Thermal Comfort of Naturally Ventilated Buildings in Warm-Humid Climates: field survey

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ABSTRACT: Several studies have shown lately that the international comfort standards for buildings and the related predictions models report a warmer sensation than the occupants report in the case of naturally ventilated buildings in warm climates. This paper exposes some aspects of the debate in the field of thermal comfort in naturally ventilated buildings located in warm and humid climates. It also describes the methodology and results of a survey performed in Old Havana concerning the thermal sensation of occupants in courtyard buildings. The application of the comfort adaptive models for the case-study is presented and the results are discussed. The results show that surveyed people are more tolerant toward the warm and humid conditions than the Fanger's PMV model predicts. Nevertheless, the responses were more critical than the prediction of the extended PMV model proposed for warm conditions with few air conditioned buildings in the considered environment. The wrong estimation of the expectancy factor could be one of the reasons for the disagreement as well as other aspects acting in the field like the stability of climatic conditions and the life quality/expectancy for improvement of the surveyed people.

Conference Topic: Vernacular Architecture: Sustainability Lessons from the Past
Keywords: thermal comfort, courtyard buildings, natural ventilation, warm-humid climates, field survey, comfort models

INTRODUCTION

Thermal Comfort and particularly comfort models for naturally ventilated buildings located in warm and humid regions are topics of wide discussion in the present literature because of their importance in the design of energy-efficient building. Other related issues under debate are the differences of comfort sensation between subjects in air-conditioned (AC) and naturally ventilated (NV) buildings and the adaptability of people to certain environments due to behavioural and psychological factors.

Concerning the thermal comfort, several studies have shown lately that the international comfort standards for buildings and its predictions models as Fanger's model (1972) [1] predict a warmer sensation than the occupants report in the case of NV buildings in warm climates. People in these regions and conditions tend to tolerate both higher temperatures with higher levels of moisture and also higher wind speed to improve their comfort sensation.

This paper has three objectives: (1) to briefly discuss about the present debates in the field of thermal comfort in NV buildings located in warm and humid climates, (2) to show the methodology and results of a survey concerning thermal sensation of occupants, and (3) to apply the comfort adaptive models for the case-study in Old Havana.

2. THERMAL COMFORT STUDIES IN NATURALLY VENTILATED BUILDINGS IN WARM-HUMID CLIMATES

Several studies have shown that there are some non-quantifiable elements of comfort that influence the thermal sensation. Aspects like culture, habits and traditions, mental states and expectations can vary the level of tolerance toward certain thermal conditions. Some studies in climatic chambers [2] [3] [4] [5] have shown that no difference on thermal preferences is found between people from different regions. Moreover, the factor of sex, age and daily or seasonal rhythms do neither affect the preferred thermal environment. The physiological adaptation of people to the environment has little influence on the preferred ambient temperature. However, in 'uncomfortable' warm and cold environments or in a changing climatic condition, adaptation will often have an influence [6] because people have a natural tendency to adapt to changing conditions in their environment [4].

It is recognised that psychological adaptation actually play an important role in people's perception of thermal conditions and also could explain the differences in observed and predicted thermal sensations on different environmental contexts like office vs. house and AC vs. NV buildings.

The adaptive approach is then based on the assumption that factors beyond fundamental physics and physiology play an important role in building occupants' expectations and thermal preferences [7] and this leads to consider the prediction and evaluation of buildings in diverse contexts and situations in a different way which is the case of the NV buildings.

In NV buildings occupants are use to encompass a close interrelation with the outdoor environment and consequently they have a broader acceptability toward the changing and non-uniform thermal conditions that include higher temperatures than that predicted by the PMV model.

Besides the psychological expectation, other causes can provoke the different response of people in AC and NV buildings. Some authors [8], [9], [10] claim that people in warmer environment reduce their activity level and change their posture as an unconscious action to adapt themselves to the environment. Nevertheless, these metabolic changes are difficult to evaluate in a short time field study. The other factor that can contribute to these differences between AC and NV buildings is the higher level of perceived control people have in NV buildings. In NV buildings the 'adaptive opportunity' [11] can be greater than in AC buildings. A wider range of adaptation actions can be taken by using common means like openable windows and blinds [12]. Thus, as a result, the difference is probably due to the sum of a wide variety of adaptive actions which lead to wider possible comfort conditions [4].

