SUBJECTIVE EVALUATION OF THERMAL COMFORT ON A VEHICLE

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Abstract. *The present study has as objective to evaluate the thermal comfort into the vehicle giving emphasis to the climatization system from the point of view of the user. The importance of having comfortable vehicles, either for security reasons, health or thermal welfare of the passengers, imposes to the automotive industry the search for methods of thermal comfort evaluation that comes as close as possible to the occupants sensation. In this work results of subjective tests conducted with a group of people in a stabilized chamber capable of simulate the environmental conditions in a warm day with intense solar irradiation is presented. The evaluation of the comfort, made for the people through grades, is related to the values of temperature, humidity, air speed and the time required to achieve the physiological welfare conditions. The interviews had been made always in the same vehicle under the same conditions, with the interviewed in the same position, with similar clothes so that the uniformity of the experiment was remained. According to the results of the interviews, the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) can also be obtained. These grades will be calculated for a comparison with the people opinion too.*

Keywords*: thermal comfort, vehicle climatization, subjective evaluation, PMV, PPD.*

1. INTRODUCTION

Nowadays, the world automotive industry is increasingly looking for new technologies to improve the satisfaction of passengers in the vehicles, seeing that people make constant use of cars for professional reasons or for leisure. The criteria of the consumers in choosing and buying a car have changed, and now it involves not only aspects related to cost and performance of the vehicle, but also the aspects of security and comfort (Gameiro da Silva, 2002). Therefore, methods of thermal comfort evaluation that reflect as close as possible the sensation of occupants should be searched and used in the case of developing a new vehicle.

Thermal comfort concept is closely associated to vehicular safety. Environmental conditions, especially in big cities, full of noise, air pollution and safety issues, make people increasingly to want a comfortable environment in their vehicles. A vehicle with a comfortable internal environment improves the safety of occupants and reduces their fatigue due to several hours spent in it (Gomes, 2005).

The purpose of this study is to compare an objective measurement of thermal comfort inside a vehicle with the points of view of a group, measured according to ASHRAE thermal comfort scale (ASHRAE 55, 2004).

2. THE THERMAL COMFORT

The human being has a very important feature to its survival. The easy way to adapt to the ambient that lives. It is no different when it comes to adapting to the thermal environment in which it is exposed. Nomads covered their bodies with the skin of their hunt; Eskimos built shelters with snow, avoiding the increase sensation of discomfort caused by the air in motion.

But only in the last century the study of the relationship between the temperature and the perception of thermal comfort has began. Fanger (1972), one of the pioneers in this area, managed to link the subjective feelings of people with physical parameters. With the purpose to target these feelings, the scale of thermal comfort sense was developed from studies made by Fanger. It was obtained through a model based on people votes in relation the thermal environment in which they were, building thus, the concept of Predicted Mean Vote (PMV) that range from very cold (-3) to very hot (+3), presented in Tab. 1.

Table 1. ASHRAE Thermal Comfort Scale.

PMV	+3 Hot	+2 Warm	+1 Slightly Warm	0 Comfortable	-1 Slightly Cool	-2 Cool	-3 Cold
PPD	100%	78%	26%	5%	26%	78%	100%

Fanger also noted that the values of PMV are not sufficient to define the feeling of discomfort, as slightly warm or too cold, not express how dissatisfied the people are. Therefore, the idea of predicted Percentage of Dissatisfied (PPD) was associated to the PMV calculation. Even with the votes equal to zero (comfortable), 5% of people are dissatisfied, and in extreme conditions there is 100% of dissatisfaction by the people. In the next sessions it will be further detailed the equation of the PMV PPD.

2.1. Heat Balance of the Human Body

The internal temperature of the body is kept constant if there is a balance between the heat produced by the body and the heat lost to the environment. The thermal interaction of the man with the environment occurs with heat exchange through the mechanisms of conduction, convection, radiation and evaporation. Through the 1st Law of Thermodynamics we have:

$$\dot{U} = M - W - Q_{Skin} - Q_{\mathrm{Breathing}} \tag{1}$$

$$Q_{Skin} = C + R + E_{es} + E_{dif} \tag{2}$$

$$Q_{\mathrm{Breathing}} = E_R + C_R \tag{3}$$

Where:

$\dot{U}$ – Energy change rate $[W/m^2]$;
M – Metabolism $[W/m^2]$;
W – External work $[W/m^2]$;
C – Heat lost through the skin by convection $[W/m^2]$;
R – Heat lost through the skin by radiation $[W/m^2]$;
E_{es} – Heat lost through the skin by evaporation of sweat $[W/m^2]$;
E_{dif} – Heat lost through the skin by diffusion of water vapor $[W/m^2]$;
E_R – Evaporative heat loss by respiration $[W/m^2]$;
C_R – Convective heat loss by respiration $[W/m^2]$.

From the thermal balance equation of the human body and applying the mechanisms of heat transfer, the thermal comfort parameters can be obtained (Fanger, 1972).

Individual parameters can be defined as those relate type of activity and type of clothing. And environmental factors are those related to air temperature, radiant temperature, air speed and relative humidity. These are parameters that should be measured according to ISO 7726.

