Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 3 (2015) 4999 – 5006

Procedia MANUFACTURING

6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015) and the Affiliated Conferences, AHFE 2015

Thermal comfort in industrial environment: conditions and parameters

Norma de Melo Pinto[a], Antonio Augusto de Paula Xavier[b], Kazuo Hatakeyama[c]

[a]*IFES – Federal Institute of Espirito Santo, Brazil*
[b]*UTFPR – Federal University of Technology of Parana, Brazil*
[c]*UNISOCIESC – University Center of SOCIESC, Brazil*

Abstract

There are two groups sharing research on thermal comfort. The first is devoted to research in environmental chambers held within an environment controlled by the investigator. The second group is dedicated to the research field in which the researcher does not interfere with environmental variables, personal and subjective, does not determine the activities to be carried on clothing and not to be used, however, notes, notes, estimates, and table or calculates the values of variables, indices and parameters of thermal comfort. The research work is based on the series of International Organization for Standardization that provides the lack of specific national legislation on the subject: thermal comfort. This survey aimed to examine the existence of thermal comfort in the mechanical manufacturing company with employees performing their normal activities. The conditions and perceptions of the thermal environment of production sector by the employees were assessed for the main variables. Survey was made to assess the influence of variables (metabolic rate, thermal clothing, air temperature, mean radiant temperature, speed and relative humidity) and the comfort subjective parameters (thermal sensation and preference) in May, August and November 2010. Based on the measurements of environmental variables, tables of personal variables, the calculation of the index of Predicted Mean Vote (PMV) and predicted percentage of dissatisfied (PPD), a collection of subjective parameters, the main results show that: a) the analyzed sectors provide heat and discomfort for employees who like a more refreshed, b) the PMV confirms that employees feel heat in industrial environments, c) the PMV model adopted by ISO 7730 (2005) applies to employees the thermal sensation with a coefficient of determination $R^2 = 0.81$ d) in situations full of comfort, i.e., PMV = 0 is I = 35.08% and there are a range of thermal acceptability ($-0.5 < PMV < 0.5$) with a maximum of 40.37% dissatisfied. Therefore, the outdoor environments have heat discomfort. There is a clear need for development of the Brazilian Code of thermal comfort, as well as conducting studies to determine the thermal insulation of work clothes and protective. The results of the survey points out to the possibility of large errors in the use of international values of metabolic rate and confirms the need for studies to determine the metabolic rate according to the characteristics of the Brazilian ethnical population. Furthermore, continuous survey on issue should be carried out as the significant agreement of the PMV with the sensation reported by employees is not characteristic of the field.

Peer-review under responsibility of AHFE Conference

Keywords: Thermal comfort; Industry environment; Predicted Mean Vote; Predicted percentage of non-satisfied; Acceptability of thermal environment

2351-9789
Peer-review under responsibility of AHFE Conference
doi:10.1016/j.promfg.2015.07.662

1. Introduction

The term thermal comfort has been the object of studies since years, by researchers [1] determined the equation and the zone of thermal comfort whereas [2] elaborated the method PMV and PPD. Also, [2] confirmed the validity of the ISO 7730 limited to the studies of laboratory, whereas [3] evaluated the perception of workers in the metallurgy. Researchers [4] reunited the standards related to the previous and present comfort and thermal stress in one single document. However, the great landmark occurs by means of studies of [2] on the thermal change of heat of the body with environment. Such studies direct the versions of the International Organization for Standards [5]. The updated version of [5] ratify the studies of [2] and incorporate the studies of [6] adding indexes for the analysis of thermal comfort and stress.

This survey was carried out with the workers of the mechanical manufacturing sector evaluating conditions and perceptions of the industrial thermal environment. This justifies due to the needs of measurement and results that make part of the Brazilian and world data bank of the research on thermal comfort with the aim to analyze and establish conditions to evaluate if the thermal environment is or not adequate to the activities for human occupations also to establish methods and principles for the detailed thermal analysis of the environment. The definition that expresses the imagination of the person somewhat the happiness in hot, cold or pleasant places is presented by [5]. However to mention on the thermal comfort, measurement are required with standardization for the parameters which can be compared and analyzed.

2. Literature review

2.1. Working environment and industrial environment with exposure to heat

Several factors that are related to the working environment which are composed by the hot and cold temperatures, colors, ventilation and artificial or natural lighting that depending on the intensity and the time of exposure can harm or benefit the human health. Is the place that the human employs hands on to execute tasks to guarantee the own survival, thus, should be the adequate place to proportionate sound quality of life. Temperature of the air, relative humidity of the air, speed of the air, average radiant temperature, as well as clothes and levels of human activity are factors that determine the thermal balance of the human body in certain thermal environment. Several models are available in the literature to relate the human sensation of comfort to these factors [7].

2.2. Environmental and thermal comfort

As to the [8], it determines that an environment be thermally comfortable when the values of the Estimate Men Vote (PMV) occur intermittently within the $- 0.5 < PMV < + 0.5$, and the values of the Percentage of Non-satisfied Persons is (PPD) 10%. To this extent, the clauses 6 and 7 of the standard [9] clarifies that the thermal environment of buildings or the work places shall be changing along the time and their later conditions can be exchanged within the recommended limits. A method to be adopted at long term for an environment thermal assessment is focused in the Clause 9 of the aforementioned standard.