2. SURVEY OF THERMAL COMFORT IN THE BELEN NEIGHBOURHOOD IN HAVANA

There are two main procedures to evaluate the accepted and preferred thermal comfort on human groups: climatic chamber and field survey. While the climatic chamber has the advantage of better accuracy in the climatic parameters setting, the field survey can account for other psychological and physiological responses that are difficult to get in an 'artificial' experiment at a closed chamber. For that reason, the selected method in this research was the field survey. The aim of the survey was to get a first approach of the thermal sensation of the inhabitants in the selected buildings rather than create a definite comfort chart for Havana's conditions.

The survey was performed during the period of two weeks in July of 2003 coinciding with the summer measurements [13]. Thermal sensation of occupants was assessed inside four different courtyard buildings that represent the most common types in the urban area of Old Havana. Two apartments (ground and upper floor) from each building were selected and the measurements were made in the centre of the living-room no more than 1.5m away from the responders' location. The measurements followed the requirements of Class II [14] with the exception of the use of a hot-wire anemometer. Instead, an axial anemometer was used.

The survey followed a similar pattern of questionnaires performed by Wong and Khoo (2003) [15] and Wong at al. (2002) [16] in Singapore. Both studies were selected because of the similarity of the climatic conditions between Singapore and Havana and for the coincidence of objectives in their studies and the present research. Other surveys [17] [18] also helped in the structuring of the questionnaire and the assumptions concerning the 'clo' value.

The questionnaire consisted of three sections: personal data, comfort sensation and the use of control-actions. In the personal data section, people were asked about their age, sex, weight, height, clothes, and the activity they were doing in the last 30 minutes. In total, there were 101 responses in which 65 corresponded to women and 45 to men.

The comfort sensation section was divided into six questions. 1 and 2 consider the ASHRAE thermal scale and the Bedford comfort scale respectively, both of them with seven points: -3, -2, -1, 0, 1, 2, 3. The preference scale and the acceptability scale are considered in questions 3 and 4. It also included an evaluation of the responders about their sensation of the air movement and air humidity. Finally, a question about the actions people performed in order to feel cooler/warmer was also asked. The questions and possible answers are as follow:

1. Rate how you feel the temperature at this moment, (cold, cool, slightly cool, neutral, slightly warm, warm, hot)
2. Do you feel comfortable now? (much too cool, too cool, comfortably cool, comfortable, comfortable warm, too warm, much too warm)
3. I would like to be: (warmer, no change, cooler)
4. How would you rate the overall acceptability of the temperature at this moment? (acceptable, not acceptable)
5. How do you feel about the air flow at this moment? (much too still, too still, slightly still, comfortable, slightly breezy, too breezy, much too breezy)
6. How do you feel at this moment in terms of humidity? (much too dry, too dry, slightly dry, comfortable, slightly humid, too humid, much too humid)
7. Which kind of actions you have taken in the last hours in order to feel better in terms of thermal comfort? (responses on table I)

The results are discussed and compared with other surveys made in countries with similar warm and humid climates like Bangladesh, Hawaii, Indonesia, Singapore and Thailand.

3. RESULTS

3.1 Thermal sensation: ASHRAE vs. Bedford scale

According to ASHRAE Standard 55-92 (1992) [19] the three central categories of the thermal scale between -1 and +1 express that at least 70% of people feel their thermal sensation acceptable. In this study, comparing the vote results, there is a coincidence of 58% between the ASHRAE thermal and the Bedford comfort scale. The Bedford scale reflects that 40% voted inside the three central categories, while in the ASHRAE thermal scale only

26% voted in this range of points (figure 1). The level of acceptability of the ASHRAE scale were much lower in relation with other studies where the percent of votes in the central part of the scale was 50% in Thailand [18], 56% in Singapore [15] and 74% in Hawaii [20]. This higher level of acceptability was, probably, because these studies also included the winter or less humid season when the thermal conditions are closer to the comfort zone. In this study, the average of votes in the ASHRAE scale was 1.76 and in the Bedford scale was 1.71.