2.2. The Fanger Comfort Equation

There are three conditions to be met for a person exposed to a particular environment during a period of time is in thermal comfort. Balance between the heat produced by the body and heat lost to the environment (Eq. (4)).

$$\dot{U} = 0 \text{ (Fanger, 1972)} \tag{4}$$

The skin temperature should be:

$$T_P = 35{,}7 - 0{,}0275(M - W) \text{ (Fanger, 1792)} \quad (5)$$

The production of sweat is given by:

$$E_{es} = 0{,}42(M - W - 58{,}2) \text{ (Fanger, 1972)} \quad (6)$$

Inserting the Eq. (5) and Eq. (6) together with the equations of heat transfer in Eq. (1), we obtain the equation of energy change rate inside the body:

$$\dot{U} = M - W - 0{,}42(M - W - 58{,}2) - 3{,}05[5{,}73 - 0{,}007(M - W) - Pv_{air}] - \\ - 0{,}0173(5{,}87 - Pv_{air}) - 0{,}0014M(34 - T_{air}) - f_R h_c (T_{\text{Clothes}} - T_{air}) - \\ - 3{,}96 \times 10^{-8} f_R[(T_{\text{Clothes}} + 273)^4 - (\bar{T}_r + 273)^4] \quad (7)$$

With:

$$T_{\text{Clothes}} = T_P - 0{,}155 I_{\text{Clothes}} \{(M - W) - 3{,}05[5{,}73 - 0{,}007(M - W) - Pv_{air}] - \\ - 0{,}42(M - W - 58{,}2) - 0{,}0173M(5{,}87 - Pv_{air}) - 0{,}0014M(34 - T_{air})\} \quad (8)$$

$$h_c = 2{,}38(T_{\text{Clothes}} - T_{air})^{0,25}; \text{ for } 2{,}38(T_{\text{Clothes}} - T_{air})^{0,25} \geq 12{,}1\sqrt{V_{air}} \quad (9)$$

$$h_c = 12{,}1\sqrt{V_{air}}; \text{ for } 2{,}38(T_{Clothes} - T_{air})^{0,25} \leq 12{,}1\sqrt{V_{air}} \quad (10)$$

$$f_R = 1{,}0 + 0{,}2 I_{Clothes}; \text{ for } I_{Clothes} \leq 0{,}5CLO \quad (11)$$

$$f_R = 1{,}05 + 0{,}1 I_{Clothes}; \text{ for } I_{Clothes} \geq 0{,}5CLO \quad (12)$$

Where:

$I_{Clothes}$ – Clothes insulation index $[CLO]$;
$T_{Clothes}$ – Clothes superficial temperature $[^\circ C]$;
T_P – Skin superficial temperature $[^\circ C]$;
T_{air} – Air temperature $[^\circ C]$;
$\bar{T}_r$ – Mean radiant temperature $[^\circ C]$;
V_{air} – Speed air $[m/s]$;
Pv_{air} – Partial pressure of water vapor in the environment $[kPa]$;
h_c – Heat exchange coefficient by convection $[W/m^2 \times ^\circ C]$;
f_R – Relation between field dressed and bare area of the body.

To calculate the mean radiant temperature can be used the following equations:

$$\bar{T}_r = \sqrt[4]{(T_g + 273)^4 + 0{,}4 \times 10^8 \times \sqrt[4]{|T_g - T_{air}|} \times (T_g - T_{air})} - 273; \text{ for natural convection (Lamberts, 2005).} \quad (13)$$

$$\bar{T}_r = \sqrt[4]{(T_g + 273)^4 + (2,5 \times 10^8)(V_{air}{}^{0,6})(T_g - T_{air})} - 273 \text{ ; for forced convection (Lamberts, 2005).} \quad (14)$$

The choice of the equation to be used depends on the coefficient of heat exchange by convection of the globe. It should take the mean radiant temperature for the heat exchange to produce a higher coefficient.

$$h_{cg} = 1,4\sqrt[4]{\frac{(T_g - T_{air})}{D_g}} \text{ ; for natural convection (Lamberts, 2005).} \quad (15)$$

$$h_{cg} = 6,3\frac{V_{air}{}^{0,6}}{D_g{}^{0,4}} \text{ ; for forced convection (Lamberts, 2005).} \quad (16)$$

Where:

h_{cg} – Heat exchange coefficient by convection of the globe $[W/m^2 \times {}^\circ C]$;

T_g – Globe temperature $[{}^\circ C]$;

D_g – Globe diameter $[m]$;

It is worth noting that a thermally comfortable person must be in comfort to the body as a whole and also to different parts of the body, without large variations in temperature between the feet and head (ASHRAE, 2005).

2.3. PMV and PPD

Measuring the individual and environmental conditions of thermal comfort cited in item 2.1 and 2.2 we can reach the Eq. (17) of comfort of Fanger:

$$PMV = (0,303e^{-2,1M} + 0,028) \times \dot{U} \quad (17)$$

Where, $\dot{U}$ is the energy change rate $[W/m^2]$, obtained from the individual and environmental conditions measured.

