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Experimental thermal comfort under lab controlled conditions:An applied case.

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ABSTRACT
The literature specialized in thermal comfort studies has shown that the study of this phenomenon from the predictive approach underestimates the adaptability that the study subjects may present to the thermal environment conditions, which is why it offers a reduced comfort range that this obtained with the study of this phenomenon from the adaptive approach; however, there is no reference regarding the approximation of the neutral temperature obtained with both study approaches. This paper shows the results obtained using the methodology of the predictive approach. The population sample is the student community of an Institute Advanced Studies located in Pachuca city, Hidalgo, whose bioclimate is semicold-dry. Experimental tests were conducted in a controlled environment chamber located in Autonomous Metropolitan University, during May 2013 to January 2014 period. The technical characteristics of the experimental equipment used were Class I. Neutral temperature and thermal comfort ranges were estimated by Averages by Thermal Sensation Intervals method, for year's each extreme thermal period: January (cold) and May (warm). To validate the results obtained with this study, a comparison was made with thermal comfort values previously obtained from field studies. The results estimated from both approaches were compared. Neutral temperature obtained in the laboratory study was similar to this estimated in the field study, the difference lies at the amplitude of thermal comfort range.
Keywords: Controlled environment chamber; Experimental thermal comfort; Laboratory controlled conditions; Predictive approach, Thermal model.

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I. INTRODUCTION

While the environmental conditions of certain days stimulate the activity in people, others repress the physical and mental efforts to carry it out[1].The interaction between the human and its thermal environment has been studied from different disciplines: Physiology and Psychology [2]. In first case, thermal comfort occurs when the human body is in a state of energy balance, it depends on the human metabolism and physiological process of thermoregulation in response to external climate [3] [4]. In second case, thermal comfort is defined as "(...) this condition of mind that expresses satisfaction with the thermal environment" [5].

Nikolopoulou [6] defines thermal comfort as "(...) psychophysiological satisfaction of the human with respect to the thermal environment", where the psychological and physiological aspects of the human intervene to perceive the environment thermal conditions [7]; while the ANSI/ASHRAE 55 [8] understands it as "(...) the condition of the mind (...), determined by subjective evaluations (...), which expresses satisfaction with the thermal environment".

Thermal comfort could be studied from two approaches: the predictive and the adaptive [9]. In the first case, it was obtained data with experimental tests under controlled laboratory conditions; the occupant is studied isolated from his habitat, so it is possible to influence his psychological perception and physiological functioning to seek an energy balance with the thermal environment. Otherwise, the adaptive approach considers data obtained in the field, the comfort temperature and the average outdoor temperature show an associated correlation, and the analysis of the evaluation focuses its attention on the set of physiological and psychological reactions that influence the thermal perception[10] [11].

However, the particularities of each study approach were developed [12] and it was identified that allows reconciliation between both methodologies to prove the existence of different levels of adaptation in the subject: physiological and psychological.

According to some authors [13] [14], analysis process of the thermal environment starts with the environment perception (psychological); subsequently, the information is analyzed and, based on it, the thermoregulation process (physiological). Then, the decision-making stage (psychophysiological) on the perceived thermal sensation continues, and finally, if it is a condition of lack of thermal comfort, a requirement is generated to realize thermoregulation adjustments or thermal environment modifications.

This paper presents the results of a thermal comfort study conducted under the methodological basis of the predictive approach, in Pachuca city, Hidalgo. The objectives pursued with this document are:

a) From experimental tests (predictive approach), estimate thermal comfort for the extreme thermal periods of a typical year in the study city: Cold (January) and warm (May);
b) Contrast the results obtained with the experimental tests, with the thermal values previously estimated with field studies (adaptive approach); and,
c) Suggest an adjustment between the thermal values obtained with both study approaches.

II. METHOD

The methodology used to develop thermal comfort studies under lab controlled conditions was divided into the following stages (Figure 1):

2.1 General considerations

According to Hernández *et al.* [15], an experiment is a "(...) research study in which one or more independent variables (causes) are intentionally manipulated to analyze their consequences on one or more dependent variables (effects), within a control situation (...)".

