Thermal comfort analysis: comparison between model and experimental data in tropical climate

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Abstract. Humans in the 21st century spend nearly 90% of their time in an indoor environment. This environment is far from the one in which humans have developed their physiological adaptation and regulation mechanisms. The indoor environment must be optimized for well-being and cognitive performance with an anthropocentric and multidisciplinary approach. The objective of this paper is to identify and evaluate the reliability of approaches to characterize thermal comfort in a humid tropical climate. To do so, we will present (i) an experiment conducted to evaluate this perception in a quantitative (physical measurements) and qualitative (field survey) way, and finally (iii) an intermodal and experimental comparison analysis. The results reveal some notable discrepancies between numerical approaches and experimental data. This finding reinforces our study perspectives on the need to engage a multimodal and multidisciplinary analysis to improve the accuracy of comfort models.

1. Introduction

The precursor to modern thought, such as Socrates, worked on the search for a better architecture to better accommodate the climate [1]. Despite this, it was not until the 1920s in England that the first attempt to define a "comfort zone" was made. Comfort within a building is determined by the state of well-being of the person, integrating the notion of a thermal environment.

Comfort is also linked to the climate in which the individual evolves. The existing standards for characterizing thermal comfort are the result of studies conducted mainly in the northern hemisphere for predominantly temperate climates. Their use is questionable when one considers the effect of acclimatization and the effect of climate-induced physiological changes, as well as the impact of sociocultural evaluations. Some studies have tried to adjust these standards to hot climates. However, they are only verified for very specific conditions of validity, without real validation for the case of the user in the tropical climate of Reunion Island.

1.1. Overview on indoor thermal comfort

Thermal comfort is the sensation sought by the occupant in a particular environment to stay there according to one's needs. It is possible to say that thermal neutrality defines thermal comfort: the occupant is unable to express a need for cooling or heating. An atmosphere warmer than thermal neutrality could be appreciated by an occupant who has been exposed to cooler temperatures before. Nowadays, several approaches have been developed to establish the appropriate thermal comfort state for the occupant. They are mainly divided into three classes (i) analytical models (ii) empirical models and (iii) adaptive models (see Table 1).

Table 1. Thermal comfort models synthesis

Classes	Output type	Designation	Reference	Model information
Analytical models	Index	PMV (Predicted Mean Vote)	Fanger [2]	*Climate :* temperate / 10 to 30°C *Environment* : CE** *User* : 1 to 4 met / 2 clo
	Rate	PPD (Predicted Percentage Dissatisfaid)		
	Index	TS (Thermal Sensation)	Rohles & Nevins [3]	*Climate :* temperate (United States) *Environment* : NV* *Individual:* low activity / 0.6 clo
	Rate	RSI (Relative Strain Index)	Lee & Henschel [4]	*Climate :* temperate / 20 to 40°C
	Temperature	T_{sub} (Subjective Temperature)	Auliciems [1]	*Climate :* airspeed <0.1 m.s^{-1} / rel. hum. 50%
Empirical models	Temperature (comfort temperature)	$Tc_{Brager\ \&\ De\ Dear}$	Brager & De Dear [5]	*Climate:* temperate / 10°C to 33.5°C *Environment*: NV *Individual:* < 1.3 met
		$TrSI$ (Tropical Summer Index)	Sharma [6]	*Climate :* tropical (India) / 20 to 41°C *Environment*: NV
		$T_{c_{Auliciems}}$	Auliciems [7]	*Climate:* dry and arid (Australia) / up to 0°C *Environment*: NV and CE
		$T_{c_{Humphreys}}$	Humphreys [8]	*Environment*: NV and CE
Adaptative models	Temperature (neutrality temperature)	$T_{n_{Humphreys}}$	Humphreys [9]	*Climate:* global surveys
		$T_{n_{Auliciems}}$	Auliciems [10]	*Climate:* global surveys / 18 to 28°C
		$T_{n_{Brager\ \&\ de\ Dear}}$	Brager & De Dear [11]	*Climate:* global surveys / 10°C to 33°C *Environment*: NV and CE
		$T_{n_{Griffiths}}$	Griffiths [12]	*Climate :* temperate *Environment*: NV
		$T_{n_{Nicol\ \&\ Roaf}}$	Nicol & Roaf [13]	*Temperature*: tropical (Pakistan) /18 to 30°C *Environment*: NV

NV : Naturally ventilated - CE : Controlled environment*

1.2. Originality of the paper
Most of the approaches listed here are frequently used by building designers in Reunion Island. We try to demonstrate, with a simple case, the inadequacy of the approaches for the combination climate/user in the local context. First of all, we present the experiment conducted in a naturally ventilated room located in the heights of the island. The empirical results allow us to perform a comparative analysis with the prediction of the surveyed models and thus identify the most representative approaches. Despite different development conditions, the results show us the approaches that will be the most adapted to a "tropicalization" to best characterize the thermal comfort in a humid tropical climate.