As already mentioned, the values of PMV are not enough to determine the grade of satisfaction of the passengers. It is necessary to know how dissatisfied the people are with the environmental conditions. Therefore, the idea of PPD, which expresses the percentage of people dissatisfied, was combined to PMV (Fig. 1). It is calculated from the PMV, according to Eq. (18).

$$PPD = 100 - 95 \times e^{-(0,03353 \cdot PMV^4 + 0,2179 \cdot PMV^2)} \quad (18)$$

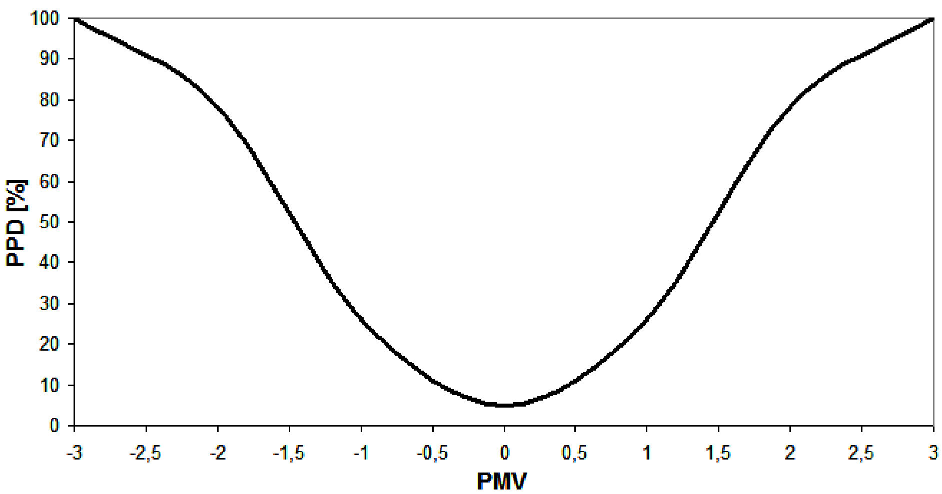

Figure 1. Predicted Percentage of Dissatisfied.

3. THE THERMAL COMFORT EVALUATION ON THE VEHICLE

3.1. Methodology

The methodology used in this study consists of subjective tests conducted with several people in an ambient capable of simulating the environmental conditions found in a warm day with intense solar radiation. These people filled out a sheet with a thermal comfort sensation scale, giving their comfort perception through the values of grades listed on Tab. 1. The sheet must be filled by the occupants at every 10 minutes since their first entered the vehicle. The grades are referred to various parts of the body, such as general condition, head, chest, back, left and right arms, knees and feet. The answers of the interviewees were correlated with temperature, humidity and air velocity reached inside the vehicle, beyond the time necessary to achieve the conditions of physiological welfare.

It is known that this is not the best methodology to evaluate the thermal comfort on the vehicle, but we are just starting the studies in this area. And the use of PMV was the first way to have a notion or to understand the cabin environmental conditions. The mean radiant temperature and the PMV were calculated by the equations shown on previous items. To calculate de the mean radiant temperature the globe temperature was measured through the globe thermometer made by plastic like polyvinyl chloride (PVC). Were used black ping pong balls with thermocouple inside it (Souza, 2002). Figure 2.

Figure 2. Globe thermometer and thermocouple.

The tests were always performed on the same vehicle with the same cycle of Cool Down test. This standard test consists of four phases which it varies the speed of the vehicle every 30 minutes, and consequently the air flow through the condenser on the cooling circuit and the engine rotation, which is directly connected to the compressor rotation. The test is initiated with the vehicle at a speed of 32km/h, increases in the sequence up to 64km/h, 96km/h and ending with 0km/h (slow speed), thus totaling 120 minutes of evidence (Fig. 3) (Maia, 2008).

Figure 3. Vehicle mounted in the climate chamber with dynamometer roller.

Ten interviews were conducted, with 7 men and 3 women aged between 24 and 30 years. People always sit in the front passenger's seat. The interviewed used similar garments, being: the short sleeve shirt, blue jeans, socks and closed shoes. The clothes insulation index was approximately 0,6clo. And the activity rate (metabolism) used was of a person seated and relaxed, 1met. These values were used according to ISO 7730.

The temperature of the head, chest, arms, knees and feet of the front passenger were measured using K type thermocouples (Fig. 4). The accuracy of the thermocouple is $\pm 2°C$.

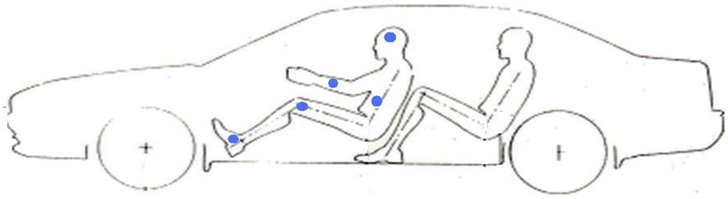

Figure 4. Regions of instrumentation of the front passenger.

