doi:10.3763/asre.2008.5108.