2. Materials and methods

2.1. Experimental studies

2.1.1. Location. The experiment is conducted in a project room of dimensions 5x5x3m located at Le Tampon (Alt. 570 m). The room is equipped with 3 openings on the west façade and 2 openings on the east façade. The porosity rate of the room is about 24% (West) and 21% (East). The room is naturally ventilated with adequate access to daylight.

2.1.2. Participants. Volunteers were students in low activities (M = 1 met). Before the study, participants were asked to complete an identity questionnaire to define the overall parameters needed for the study. This initial approach identified the following: (i) Age: between 20 and 30 years old ; (ii) Addictions: none ; (iii) BMI: between 16.3 and 32.7 ; (iv) Location: altitude of the study ± 100m.

2.1.3. Measurements. The experiments were conducted from April 26 to May 7, 2021. This period marks the beginning of the southern winter in Reunion Island, with sustained rain episodes. All the measuring instruments are referenced in Table 2. Apart from the autonomous thermohygrometers and the infrared thermometer, the other sensors are connected to an ALMEMO 2890-9 data acquisition unit. The data acquisition chain is synchronized and scanned with a time step of one minute. The measurements taken with the infrared thermometer were made every hour, in parallel with the perception questionnaires.

Table 2. Measuring instruments used in the experiments

Sensors	Accuracy	Location	Measured parameter
5 autonomous thermohygrometers TESTO 174H	± 0.5 °C ± 3%	1 near each individual	Air temperature and relative humidity near each occupant
1 infrared thermometer	± 0.5 °C	For T_{sk}: average temperature of the arm, temple and forehead For T_{scl}: average temperature of the bust, waist and hip	Average skin temperature T_{sk} Clothes surface temperature T_{scl}
1 black globe associated with a Pt-100 ALMEMO sensor	± 0.3 °C	Center of the study room	Globe temperature
1 ALMEMO hot wire anemometer	± 1%		Airspeed
1 ALMEMO thermohygrometer	± 0.2 °C ± 3%		Air temperature Relative humidity

2.1.4. Perception questionnaires. Participants were asked to answer a questionnaire in Google Forms format every hour. They had to indicate their level of clothing. They were then asked to rate their thermal and visual sensations, based on a 7-point scale of the ASHRAE [1].

2.2. Inter-model analysis

The models are implemented into a spreadsheet. The results are grouped into three types of data. First, comfort and neutrality temperatures indicate a reference temperature in [°C] at which the occupant is assumed to be in a comfortable or neutral state. Secondly, the thermal perception index represents the thermal sensation of the occupant according to the ASHRAE scale. Finally, the rate (in percentage) of the discomfort of the population. Some authors encourage that the adaptive approach should be favored, as it takes into account the occupant's behavior in the face of thermal discomfort.

3. Results and discussion

Of the two weeks of measurement, we chose to present two days with the highest response rate to the comfort questionnaires. This selection led us to choose April 26 and 29, 2021 (9 AM to 4 PM). The porosity of the room was about 16% (West) and 17% (East). April 26 is an overcast day. Outside, the average relative humidity is about 95% ±5, the average air temperature is 23°C ±1 and the average global irradiance is about 362 W.m^{-2} (max: 849 W.m^{-2}). Inside, the air temperature is on average 26°C with a mean relative humidity of 76%. The airspeed is low (0.05 m.s^{-1}). April 29 is a clear sky (morning) and overcast sky (afternoon). Outside, the average relative humidity is about 90%±10, the average air temperature is 24°C ±1 and the average global irradiance is about 617 W.m^{-2} (max: 1058 W.m^{-2}). Inside, the air temperature is on average 26°C with a mean relative humidity of 77%. The airspeed is low (0.06 m.s^{-1}).