The air speed and humidity were measured with the hot wire anemometer and the electronic station time, shown in Fig. 5. The accuracy of the anemometer is $\pm 5\%V$, and the electronic station time is $\pm 2{,}1\%RH$.

Figure 5. (a) Heated wire anemometer, (b) Electronic station time.

During the tests, the temperature was recorded for the realization of the PMV calculation in order to compare them with the opinions of respondents. Only the air speed and humidity were measured and written to be used in the calculations. Particularly, the people in the car wrote the humidity values while gave their comfort perception.

3.2. Results

Figure 6 shows the correlation between the average votes of the respondents with the temperature and humidity in the cabin of the vehicle. In general, it can be seen that, people felt comfortable around 1 hour of test. The temperature at the head in these moments was around 23°C to 25°C. The relative humidity (RH) ranged from 30% to 32%. With 90 minutes of test, the respondents tended to feel slightly cold. At this moment, the temperature was between 21°C to 23.5°C and humidity around 32%.

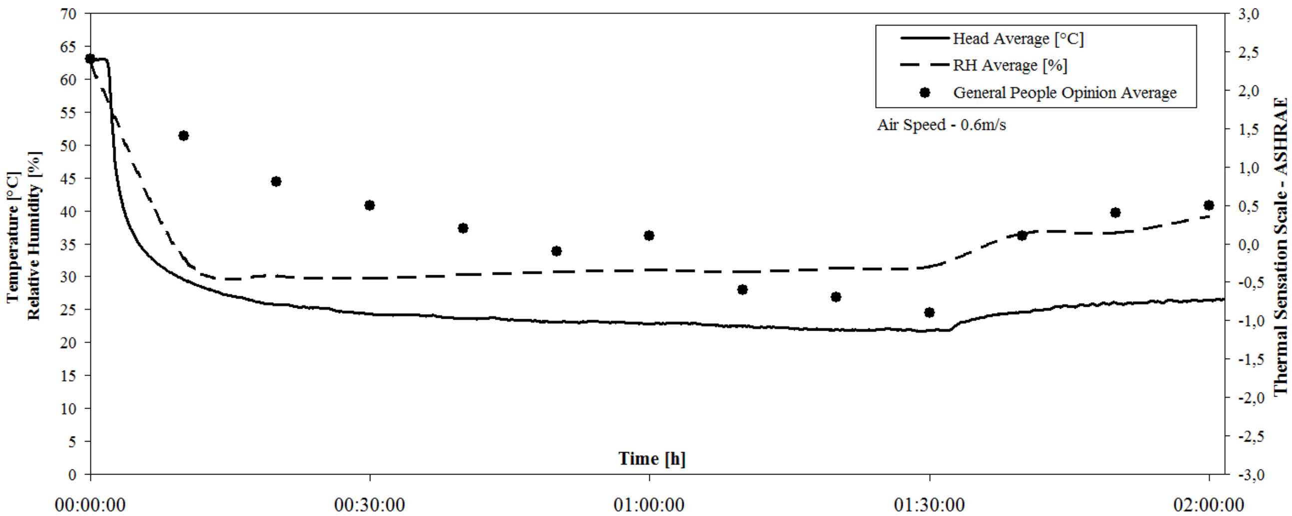

Figure 6. Correlation between weather conditions and general votes inside the vehicle.

It can also be seen, how the relative humidity inside the vehicle is high at the beginning of the test, around 60%. And there is a quickly decreasing when the air-conditioning in the car is switched on. In approximately 12 minutes the humidity reached 30%. At the final stage of the test, the humidity back up, and stay around 35%. These values are basically due to the presence of the person inside the vehicle, since there is only internal movement of air. The air speed can be considered a constant in each region of the body.

The opinions of respondents tend to reflect the climatic conditions inside the car. The grade of satisfaction decreases until 90 minutes of test, increasing when the temperature and humidity levels came rise.

For the chest region the air speed comes from 0.6m/s (on head) to 0.2m/s. This improved the level of people satisfaction between 01:00:00 and 01:30:00 of the test. Should be noted that the others environmental parameters inside the vehicle have not changed at the same time. A higher air speed is very important in hot conditions, as soon as a lower air speed is significant in cold conditions (Fig. 7).