Experimental studies are explanatory and correlational due to the relationships and causal effects between independent and dependent variables [16]. The variables that have less influence on the thermal perception of people and that could be controlled with a specific value (dependent) are such as: age, gender, residence time in the site, the last food ingested, the moods and health, the time and means of transfer before and after the evaluation, the level of clothing. The independent variables for this study were: Dry bulb temperature (DBT), relative humidity (RH) and wind speed (WS).

2.2 Study case and target population

Study case used in this work was Pachuca city, Hidalgo. It has a semicold-dry bioclimate, with an average of 70 frost days per year. Its average annual temperature is 14.3 °C, the warm month corresponds to May, while the cold to January, with average temperatures of 16.7 °C and 11.6 °C, respectively. The annual average relative humidity (RH) is 62.6%, the dry month is March with 46.4% RH and the wet month is September with 78.2% RH. The annual rain precipitation corresponds to 345.2 mm; and prevailing winds, at 2.7 m/s, with predominant NE direction [17].

Target population consists of the demographic universe in which the results obtained can be generalized with the study of a sample of it. The target population used to this manuscript was the group of undergraduate students, both genders, 15 to 24 years old, residents of Pachuca city, with sedentary activity of 1.2 met [18], a clothing level of 1.0 clo [8] and that inhabited predominantly ventilated spaces naturally.

2.3 Evaluation periods

It´s recommended developed thermal comfort studies based on the hygrothermal conditions of the warm period(highest monthly average temperature), the cold period (lowest monthly average temperature) and the thermal transition periods: one that is intermediate to warm and cold periods and other that is intermediate to cold and warm periods. With this consideration, it is possible to define the study periods and, consequently, identify the hygrothermal conditions mean, minimum average and maximum average, which give environmental parameters to develop the experimental test under lab controlled conditions.

In this sense, the hygrothermal reference conditions used in the experimental tests corresponds to May (warm period), September (thermal transition from warm to cold), January (cold period) and March (thermal transition from cold to warm). Experimental tests were conducted during the warm and cold periods (May 2013 and January 2014, respectively).

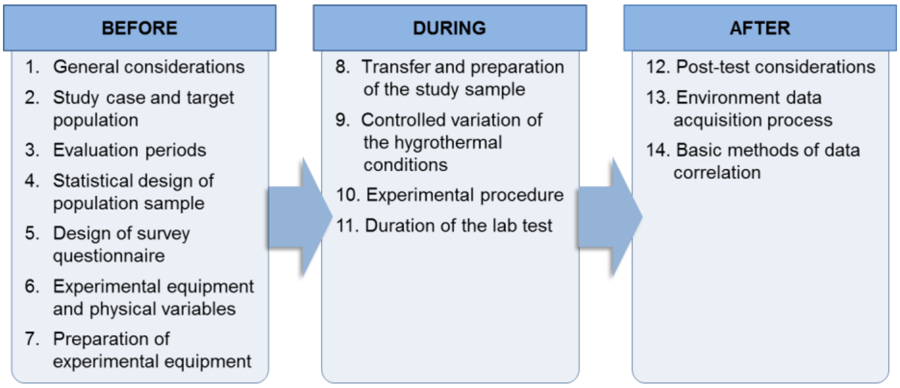

Figure 1. Stages and activities associated with the methodology used.

2.4 Statistical design of study sample

Bojórquez [19] argues that the design of the sample is a crucial component of the correlational method because the results obtained must be a consistent representation of the target population.

Sample design used for the experiment tests had a confidence interval of 5.0% and a confidence level of 95.0%; thus, the sample was 348 observations. However, it was possible to collect 968 observations; only 917 were used to perform data correlation.

2.5 Design of survey questionnaire

The questionnaire was designed in six sections and 23 questions. Sections and questions related to thermal sensation were based on the seven-point subjective scale suggested in ISO 7730 [5] and ANSI/ASHRAE 55 [8] (Table 1).

Table 1. Thermal sensation scales used in questionnaire.