3.1. Comparison of comfort indexes

Figure 1 shows the evolution of three thermal sensation indices (PMV, T_S and the average of the sensations of occupants). Figure 1a shows that the occupants felt uncomfortable for most of the day (feel of cold). However, the other indicators did not show the same trend. The PMV was designed for a temperate climate and there are many reports of its application mainly for centrally air-conditioned buildings, which is different from the case study (naturally ventilated). Still, this indicator is the most frequently used for design. T_S was also designed in a temperate climate and climate chambers. These design conditions result in a bias for applications in the current study environment. This observation is the same for Figure 1b, but it can be noticed that the models follow the trends in the afternoon. This may be due to the clear sky condition that appeared in the morning.

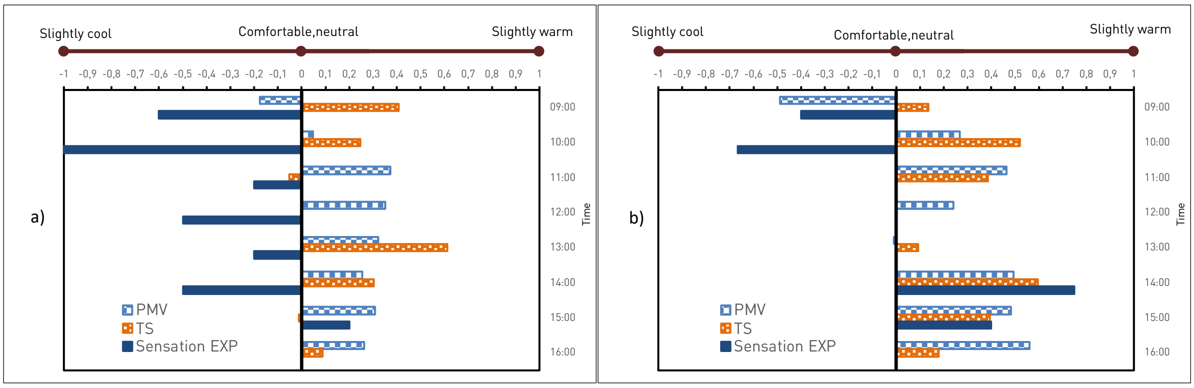

Figure 1. Hourly evolution of the average comfort index of the group a) April 26 ; b) April 29

3.2. Comparison of comfort and neutrality temperatures

Figure 2 presents the evolution of the comfort temperatures of the models surveyed while comparing them to the average occupant thermal sensation and the average empirical operative temperature. The occupants indicate that they are in a neutral situation for 11 AM, 1 PM, 3 PM, with an exact match at 4 PM, which indicates that operative temperature is the comfort temperature (26.3°C), see Figure 2a. Comparing the model values with the empirical data, we notice a very marked discrepancy demonstrating unsuitable approaches for the survey conditions. The observation is notable for the Brager and De Dear and Auliciems models. Although these models show a similar evolution in Figure 2a: they seem to be the least appropriate here. However, the conditions of the experiment are in the range of validity of the approach of Brager and De Dear. The relative humidity may be the cause of these disparities. Indeed, Auliciems approach was developed and valid for the dry and arid climate. The Humphreys model seems to be the most efficient, especially since the author suggests an approximation of ±1°C on the value obtained [8]. Despite some similarities with the empirical data, the models here remain inadequate, even though their conditions of validity are close to those of the experiment. Some physical (relative humidity or airspeed) or physiological (clothing, metabolic level, acclimatization) parameters are not considered in the models. These should therefore be excluded in a future approach.

