Comfort Temperatures Inside Low-Cost Housing
Case: six warm climate cities in Mexico

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ABSTRACT: The results of a field study developed according to the adaptive approach principles are presented in this paper. The survey was carried out in low cost housing units in six Mexican cities with warm climate from 2006 to 2007. In all cases, they were naturally ventilated houses. The field study was done according to ISO. The measuring periods were determined according to the climatic characteristics of each city. The collected data were analyzed by a non-conventional method developed for "asymmetric climates". The results demonstrate the values of comfort temperatures defined by the collected data in the field study are higher than the values of comfort temperature based on several conventional formulas, and also reveal the importance of having standards of thermal comfort specific to each location, which should be defined through the direct response of individuals and in the environment in which they perform their daily activities. This can facilitate the work of housing designers, who often have to work with unconfirmed assumptions.
Keywords: Adaptive Model, thermal comfort, Low-Cost Housing, Warm Climate

INTRODUCTION

The results presented in this paper are part of a broader research project called "Thermal Comfort and Energy Savings in Economical Housing in Mexico: Hot Dry and Warm Humid Weather Regions", which has been granted support from the Consejo Nacional de Vivienda CONAVI (National Council for Housing) and from the Consejo Nacional de Ciencia y Tecnologia CONACYT (National Council for Science and Technology), both Mexican institutions.

A particular objective of the aforementioned project was the establishment of thermal comfort models to provide reliable diagnostic tools for architectural designers of low cost housing. Another objective was the promotion of energy savings through the adjustment of operative temperatures in air conditioning equipment.

The approach of the research was an adaptive one, because it can evaluate the thermal sensation of individuals in their own habitat; allows the integral study of both physiological and psychological reactions; and considers the individuals as proactive occupants, in search of their thermal comfort. All of which is broadly consistent with the purposes of the project.

THE ADAPTIVE APPROACH

Thermal comfort is defined by ISO 7730 [1] as a "mental condition that expresses satisfaction with the thermal environment". Nikolopoulou [2] in turn defines the thermal comfort as the psycho-physiological satisfaction of individuals, regarding the terms of their thermal environment.

There are two theoretical approaches to explain the thermal comfort phenomena. The rational approach states that the comfort sensation occurs when the interchange of heat between the human body and the environment is in balance. Thus, the human brain produces the mental condition of wellbeing as a result of a physicochemical condition only. The model does not consider other sorts of influences such as climatic, cultural or psychological.

The adaptive approach, developed by Humpreys [3] after several years of field research in England, raises the dependence between neutral temperature (taken as comfort temperature) and the average outside temperature, where acclimation and other psychological issues are involved. This relationship is most evident in natural ventilated buildings, where the correlation is often highly significant. The model is based on the following argument: when the climatic conditions change and produce discomfort, people react instinctively trying to restore the comfort conditions [4].

In contrast to the rational standards for thermal comfort, the adaptive point of view maintains that individuals are not passive recipients of sensory stimuli, but they are active participants in the fashioning of a dynamic balance between the human body and their surrounding environment.

During the adjustment process, all the variables affecting the thermal comfort are controlled by involuntary physiological processes, by the autonomic nervous system, or by voluntary behavioral responses, and by the central nervous system. It has been observed that through this combination of both physiological and psychological reactions it is possible to reach conditions of indoor thermal comfort that range from 17 to 31 ° C [5].

The adaptive approach accepts that people can reach thermal comfort inside of buildings, by modifying their schedules, clothing and even manipulating their architectural environment, and not only by physiological settings. A study by de Dear et al [6] has contributed to the reconciliation of the rational and adaptive models. Their study indicates the existence of different levels of adaptation (physiological and psychological), which were not recognized in the past. This contributed to the development of hybrid standards such as ANSI-ASHRAE 55:2004 [7].

According to Nikolopoulou and Steemers [8], human thermal adaptation is seen as the gradual decrease of physiological response to repeated exposure to the same environmental stimuli. This is called acclimation. In the context of the adaptive approach, this description considers all the processes, both physiological and psychological, through which people tend to reach the equilibrium between the climatic environment and their hydrothermal requirements.

The psychological adaptation maintains that the way of perceiving the environment of people is different from one another. Consequently, the human response to a physical stimulus is not directly related to their size, but it depends on the information that people receive from each situation in particular. Psychological factors are therefore influenced by the perception of space and the thermal changes that occur in it. Thus, expectation, previous experience, exposure time, environmental perception, spatial conditions and ability to control the environment stimuli are variables, which should be considered [8].