ISO 7730 [5] ASHARAE 55 [8]	Scales adapted for this study	Thermal Sensation
3	7	Hot
2	6	Warm
1	5	Slightly warm
0	4	Neutral
-1	3	Slightly cool
-2	2	Cool
-3	1	Cold

2.6 Experimental equipment and physical variables

Experimental equipment used in the laboratory tests is a closed chamber that can control, monitor and record air temperature (AT), RH and WS. Other variables that influence the thermal sensation that people perceive in their environment can be considered as constants, such as clothing levels, metabolic activity, gender, age.

Laboratory tests were developed in the Controlled Environment Chamber (CEC) located in the Autonomous Metropolitan University, Iztapalapa (AMU-I) [20] [21].

The CEC is the space in which the experimental tests on thermal comfort are developed, allowing the study sample to be integrated by 12 people; It has an area of 21.9 m^2 and an interior height of 2.3 m. The temperatures can be controlled between 15.0 °C and 50.0 °C and the relative humidity from 10.0% to 95.0%. Measurement resolution is 0.01 °C for the AT (Precon, mod.ST-R3S-C) and 0.1% for the RH (General Eastern, mod. MRH-3); also, its accuracy is ± 0.2 °C for AT and ± 2.0% for RH, which allows classifying the database obtained in each of the experimental tests as class I [22].

2.7 Preparation of experimental equipment

According to Bernal [23] and Carrera & Ambríz [24]:

1. Before the start of each test, to customize the location, the height, location of the seats for the participants and the number of thermal, hygrometric and wind speed sensors. The thermistors must be located at the point where the space occupants operate most of the time [8] (Figure **2**). Also, by ISO 7726 [25] and ANSI/ASHRAE 55 [8], temperature sensors height must be located to 1.10 m from floor level for people seated (Figure 3).
2. Hygrothermal conditions of the controlled environment chamber were personalized (15°C of air temperature and 95 % of relative humidity).

2.8 Transfer and preparation of the study sample

The transfer of subjects was a relevant aspect that has inference in the thermal perception, therefore, it was necessary to consider the duration of the trip, the conditions of the vehicle, the activities that take place during the tour, the time at which the journey begins and ends, and the routes that are used to reach the destination.

2.9 Controlled variation of the hygrothermal conditions

The duration and intervals of hygrothermal variations correspond mainly to two periods: a) Period of variation and b) Stabilization period. The period of variation refers to the time it took the climatic chamber to modify hygrothermal conditions from one magnitude to another, for example, going from 15 °C of TBS and 95% of RH, to 22 °C of TBS and 75% of HR. According to ANSI/ASHRAE 55 [8] the period of cyclic fluctuation in which the subjects can perceive a significant variation in the operative temperature is 15 minutes.

In this case, hygrothermal conditions were manipulated, monitored, measured and recorded throughout each experiment; however, given the duration of the experimental test (90 min), there were only eight moments in which the comfort vote of each subject was collected (Figure 4):