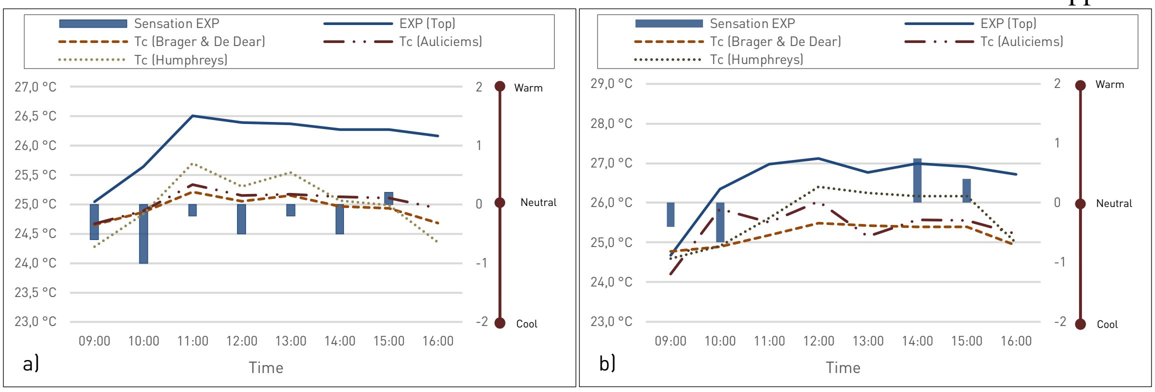

Figure 2. Evolution of occupants perception, and comfort and operative temperatures a) April 26 and b) April 29

Figure 3a shows that all the neutrality models present similar trends, except for the Nicol & Roaf approach. As we had noted earlier, the occupants are in a perfectly neutral sensation at 26.3°C (4 PM) which is far from the value indicated by the majority of the models at the same time. However, as before, some models have their conditions of validity similar to our experience. Even the model of Nicol and Roaf, although developed in a tropical climate, does not allow transcribing the neutrality temperature. Figure 3b confirms these results. The models defining the neutrality temperature are adaptive. However, some parameters that we consider necessary are not taken into account (relative humidity, metabolic level, clothing, etc.). They are globalized using empirical constants adjusted to the conditions of each study.

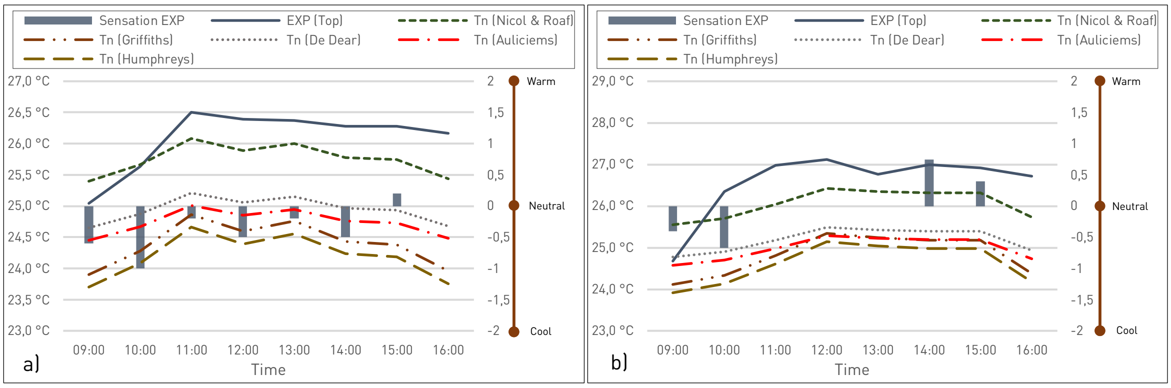

Figure 3. Evolution of occupant perception, and neutrality and operative temperatures a) April 26 ; b) April 29

Figure 4 presents the evolution of two different families of models both using only physical parameters (i) the analytical model of Auliciems (subjective temperature) and (ii) the empirical model of Sharma (tropical summer index). The empirical mean operating temperature is also presented along with a histogram of occupants' sensation. As described in previous analyses, this felt temperature is close to the actual comfort temperature at 11 AM, 1 PM, 3 PM, and 4 PM. The Auliciems model overestimates the ideal temperature by nearly 4°C. It does not even show the same trend. This is probably due to its range of validity: relative humidity at 50% while the average relative humidity within the room is 76%. Sharma's model appears to be the most effective here. It follows the same operating temperature trend with an average difference of 1.5°C. This is due to the climatic conditions under which this approach was developed (hot and humid climate of India).