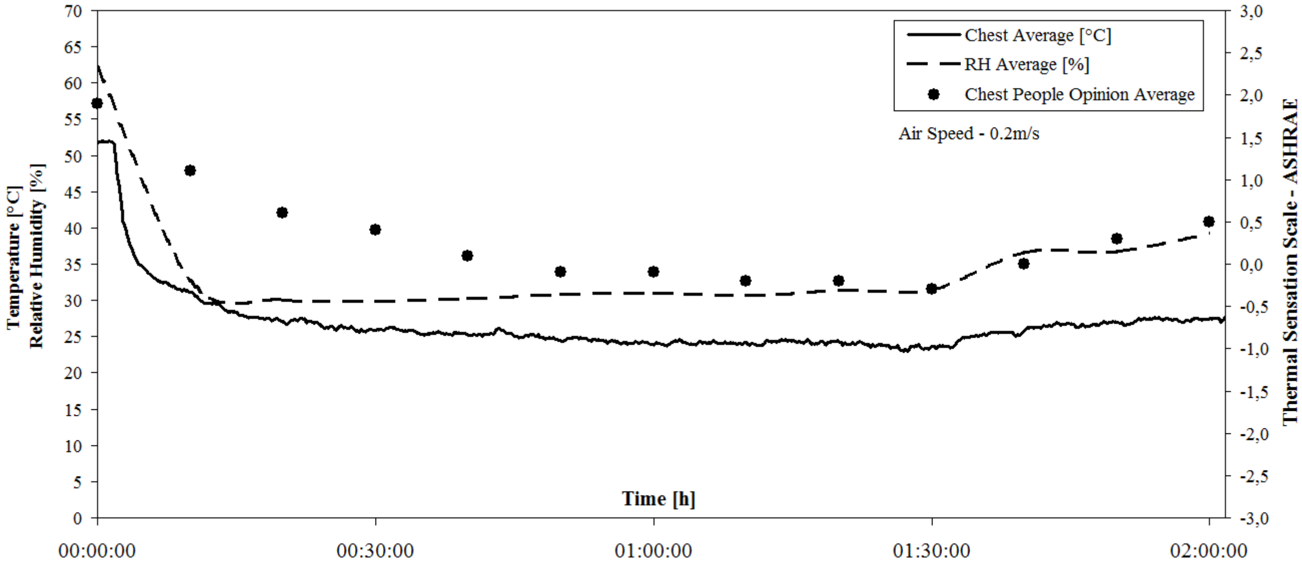

Figure 7. Correlation between weather conditions and chest votes inside the vehicle.

3.2.1. Comparison between Calculated PMV and Interviewed PMV

Figures 8 to 14 show a comparison between the opinions (PMV) of the interviewed and the PMV calculated, for the measured temperature points.

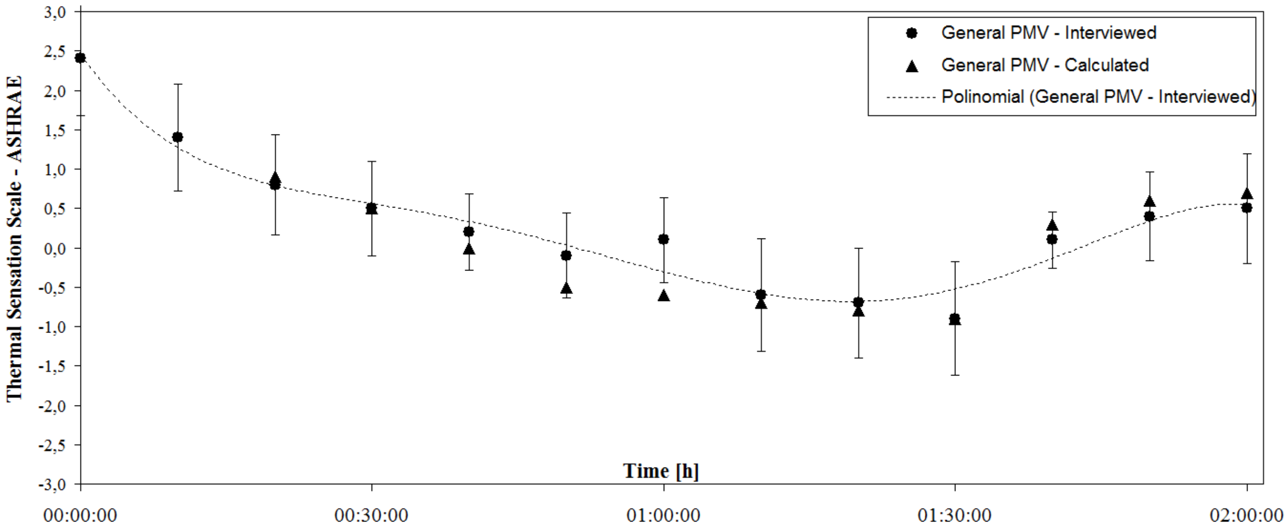

Figure 8. General Comparative.