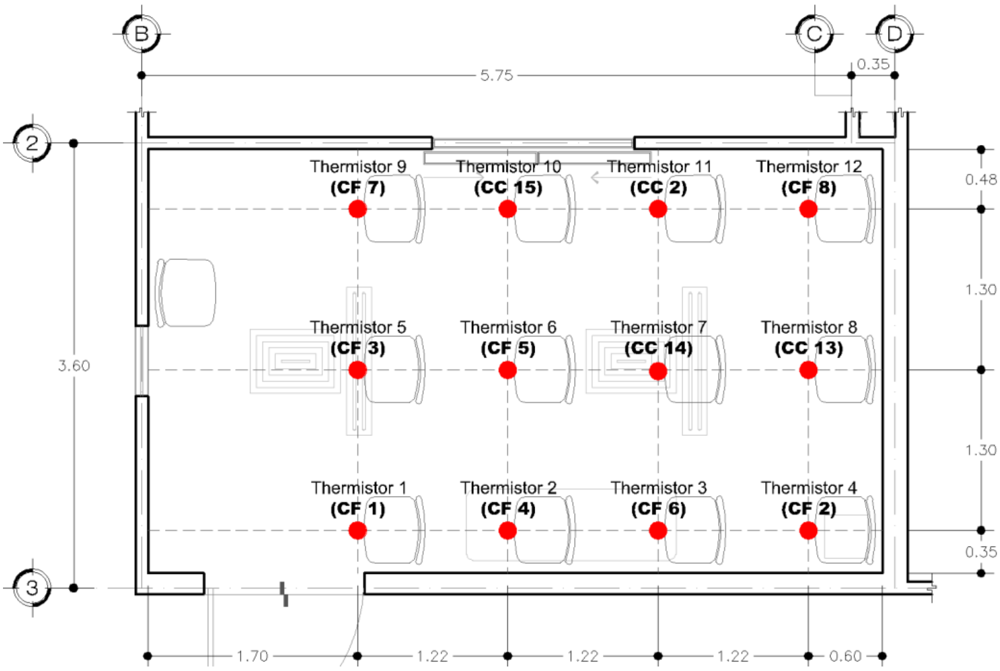

Figure 2. Thermistor location in CEC.

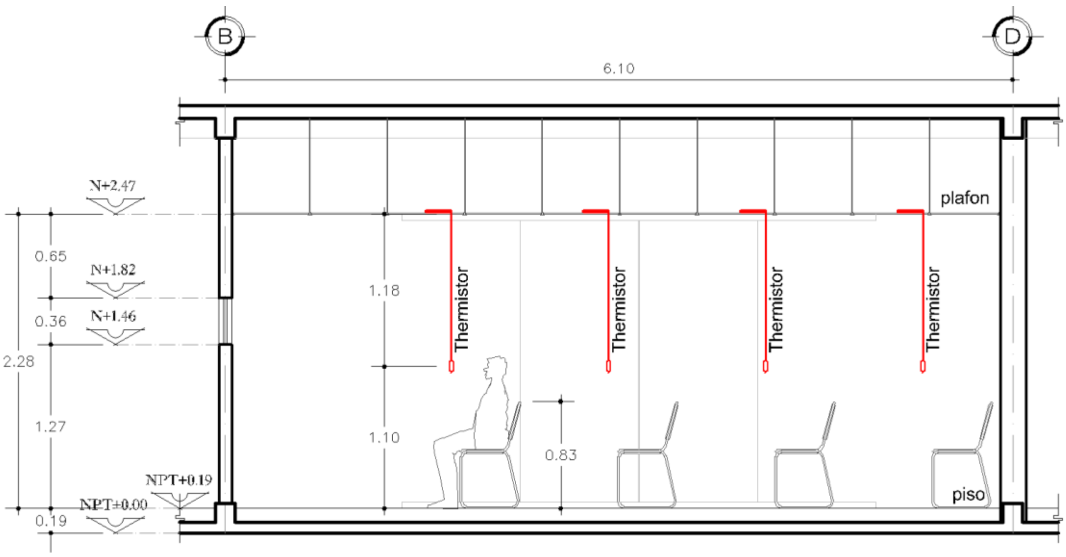

Figure 3. Thermistor height in relation to the floor and ceiling levels.