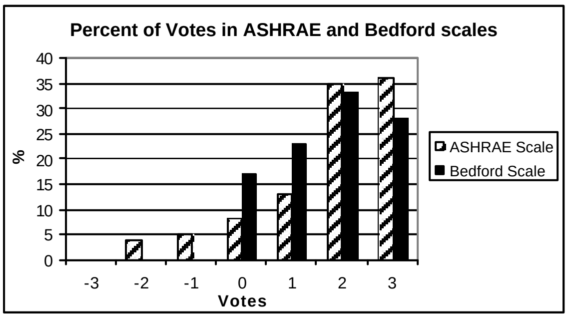

Figure 1: Distribution of votes in ASHRAE and Bedford scales in percent.

Similar and even higher differences between both scales were found in the consulted literature. Although both the Bedford's and ASHRAE scales have the same amount of points, the different way of describing the environmental thermal condition may lead to discrepancies when a subject is expressing its thermal sensation. The semantic differences between the scales make that the significance of the extremes points (-3 and +3) is more obvious in the Bedford scale (much too cool and much too warm) than in the ASHRAE scale (cold and hot). As a result, in the Bedford scale there are higher agreement between people voting in the three central points and their acceptability than in the ASHRAE scale where some people who voted in the extremes points (-3 cold and +3 hot) also voted as having an acceptable condition.

The actual conditions of those who voted in the central three points of the scale were in the range of 28.9-33ºC ET* (effective temperature) and 24.3-31.8ºC SET* (standard effective temperature). People who voted in the extreme right position (+3) of both scales were in a range of 30.8-34.5ºC ET* and 26.5-34.1ºC SET*.

3.2 Preferences and acceptability

Figure 2 shows the thermal acceptability according to the different thermal scales. Concerning the acceptability level in column 3, 34% of people voted that they had an acceptable thermal condition. Concerning the preference condition in column 4, only 6% wanted no change in their thermal condition. Thus, 91% from the total responses preferred to be cooler and 3% warmer. Sixty six percent of people who voted that they preferred to be cooler also voted that they feel a not acceptable thermal condition.

Eighty percent of the total responses were in agreement with the direct acceptability vote and the indirect level of acceptability expressed on both the ASHRAE and Bedford scales. People who voted to be cooler were in a range of 28.9-34.5ºC ET* and 24.3-34.1ºC SET*. Those with prefer no change were in a range of 31.5-33.4ºC ET* and 26.3-31.3ºC SET*.

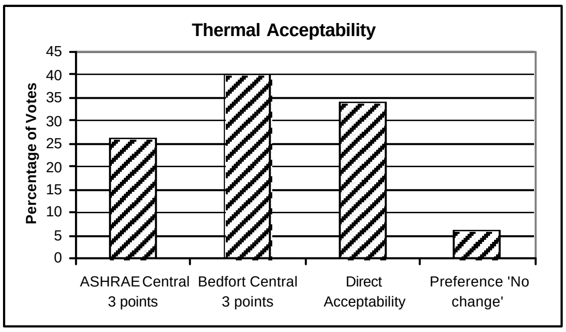

Figure 2: Thermal acceptability from different scales and methods.

As reported by other researchers many subjects responding in the neutral zone, thus having thermal comfort, also voted that they prefer to be cooler [18]. Nevertheless, is our opinion that the preferable condition could be a qualitative instead of a direct factor to be utilised for the thermal design or building evaluation. Designing based on the preferable temperature instead of the neutral condition can neglect the positive effect the adaptive opportunities have on thermal comfort. Taking into account the neutral instead of the preferable condition an extension of the comfort zone is possible saving, then, considerable energy and environmental costs.

3.3 Air speed

Concerning the air speed the majority of people (80%) voted in the right part of the scale, that means the air is from 'slightly still' (+1) to 'much too still' (+3). Ninety-six percent of people who voted in this range of +1 to +3 also voted that they prefer to be cooler in the preference scale. But only 36% of people who wanted no change in air movement also voted for no change in their general thermal sensation. The rest voted for a cooler situation.

Due to the small range of air speed no enough evidence exists about the cooling effect of wind. Nevertheless, as can be seen in figure 3 with higher air speeds people voted in the central points of the Bedford scale.