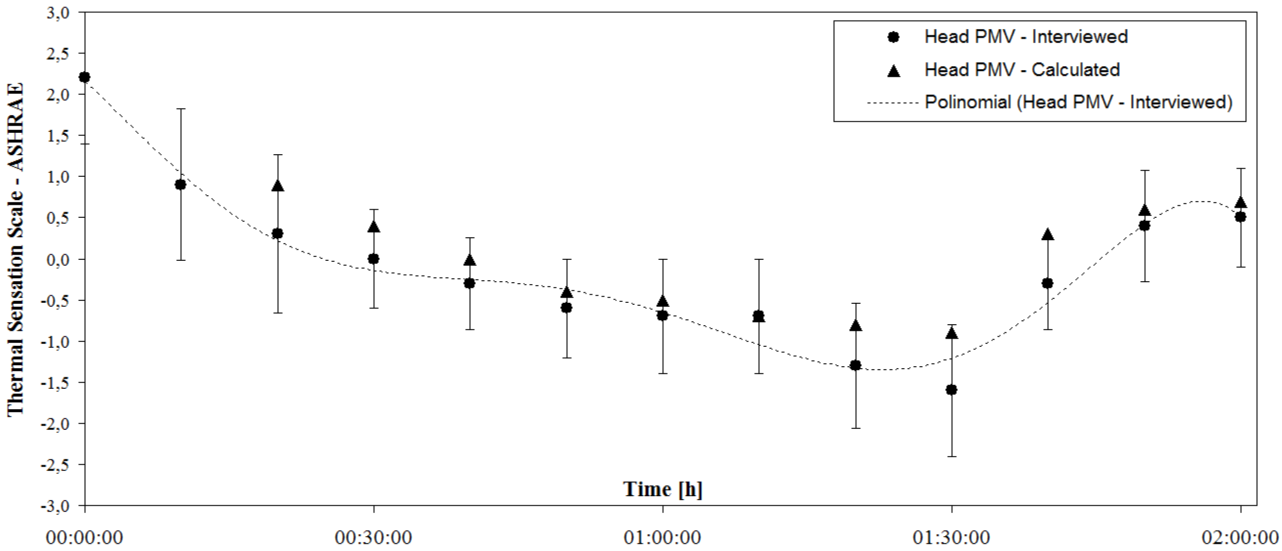

Figure 9. Comparative at head.

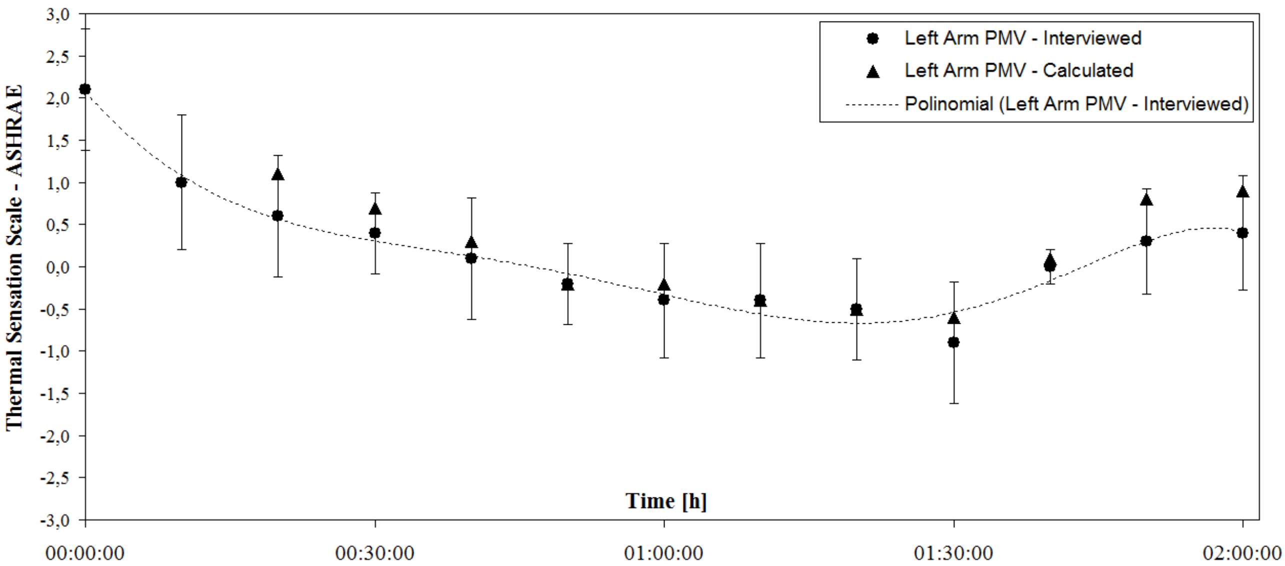

Figure 10. Comparative at left arm.