METHOD

In order to achieve the research objectives, a field study was conducted in low cost housing units in six Mexican cities. Mexicali, Hermosillo and La Paz are located in the northern region of Mexico, and they all have hot dry weather. Culiacan and Colima are located on the Pacific coast with warm sub-humid climates; and Merida is located on the coast of the Gulf of Mexico with hot and humid climates. The complete data of localization of the six cities are presented in Table 1.

Table 1: Localization of cities:

City	Latitude	Longitude	Altitude*
Mexicali	32°39'54" N	115°27'21" W	4
Hermosillo	29°04'23" N	110°57'33" W	200
La Paz	24°08'05" N	110°20'10" W	16
Culiacán	24°49'00" N	107°25'00" W	40
Colima	19°12'50" N	103°43'21" W	433
Mérida	20°59'00" N	089°38'00" W	22

**Meters above sea level*

A correlation method was used to lead the research process, based on the principles of adaptive approach. The method consists in the application of surveys to healthy subjects over the age of 12, and the simultaneous register of climate data: dry bulb temperature (DBT), wet bulb temperature (WBT), black globe temperature (BGT), relative humidity (RH) and wind speed (WS). The questionnaire was done according to ISO 10551 and ISO 7730 [9, 1], and it is based on the ASHRAE Scale (Table 2).

Table 2: ASHRAE Scale [7]

Value	Descriptor or “comfort vote”
3	Hot
2	Warm
1	Slightly warm
0	Neutral, neither cool nor hot
-1	Slightly cool
-2	Cool
-3	Cold

The register of climate data was made with monitoring equipment of thermal stress, which complies with ISO 7726, [10] (Fig. 1). So, the collected data is classified as Class I.

Figure 1. Thermal Stress Monitor.

The surveys were conducted in houses built with financial aid provided by "Vivienda económica" (Economical Housing), a government program designed to help the country's most deprived people. In most cases, they were naturally ventilated. The measuring periods were determined on the basis of the climatic features of each city (Table 3). The field study was conducted from August 2006 to May 2007.

Table 3: Field Study Seasons by City:

Climate	Cities	Season	Months
Warm Sub-humid	Culiacán	Warm Dry	March
	Colima	Warm Dry	April, May
		Warm Humid	September, October
		Temperate	January, February
Hot Humid	Mérida	Hot Humid	May, July
		Temperate	January, February
Hot Dry	La Paz	Temperate	March, April
	Mexicali	Transition	September, October
		Hot Dry	July, August
		Fresh	January, February
	Hermosillo	Hot Dry	August, September
		Temperate	February-April

The study sample was determined by the amount of housing built through the aforementioned program in each city [11]. The volunteers surveyed were chosen randomly from among the inhabitants of the selected households. It was decided, based on statistical data, that the sample should include at least 150 people per climatic season, by each city. The respondents were individuals without any particular condition such as pregnancy, menstrual period or chronic illness, because these conditions might affect their perceived thermal sensation. The survey was 50% men and 50% women.

Students of Architecture and Engineering of the various participating Universities (Fig. 2) conducted the logging of information. The students were trained to ensure uniformity in data collection. Also, a handbook for survey implementation and data entry was developed as a guide for consultation.

Figure 2. Students apply a questionnaire and adjust the monitor of thermal stress inside a low cost housing unit, at Colima.

Previously to the fieldwork, a pilot test was implemented with three specific objectives: 1) assessing the understanding level of the surveyed regarding survey questions, 2) refine the performance of the students and improve their skill in the handling of the monitoring equipment, 3) estimating the average duration per each survey. With the results of this test the necessary adjustments were made for the final implementation of the fieldwork. The definitive survey was conducted during the selected seasons, between 8:00 and 19:00 hours. The collected data was entered on an Excel data sheet in order to perform its statistical analysis.

The six cities have "asymmetric" climates according to Nicol [12]. In such climates the responses of individuals to thermal sensations during the field studies show a tendency to one end of the assessment scale, for example to the sensation of "heat". In which case, the surveys did not generally collect answers at the other end of the assessment scale, the sensation of "cold". Accordingly, the conventional method of regression distorts the results (Fig. 3). Therefore in order to estimate the neutral temperature (Tn) and the limits of thermal comfort in each city, a non-conventional method of statistical regression by layers was applied in order to avoid the characteristic bias of asymmetric climates [12].