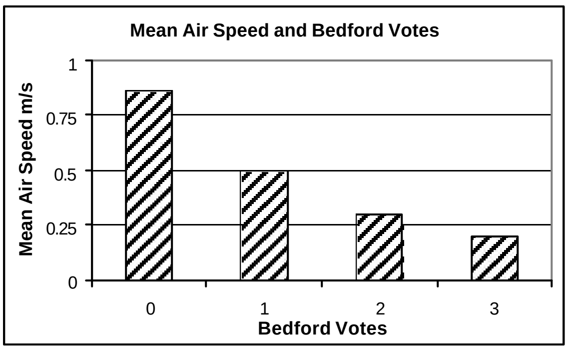

Figure 3: Mean air speed for 'zero' and 'positive' Bedford points.

3.4 Actions to be cooler

Table I shows the actions people performed in order to feel cooler. The most common activity was to open total or partially a window with 72% of people. Then, drinking cold beverages had 62% and turn on the fan 59%. Washing or taking a shower also had a high score of 48% of people. Even if the environmental adjustments are placed in the first and third place on the list of preferred actions to be cooler, the personal adjustments also represent an important contribution toward achieving thermal comfort like drinking cold beverages and use water to refresh themselves. This reflects the higher freedom people have in houses over the office and more controlled environments.

Table I: Actions performed by surveyed people.

Actions (selection)	Percentage of reported actions
Open complete or partially the window	72
Cold drink	62
Turn on fan	59
Washing / Shower	48
Resting / Lower activity level	39 / 28
Move to a cooler place in the house / outside	33 / 26
Lighter clothes	29

4. COMFORT CRITERION FOR OLD HAVANA

4.1 Application of the PMV model extension

The thermal conditions of the room during the questionnaire were measured close to the respondent (<1.50m). The data from these measurements were plotted and using the Fanger model the values of PMV were calculated both using a spreadsheet [21] and a software 'WinComf' developed by Fountain and Huizenga (1997) [22]. Using the format of the spread sheet, the original PMV formula of Fanger were converted to the extended formula that considers a reduction of the activity level when PMV is higher than zero and also includes the 'expectancy factor' (*e*) which gradually expresses the higher acceptability to warm conditions of people who live in regions with long summers and also who are not used to AC buildings [9].

The average PMV value in the original formula was 2.01 while in the extended formula was 1.1. The votes from the questionnaire had an average of 1.7 which is more critical than the extended formula of PMV. However, it is demonstrated that the original formula overestimate the warming conditions in NV buildings of warm climates having 3 decimal units higher than the votes from the questionnaire.

The result of the PMV extension formula considering only the reduction of the metabolic rate and not the *e* factor was 1.77 which is very close to the obtained votes from the questionnaire. Thus, apart from the possible errors in the measurements and the estimation of the activity level in the survey, one cause of the discrepancy between the questionnaire results and the extended PMV formula could be the wrong interpretation of the *e* value that influences greatly the final PMV value. The *e* value considered here is equal to 0.58. This takes into account both the summer conditions in Havana that last more than 8 months per year and also the amount of AC buildings. Even if there is not large amount of nearby AC buildings people experience AC spaces when they enter in a big shop or a public building about twice per month.

Other cause for the general disagreement in both the original and the extended PMV formula could be the stability of the thermal conditions during the day in summertime (figure 4). A small air movement or the sudden lack of ventilation, for example, can change the people's perception of the thermal condition and therefore, they express by voting, that improvement or worsening in an exaggerated way in comparison with the calculated PMV formula. Therefore, the expectation of people is even more important and changeable in stable warm conditions than in a more varied climatic situation in which people have a wider range of sensations. Therefore, the influence of a small range of daily and hourly warm thermal conditions should be further studied and could also be considered in order to calculate the final PMV value as a 'thermal stability' factor.

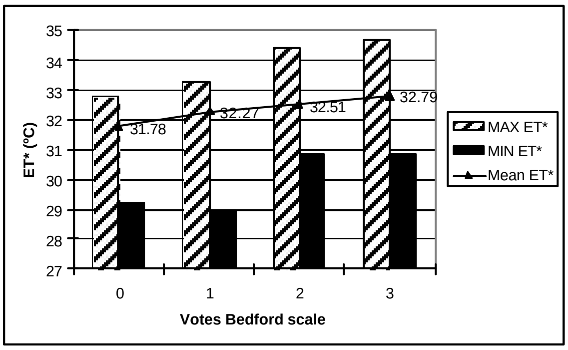

Figure 4: Range of mean ET* during the survey according to the Bedford votes.