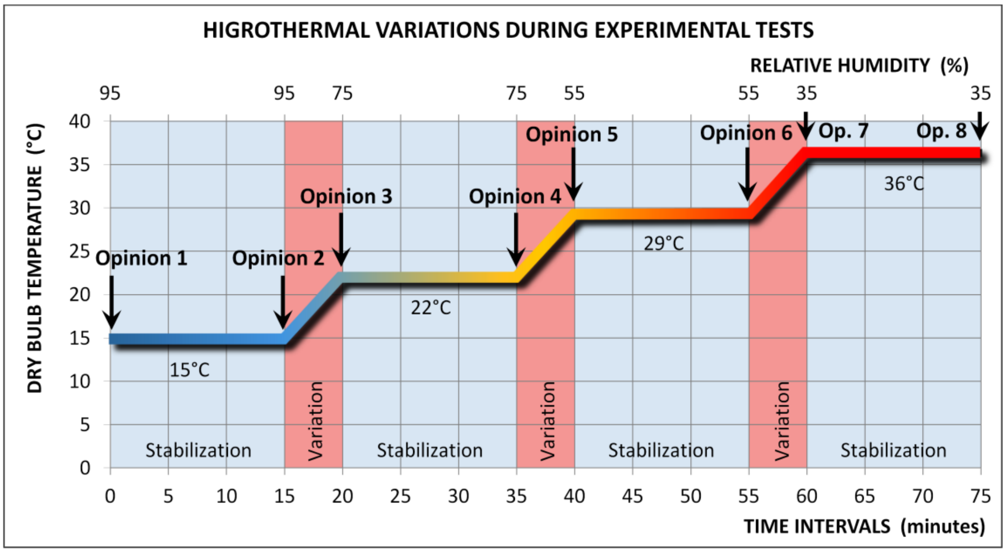

Figure 4. Hygrothermal conditions programmed for each experimental test in CEC.

2.10 Experimental procedure

Experimental procedure was made up of the following steps:

1. Study subjects were randomly selected [15] from the variables that Fanger [26] considers as little significant in the human thermal perception: place of origin, gender, and age, among others.
2. The experimental group was moved from the place of origin to the CEC.
3. Study subjects were taken to the CEC.
4. Once entered into the CEC, the test was initiated.
5. Subjects were asked to answer moment one of questionnaire.
6. Study subjects answered the questionnaire throughout the experimental test. They responded during the eight moments in which they were asked about their thermal sensation.
7. When the experimental test concludes, the study subjects returned to their origin place.

2.11 Duration of the lab test

Experimental test lasted 150 minutes. The foregoing, because according to Hernández *et al.* [15], the maturation of the subjects in an experiment is a source of internal invalidation and is conceived as the participants internal processes that operate because of the exposure time (such as tiredness, hunger, boredom), which can affect the experiment results.

2.12 Post-test considerations

Hernández *et al.* [15] mention that at the end of the experiment, the investigator should give a complete explanation to study subjects of the reasons why this was carried out.

The subjects that make up the experimental groups in each of the laboratory tests should not be repeated in another experimental test.

Based on Hernández *et al.* [15], the measurement instruments had to be equal and applied in the same way, so the questionnaires and physical measurement instruments (sensors) should be the same used in all experimental tests.

2.13 Environment data acquisition process

The coordinator of the experimental test requested the technical manager of the CEC the database (in a spreadsheet to manipulate the data), in which the monitoring and the registration of DBT, RH and WS should be detailed.

2.14Basic methods of data correlation

Data were processed by Averages by Thermal Sensation Intervals (ATSI) method [27].

III. RESULTS AND DISCUSSION

Results correspond to studies conducted under lab controlled conditions with a population sample of Pachuca; the data obtained were compared with the field studies carried out previously, in order to have a comparative reference between experimental thermal comfort obtained in a CEC and adaptive thermal comfort obtained on field. This section presents the warm and the cold period results.

Comparative analysis consisted of graphing in the same diagram, the values of neutrality and comfort ranges estimated by both studies and identify and describe the possible similarities or discrepancies that each case represented, to find the relationship and the correspondence between the data obtained.

For the cold period, Figure **5** shows the neutrality value and the comfort ranges (reduced and extensive) obtained with the TS and DBT correlation.

The values estimated from the field studies were more significant than those estimated with the laboratory studies. The difference between each pair of homologous values oscillated between 0.6 K and 1.4 K. Regarding the comfort ranges amplitude, a difference of 0.3 K can be noted between the reduced comfort ranges and, a 0.7 K, between the extensive comfort ranges.

Comparison of TS responses expressed by residents of different countries and the expected responses with the Fanger model [26] and the ANSI/ASHRAE 55 [8] and ISO 7730 [5] indices, show a significant difference between them, since in the case of the laboratory studies an underestimation of the adaptation capacity is observed —notably, in high temperature and relative humidity conditions—, as well as the absence of geographic, climatic, socioeconomic and cultural factors of the evaluated subjects .

For the warm period, Figure **6** shows the results obtained for the neutrality value and the comfort ranges (reduced and extensive) obtained with the TS and DBT correlation.