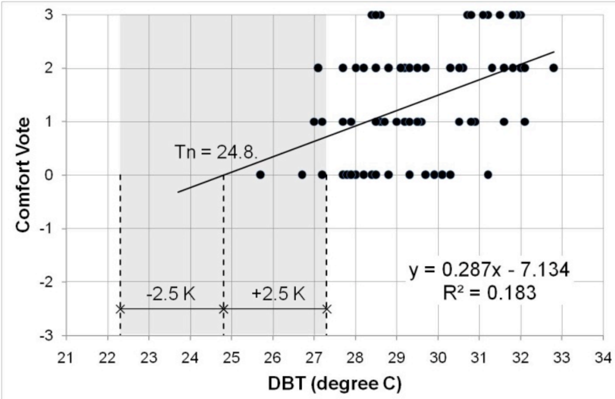

Figure 3. Determination of the Neutral Temperature (Tn) by the conventional method. Tn and the comfort limits do not represent accurately the collected answers. September and October 2006 in Colima.

The method is based on the proposal of Nicol for "asymmetric" climates [13], which uses descriptive statistics to determine the Tn. The fundamental difference with the conventional method is that instead of obtaining the regression line, that characterizes the complete studied sample, several layers are grouped by level of expressed thermal sensation. When the number of responses of a group is not sufficient to obtain reliable results, this layer is eliminated. Later, the average temperature and standard deviation per each layer is obtained.

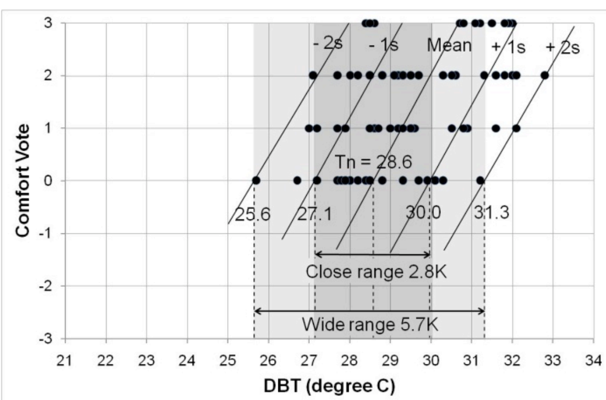

Figure 4. Determination of Tn by the method for asymmetric climates. Tn and the comfort limits are more representative of the collected answers. September and October 2006 in Colima.

Accordingly, a regression line is not obtained by all pairs of data from the sample, but by the average values and the established ranges by the addition and subtraction of the standard deviation (s) of each layer. The intersection of the obtained regression line with the y-coordinate zero (which is the sensation of thermal neutrality) determines the Tn value, as well as the limits of the comfort range, which are determined by the addition of Tn ± s. This range includes theoretically two thirds of those who have expressed a same thermal sensation (Fig. 4).

As a final stage of the method, the obtained Tn values are correlated with the average values of outdoor temperature (To) provided by the National Weather Service, for all periods of study in each city. This is done in order to obtain the corresponding linear regression, whose resulting equation can serve as a model to calculate a preliminary Tn from the local average outdoor temperature in localities of warm climate, where there are no standards of comfort determined in field studies.

RESULTS

The comfort values found in the field study are presented in Table 4, as well as the values of the comfort limits corresponding to a range of **±** *s* are include.

Table 4. Comfort temperatures determined in the field study:

City	Season	Tn ºC	Comfort lower limit	Comfort upper limit
Culiacán	Warm Dry	28.1	25.2	31.0
Colima	Warm Dry	28.0	26.7	29.5
	Warm Humid	28.6	27.1	30.0
	Temperate	27.1	25.9	28.3
Mérida	Hot Humid	32.3	27.9	35.1
	Temperate	27.4	25.4	29.3
La Paz	Temperate	26.7	22.9	30.4
Mexicali	Transition	33.7	30.1	37.1
	Hot Dry	35.2	32.2	37.8
	Fresh	24.3	20.9	27.6
Hermosillo	Hot Dry	32.2	29.6	34.7
	Temperate	26.9	23.5	31.3

In all the cases, the comfort temperature values defined by the collected data in the field study are higher than the comfort temperature values based on the conventional formulas of different authors (Table 5).

Table 5. Comfort formulae applied to compare with the results:

Author	Comfort Formula
Humpreys [14]	Tn = 11.9 + 0.534 (To)
Auliciems [15]	Tn = 17.6 + 0.31 (To)
Brager and de Dear [16]	Tn = 17.8 + 0.31 (To)

Table 6. Comfort temperatures determined by different formulas.