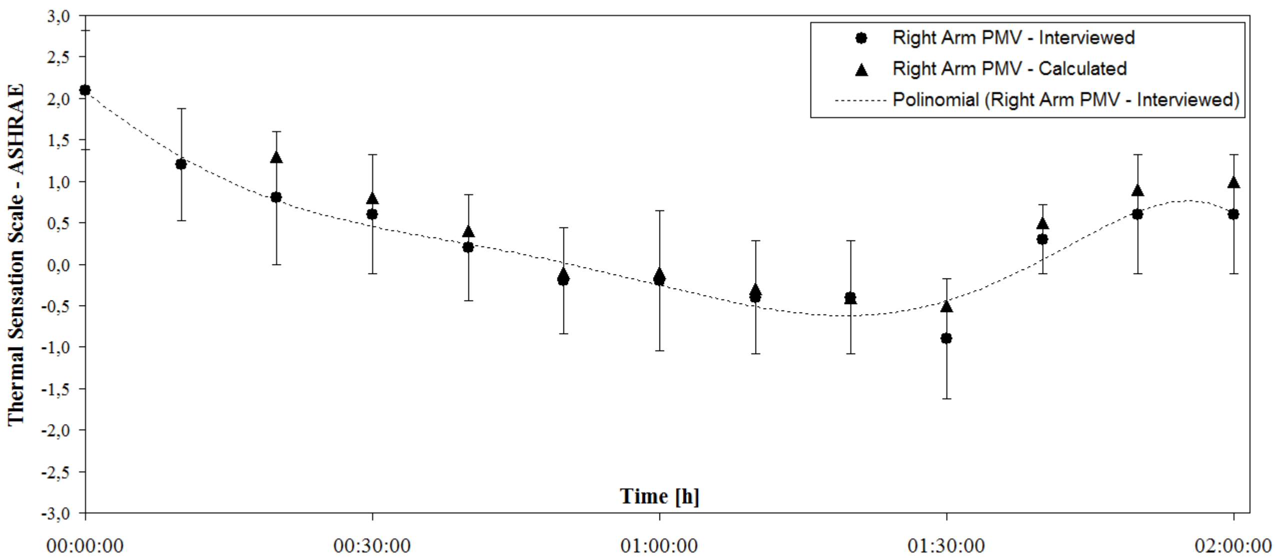

Figure 11. Comparative at right arm.

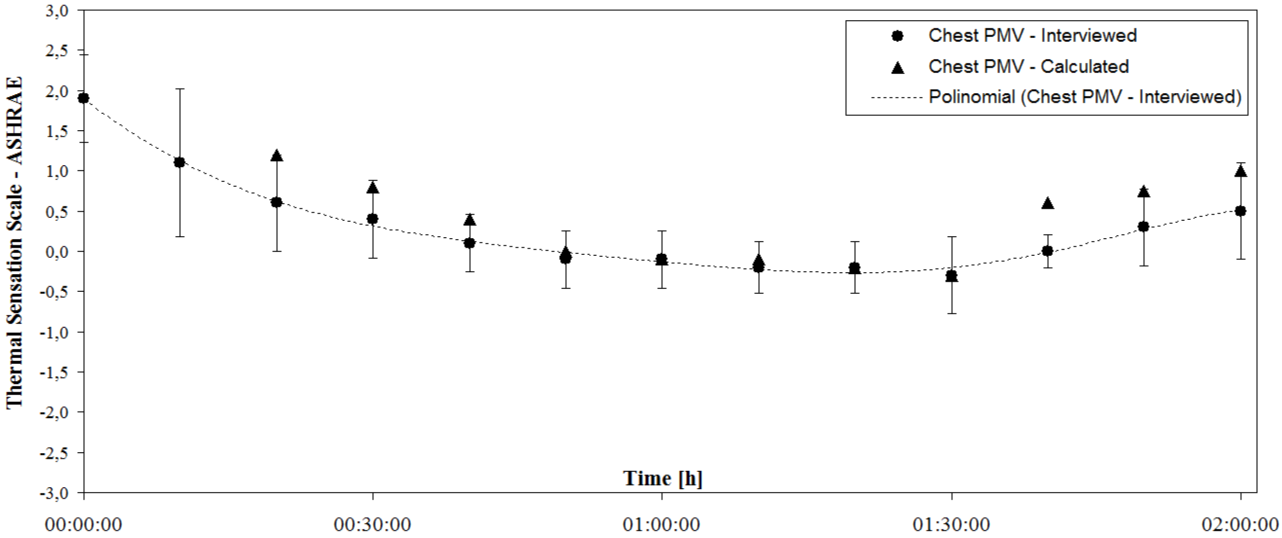

Figure 12. Comparative at chest.

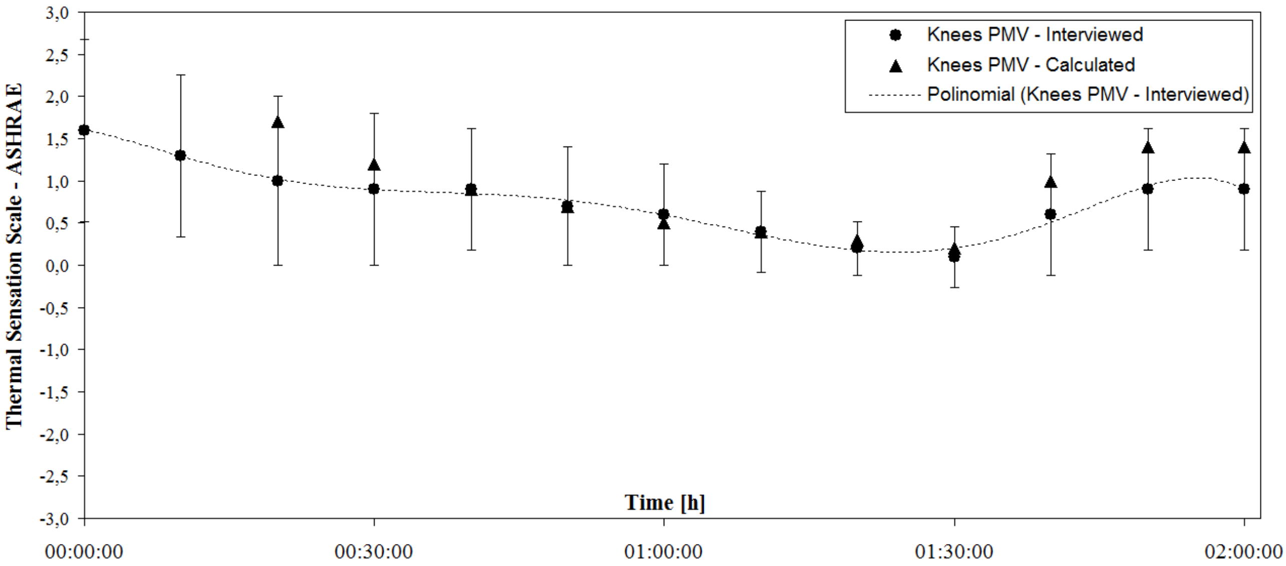

Figure 13. Comparative at knees.