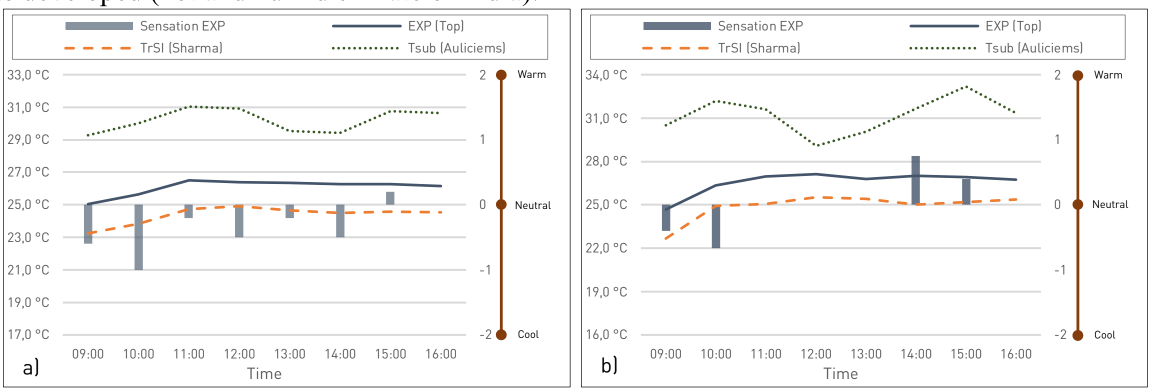

Figure 4. Evolution of $TrSI$, T_{sub} and $T_{op_{average}}$ and occupant perception a) April 26 ; b) April 29

3.3. Comparison of subjective temperatures

Figure 5 shows a significant difference between the occupants' sensations and the PPD and RSI approaches. These two dissatisfaction rates are, however, very close to each other. However, the experimental results must be qualified. The notion of "dissatisfied" is linked to the absence of neutrality (here a thermal index equal to 0, according to ASHRAE). When our empirical indicators indicate a value different from zero, thermal dissatisfaction is counted. This quasi-binary approach may be the reason for our very high rates. Thus, an indicator of +0.2 would possibly be considered "satisfactory" under the PPD and RSI approaches, but unsatisfactory in our scale. This transcription of the neutrality state is faithful to the ASHRAE recommendation. We can nevertheless note a concordance of the results on April 29 at noon, when the global outdoor irradiance and the outdoor temperature are at their nominal value. For the RSI, let us recall that this model was established for the United States for reception centers, thus in a temperate climate, far from the tropical and humid climate of our experiment. The occupant must not exceed a clothing insulation of 0.85 clo and be located in an environment where the air temperature varies from 20°C to 40°C.

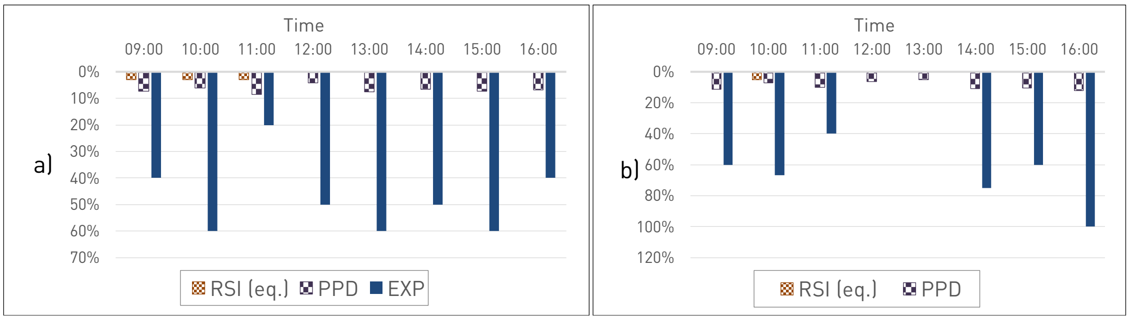

Figure 5. PPD and RSI evolution compared to the results of the questionnaires a) April 26; b) April 29

4. Conclusion and perspectives

The comparative studies carried out in this paper verified the applicability in a tropical climate of widespread comfort models using an experimental comparison with the actual occupant sensation in a naturally ventilated building in Reunion Island. The results show that most models fail to predict the thermal sensation of the occupants. Overall, several physical environmental (such as relative humidity) or physiological (such as metabolic level or clothing) parameters are not directly taken into account in the models. They are globalized in empirical constants to be adjusted according to the climatic conditions of the place of study or the occupants. Thus, it is obvious that the models could not effectively transcribe the thermal sensation. Despite significant differences, the best performing model is Sharma's approach, developed for the hot and humid Indian climate and which defines the $TrSI$. This confirms what was said earlier: the similarity of the design climate of the models favors their effectiveness. These findings highlight the need to adapt the models to the local context, and not to use them as they are.

Some indicators collected during the experiment (BMI, personality type, chronotype) were not used in the analysis. Future work will seek to understand the link between perception (thermal or visual) according to these elements intrinsic to each individual. Given the literature, the prospects are very encouraging.

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