Climate	City	Season	To	Humpreys	Auliciems	Brager and de Dear	Field Study Formula	Field Study Data
Warm Sub-humid	Culiacán	Warm Dry	21.3	23.3	24.2	24.4	27.2	28.1
	Colima	Warm Dry	25.6	25.6	25.5	25.7	29.5	28.0
		Warm Humid	25.3	25.4	25.4	25.6	29.4	28.6
		Temperate	23.5	24.4	24.9	25.1	28.4	27.1
Hot Humid	Mérida	Hot Humid	28.2	26.9	26.3	26.5	30.9	32.3
		Temperate	24.3	24.9	25.1	25.3	28.8	27.4
Hot Dry	La Paz	Temperate	20.4	22.8	23.9	24.1	26.7	26.7
	Mexicali	Transition	32.8	29.4	27.8	28.0	33.5	33.7
		Hot Dry	33.7	29.9	28.0	28.2	33.9	35.2
		Fresh	13.8	19.3	21.9	22.1	23.1	24.3
	Hermosillo	Hot Dry	31.1	28.5	27.2	27.4	32.5	32.2
		Temperate	20.2	22.7	23.9	24.1	26.6	26.9

It is important to point out that during the warm seasons the comfort temperature was above the values that the aforementioned authors qualified as uncomfortable (Table 6). In fact, neutral temperature values above 30º C were found in three of the studied locations: Mexicali, Hermosillo and Merida. Obviously the upper limit of the comfort range rose between 35º to 38º C in these cases. Particularly, in all the studied cities there is at least a season in which the upper limit of comfort is above 30º C (Table 4).

High values of neutral temperature might seem overstated when compared with reported values of cooler climates, as reported in scientific literature. Nevertheless, the individuals expressed their conformity to temperatures that most authors consider uncomfortable or even frankly intolerable. These values demonstrate that people have a wide acclimation capability.

Finally, the comfort temperature values defined in the field study were correlated with the average monthly outdoor temperature values (To) for each season, which resulted in a high correlation (r = 0.898). Thus the formula for linear regression can quite accurately predict the comfort temperature values from the average monthly outdoor temperature (Fig. 5):

$$Tn = 15.6 + 0.545\ (To)$$

Figure 6 shows the regression lines obtained from the formulae of the aforementioned authors, as well as the data obtained from the field study. It can be noted that the slope of the result line (0.545) is almost the same as those obtained from the Humpreys formula (0.534), however, it is almost 4 degrees higher.

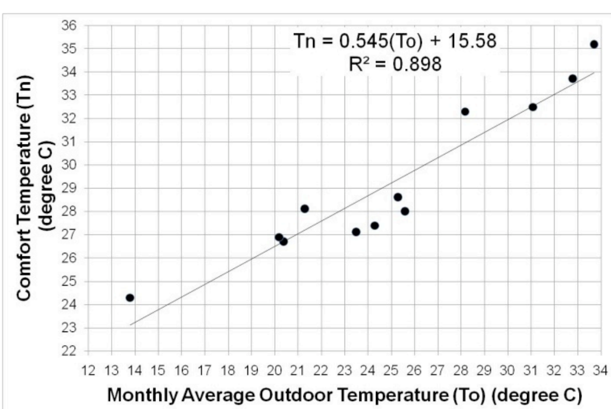

Figure 5. Correlation among Monthly Average Outdoor Temperature (To) and Comfort Temperature (Tn).

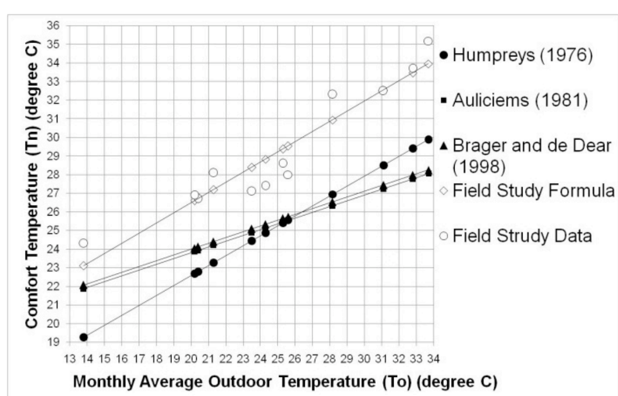

Figure 6. Comparison between calculated values using different formulas and estimated values from the field study.

CONCLUSIONS

The results of this field study demonstrate the importance of having standards of thermal comfort specific to each location, which must be defined through the direct response of individuals and in the environment in which they perform their daily activities. This can ease the task of housing designers, who often work based on assumptions.

The results also show that in hot climates, acclimated people may find comfort in temperatures around 30º C during the warmest seasons. Therefore, reducing the operating temperatures of air conditioning in such conditions represents a huge opportunity for saving electricity.

The results presented in this paper have already been delivered to the National Housing Commission of Mexico (CONAVI) to promote their application on the design of low-cost housing.

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