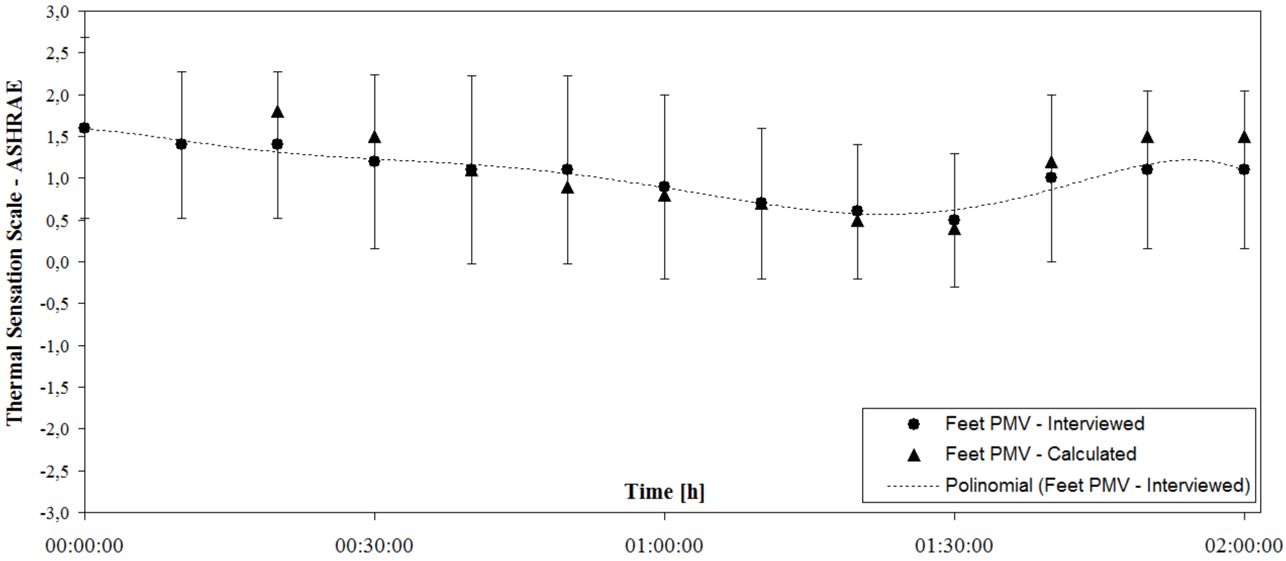

Figure 14. Comparative at feet.

In general, there was a great proximity between the calculated results and interviewed. Some points were overlapped. Another positive point of the test is that the calculated and interviewed items were within the mean deviation (vertical lines). These mean deviations were calculated through the arithmetic average of deviations from the sample average.

Results show that between 30 and 90 minutes the climatic conditions in the vehicle have tendency to be more stable. This led to a convergence between the responses measured and interviewed in spite of a low dispersion because of the low number of respondents. There are, until, some points coincident in these phases.

On the other hand, there was a divergent behavior between the responses of those interviewed and measured in some regions at the beginning of the test. This is due to the fact that in this stage there is a transient behavior. The climatic conditions in the passenger compartment of the vehicle change very quickly on the 1st phase of the test. And there is great possibilities of the interviewed have expressed the sensation for a moment other than that recorded. Other reason for this discrepancy maybe comes from Fanger’s method that is very good for steady state conditions.

Generally the carrier of the vehicle presented itself a comfortable environment, with exception of the feet region, which was slightly warm.

This test allowed to evaluate the thermal comfort of the occupant of the vehicle in a fractional way, in other words, each region of the body separately. Thus, possible problems can be addressed individually for each region.

4. CONCLUSIONS

This work has shown the importance of having a more fragmented thermal comfort evaluation of a little homogeneous environment, like a vehicle. So, problems of discomfort that are occurring in specific regions of the car can be detected and the individual parameters of comfort that needs to be changed to an overall improvement can be attacked.

The air distribution trough the ventilation diffusers is very important, since it assures the better homogenization of the air inside the vehicle, increasing the occupants thermal comfort. This study helped to understand how it affects the degree of satisfaction of the occupants.

The method allows the evaluation of the thermal comfort, in a simple way, with a simple instrumentation mounted on the vehicle. Moreover, the calculated results were very close to the people opinion on the steady state condition giving a good idea of the thermal comfort inside the vehicle carrier.

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