And finally, the general living condition of people and the hope of an improvement by answering a questionnaire could also influence their estimation of the thermal conditions. In the case of Old Havana, where there is a comprehensive recovering program that includes building and social conditions, people automatically link any questionnaire with the possibility of a posterior action for improving their life conditions. One hypothesis is that some of the people answered hypercritically both as a means to express their general live discomfort and also their hope that the authorities take note of their problem and further upgrading the building conditions. Thus, the psychological factor is not only affected by the thermal expectation of people but also by their general mental state and satisfaction level which is very hard to predict or asses. Since both, the *e* factor and the proposed 'thermal stability' and 'satisfaction' factors have opposite effects, one could take the actual votes of the questionnaire, which are in between the original and the extended PMV formula, as the most appropriate PMV values.

4.2 Comfort temperature (T_{comf})

The calculation of the comfort temperature (T_{comf}) together with a preliminary definition of the comfort zone was one of the objectives of the climatic measurements and survey. These parameters are used in a next phase [23] to evaluate and compare different geometries of courtyard buildings in Old Havana. To calculate the T_{comf} linear regression analysis was performed between the actual votes of both comfort scales (ASHRAE and Bedford) and the values of both effective temperature (ET*) calculated by the 'WinComf' software and the operative temperature (T_o). Figure 5 shows the regression analysis in which the y axis represents the comfort scales and the x axis the ET*. The value of the neutral or T_{comf} results from the interception of the linear regression with the x axis. The resultant T_{comf} (ET*) for the ASHRAE thermal scale is 28.5ºC while for the Bedford scale is 28.1ºC. For 90% of people the upper temperature limit for thermal comfort that correspond with the PMV=0.5 (PPD=10%) is 29.6 and 29.3ºC of ASHRAE and Bedford scales respectively. For 80% of people that correspond with the PMV= 0.85 (PPD=20%) the limits are 30.3 and 30.2ºC.

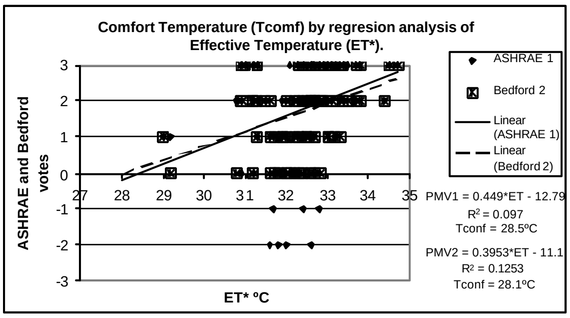

Figure 5: T_{comf} analysis by linear regression. PMV-1 from ASHRAE scale, PMV-2 from Bedford scale.

Comparing these T_{comf} with other studies that used the ET* for the calculation we can see that the obtained values are two degrees higher than the one obtained by Ellis in 1952 in Singapore and Hong Kong (26.1 ET*) [16] and very similar to the one obtained in Thailand (28.5 ET*) [18].

The T_{comf} obtained in this study using the ET* can be compared then, with the adaptive models proposed by several authors. WinComf software uses two equations from Humphreys and Auliciems to calculate the neutral temperature. Humphreys's (1978) [24] equation is based on more than 100 000 observations in climate-controlled and non-climate-controlled buildings. T_n is the neutral temperature (ºC) and T_{mmo} is the mean monthly outdoor temperature (ºC).

Eq. 1

$$T_n = \frac{23.9 + 0.295(T_{mmo} - 22)}{e\left[\frac{(T_{mmo} - 22)}{24 * \sqrt{2}}\right]^2}$$

Auliciems's (1983) [25] neutral temperature model fit sensation data based on field investigations of thermal comfort in Australia spanning several climates.

Eq. 2 $T_n = 9.22 + 0.48T_a + 0.14\ T_{mmo}$

Another two equations are also used here from Nicol and Humphreys (2002) [4] and the comfort temperature equation from de Dear and Brager (2002) [7] which has been included as the adaptive comfort standard in the revision of ASHRAE 55 Standards (2003) [26].

Eq. 3 $T_{comf} = 13.5 + 0.54\ T_o$

where T_o is the monthly mean of the outdoor air temperature that in this case is equal to 27.3ºC.