Extended comfort range's upper limit (+2 SD), reduced comfort range's upper limit (+1 SD) and the comfort temperature (neutral), estimated from the field studies, resulted in a magnitude higher than those estimated with the laboratory studies; the difference between each pair of homologous values mentioned oscillates between 0.3 K and 0.5 K. Otherwise it was presented the extended comfort range's lower limit (-2 SD), whose magnitude was lower than the estimated with the predictive approach; here, the difference was 0.3 K. However, it was possible to identify that in reduced comfort range's lower limit (-1 SD) of both study approaches, the estimated values were equal.

ADJUSTMENT OF DRY BULB TEMPERATURE - THERMAL SENSATION: JANUARY

Measurement scenery	TSR *(processed)*	Proportion	Neutrality temperature and thermal comfort range					Reduced thermal range	Extensive thermal range
			- 2 SD	- 1 SD	Neutral	+ 1 SD	+ 2 SD		
Field	404	73.6%	17.3	19.4	21.4	23.4	25.4	4.0	8.1
CEC	145	26.4%	16.7	18.5	20.4	22.2	24.1	3.7	7.4
	Results adjustments (X)		17.1	19.2	21.1	23.1	25.1	3.9	7.9
	Amplitude		-4.0	-2.0		1.9	3.9		

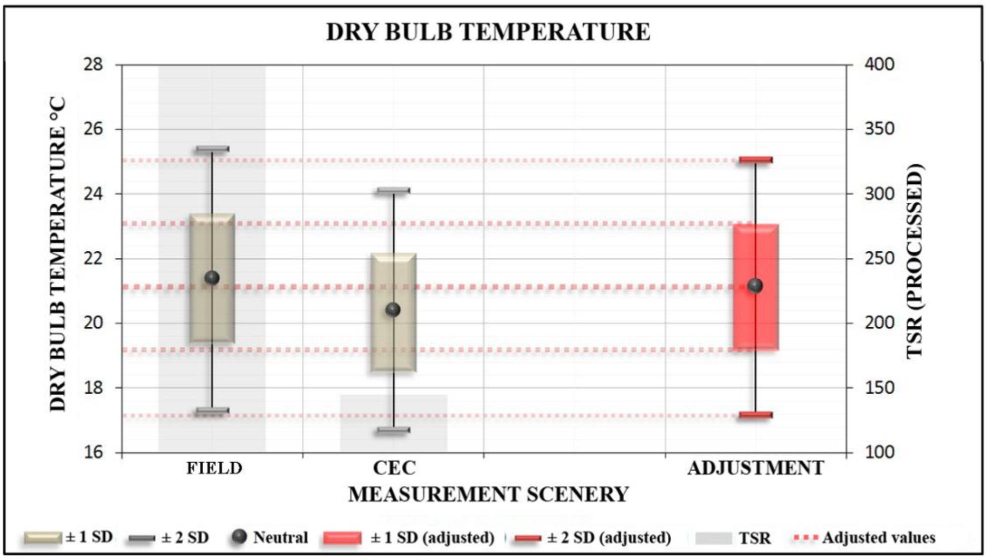

Figure 5. Comparison and adjustment of TBS values estimated with both study approaches. Cold period: January.

ADJUSTMENT OF DRY BULB TEMPERATURE - THERMAL SENSATION: MAY

Measurement scenery	TSR *(processed)*	Proportion	Neutrality temperature and thermal comfort range					Reduced thermal range	Extensive thermal range
			- 2 SD	- 1 SD	Neutral	+ 1 SD	+ 2 SD		
Field	302	51.9%	19.1	21.3	23.4	25.3	26.9	4.0	7.8
CEC	280	48.1%	19.4	21.3	23.1	24.8	26.4	3.5	7.1
		Results adjustments (X)	19.2	21.3	23.3	25.1	26.7	3.8	7.4
		Amplitude	-4.0	-2,0		1.8	3.4		