Eq. 4 $T_{comf} = 0.31\ _{Ta,out} + 17.8$

where ($T_{a,out}$) is the mean outdoor dry bulb temperature which is equal to T_o in equation 3.

De Dear et al (1997) [27] propose also an adaptive model that considers the mean daily outdoor ET* for the calculation of the T_{comf} and it is the equivalent of equation 4 that uses the value of T_o.

Eq. 5 $T_{comf} = 0.225\ TE^*_{out} + 18.9$

where ET^*_{out} is the mean daily outdoor ET*. The mean value of ET* during the questionnaire will be used instead of the mean daily ET*.

Table II shows the mean T_n and T_{comf} using the 5 equations and the calculated T_{comf} using regression analysis. As can be seen the adaptive models and neutral temperature equations give values above the upper level of comfort zone defined by ASHRAE. Nevertheless, the differences between them can be roughly as high as 3ºC which is the case of the Humphreys's (eq.1) and the Nicol and Humphreys's (eq.3) equations. The obtained values of T_{comf} in this study are very similar to the model of Nicol and Humphreys that is a correction from a previous model of Humphreys based also in the relation with the mean outdoor temperature.

Table II: Obtained comfort and neutral temperature according to various adaptive models.

	Adaptive models and equations for Neutral and Comfort temperature	ºC
1	T_{comf} (Regression analysis-ASHRAE) ET*	28.5
2	T_{comf} (Regression analysis-Bedford) ET*	28.1
3	T_n (Humphreys) (eq. 1)	25.4
4	T_n (Auliciems) (eq. 2)	27.6
5	T_{comf} (Nicol and Humphreys) (eq. 3)	28.2
6	T_{comf} (de Dear and Brager) (eq. 4)	26.3
7	T_{comf} (de Dear et al) ET* (eq. 5)	27.2

In the case of this study, due to the similarity of the obtained results with other studies in warm and humid climates and with the adaptive models, the T_{comf} that will be used for further research is the Bedford's scale comfort temperature which is equal to 28.1ºC (ET*). The upper limit for the comfort zone will be assumed for 80% of people as 30.6ºC (ET*).

The lower limit will not be re-defined through regression analysis due to the lack of cooler conditions during the survey. Thus, taking into account the mean outdoor temperature of 27.3ºC, one possible assumption is to take the value of 22.5ºC as the lower limit of the comfort zone according to the adaptive model [7]. But 22.5ºC is 5.6ºC lower than the comfort temperature. Then, taking into account that in humid climates the width of the comfort zone is narrower than in dry conditions [28], the lower limit of the comfort zone for the summer conditions will be assumed to have the same separation from the comfort temperature (28.1ºC ET*) of the upper limit that is 2.5ºC, being then 25.6ºC ET*. Therefore the width of the comfort zone is 5ºC from 25.6 to 30.6ºC. In a study made in a climatic chamber in Havana the upper limit of the comfort zone was 30.2ºC SET* and 31.3ºC ET* [29]. Other studies have found similar upper limits for the comfort zone in NV buildings in warm and humid climates while the lower limit is more variable (Singapore, 27.1-29.3ºC To [15]; Hawaii, 22-29.5ºC To [20]; Thailand, 22-30.5ºC TE* [17]).

CONCLUSION

The results of this survey are neither definitive nor automatically applicable for other research due to the small amount of surveyed population. Nevertheless, due to the similarity of the obtained results with other studies and with the adaptive models, the obtained results brings about valuable criteria in order to use them in the simulations and calculations of the thermal comfort of the new courtyard buildings in the Historical Centre of Old Havana.

Further research is needed to account for the thermal sensation of occupants in courtyard buildings during the winter or less warm period in the area of Old Havana. Accordingly, the proposed preliminary comfort temperature and comfort zone of this study is confirmed or readjusted.

Field studies concerning the adaptive models should be performed also in other warm and humid regions of the Caribbean, Latin America and Africa in order to have a wider picture of the thermal adaptive phenomenon in regions with different cultural and behavioural patterns.

The extension of the PMV model should be further improved so the calculation of the expectancy factor (*e*) could be more accurate and also include other factors concerning the live satisfaction level of people and the stability of the warm thermal conditions.

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