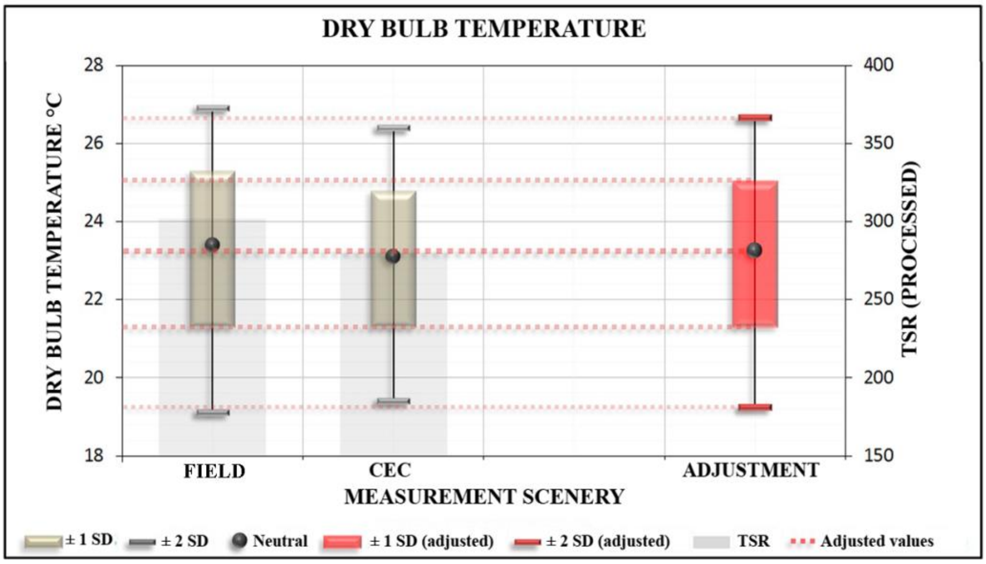

Figure 6. Comparison and adjustment of estimated TBS values with both study approaches. Warm period: May.

With the above, it is possible to appreciate that technically the thermal comfort values (neutrality and comfort ranges) estimated with the laboratory studies were within the interval generated with the thermal values estimated with the field studies.

Although the difference between each pair of homologous results was identified, this could be considered negligible from the thermal environment if it was observed that in none of the cases it was higher than 0.7 K. In this way, it can be interpreted that the results obtained in both cases for the warm period show a close approximation to each other.

IV. CONCLUSIONS

Laboratory conditions can correctly simulate the environmental conditions of a long period on field, and, therefore, the subject conditions of acclimatization, including, can allow specific adaptability actions, voluntary and involuntary, to achieve thermal comfort (position change, level of clothing adequacy, mechanical ventilation with hands, drink intake, etc.).

Thermal comfort estimated for the cold period (January) was 16.7 °C to 24.1 °C, with laboratory studies, while from 17.3 °C to 24.5 °C, with field studies. The adjustment obtained with both cases resulted in a thermal comfort range of 17.1 °C to 25.1 °C.

On the other hand, thermal comfort estimated for the warm period (May) was 19.4 °C to 26.4 °C, with laboratory studies, while from 19.1 °C to 26.9 °C, with field studies. The adjustment obtained with both cases resulted in a thermal comfort range of 19.2 °C to 26.7 °C.

This studies type allows obtaining an essential degree of certainty in the neutrality estimation in each thermal period's representative of a typical year, but an approximation in the comfort ranges, which they were regularly underestimated to those that could be obtained under real habitat conditions.

Results obtained with the field studies and those developed in laboratory studies are close in neutrality value, the difference lies in the comfort range amplitude. This is due to the fact that the controlled laboratory conditions guarantee the estimation of values for a specific population segment, while the values estimated with field studies could be considered as a sample "random" population product that does not address characteristics such as age homogeneity, gender, clothing, metabolic activity, BMI; since most of the studies that analyze this phenomenon under the purely adaptive approach, and that report simple thermal comfort models, obtain results in which the aforementioned characteristics were neglected, even though they have been collected during the field studies. For the above, as well as the influence that time, from its chronometric and climatic meaning, has on this type of evaluations carried out under the adaptive approach, different biological and behavioral factors of the experimental group studied can influence the thermal perception manifested in the results obtained.

Although the tests are carried out in a controlled environment chamber, the adaptation is noticed with actions such as position change, ventilation generation with the hand and expectations after the test (taking a beer, for example); actions that, under the scheme of control of dependent variables practiced in each of the tests carried out were optionally chosen by the subjects.

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