2.3. Heating exchanges between the human body and the environment: thermal balancing

In hotter environments above 35 ^{o}C, the evaporation is the only available resource for the body organs to eliminate its overheating and keep the comfortable thermal balancing with a nice breezing close to the skin. The speed of air is considered to be pleasant between 0.1 to 0.2 m/s in soft works at a temperature around 24 ^{o}C. Activities of heavy works above 24 oC under saturated air, the preferred air raises to 0.2 to 0.5 m/s. The Norm NR-17 determines the air maximum speed of 0.75 m/s for soft work activities. This speed must be reduced to 0.15 m/s along the winter. In order to maintain the thermal balance, the heat must be dispelled in the environment so as to prevent the raise in the body´s internal temperature which may go up to around 37 oC. The heat dispelling occurs by means of thermal changes mechanisms which can be observed in Figure 1.

The International Standard [5] utilizes the "standstill state" or "permanent" as developed by [2] in which the body´s heat is kept in balance if in a specific environment, not occur increase of internal heating. On Fanger´s concept the first condition for an individual be in a state of comfort is be in a thermal balance, or that all the heat generated by his organs is dispelled in a proportion related to the environment, with the use of heat exchanging by convection, radiation, conduction and evaporation. The balance of the gains and loss of heat of the body is expressed by the equation 1.

$$M - W = Q_{SK} + Q_{RES} = (C + R + E_{SK}) + (C_{RES} + E_{RES}) \quad (1)$$

- M - metabolic rate of production of heat, in (W/m²);
- W - rate of the mechanical efficiency, in (W/m²);
- Q_{SK} - total rate of loss of heat by the skin, in (W/m²);
- Q_{RES} - total rate of loss of heat by the breathing, in (W/m²);
- C + R - perceptible loss of heat by the skin (convection+ radiation), in (W/m²);
- E_{SK} - total rate of loss of heat by the evaporation of the sweat in the skin, in (W/m²);
- C_{RES} - rate of loss of heat by the convection by breathing, in (W/m²);
- E_{RES} - rate of loss of heat by the evaporation by breathing, in (W/m²).

Those expressions incorporate environmental factors as well as skin temperature and moisture, thermal insulation and permeability to the moisture of the clothing.

3. Factors that influence thermal comfort

3.1. Environmental variables

The environmental variables are: the temperature of the air (Tar), the relative speed of the air (Var), the average radiant temperature (Trm) and the relative humidity of the air (UR). The temperature, the humidity, the radiation and the motion of the air produce thermal effects and must be considered simultaneously to the human responses [6].

Through the skin: Perceptible loss of heat, by convection and radiation (C and R);
Latent loss of heat by the evaporation of sweat and by the dissipation of humidity of the skin (E_{sw} and E_{dif}).

Through the breathing: Perceptible loss of heat: convection (C_{res});
Latent loss of heat: evaporation (E_{res}).

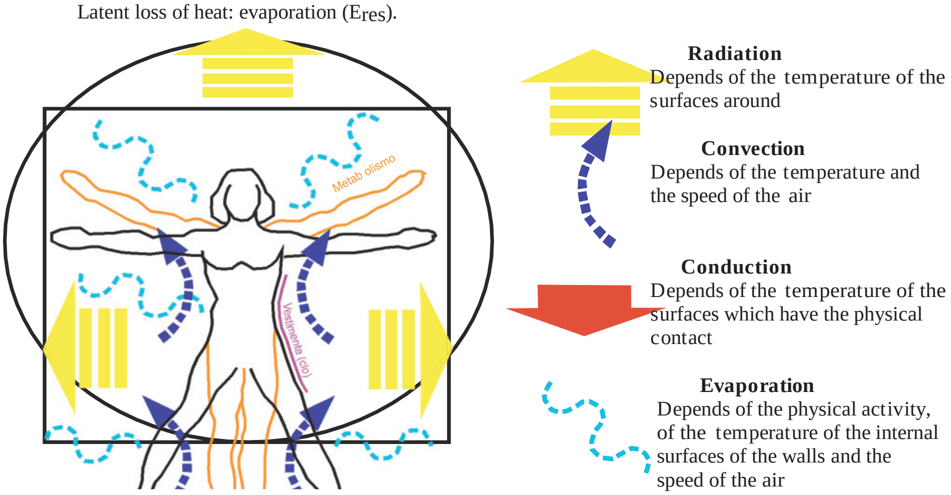

Fig. 1. Schematic representation of the human physiology and thermal exchanges; Source: LabEEE UFSC (2011).

Further [5], the absolute air moisture (Pa, KPa) is distinguished by the water quantity of steam found in a volume of damp air. The variable temperature of the air (Ta), temperature of globe (Tg), absolute speed of the air (As) and relative humidity of the air (Rh) were collected by the Comfortimeter Sensu apparatus. The rigor in taking of measurements and the accuracy in the response time of the sensors is established in [5]. Establish also the positions for the measurements and weigh up coefficients to estimate the average value, according to the type of the environment evaluated and the class of the specifications of measurements, shown in the Table 1.

Table 1. Positions of the measurement for physical variables of environment.

Position of the sensor	Weigh up coefficients for the estimation of the variables				Recommended higths	
	Homogeneous environment		Heterogeneous environment		Seated	Stand up
	Class C	Class S	Class C	Class S		
Level of the head			1	1	1.1 m	1.7 m
Level of the belly	1	1	1	2	0.6 m	1.1 m
Level of the heel			1	1	0.1 m	0.1 m

Source: Adapted from International Standard ISO 7726 (1996)

The specifications and methods containing in this Standards are sub-divided into two types used in accordance with the situation to be analysed:

- Type C - Refers to measurements carried out for moderate environment.
- Type S - Refers to measurements carried out in environments liable to thermal stress.

3.2. Personal variables

The personal variables that influence in the thermal comfort are: the metabolic rate and thermal isolation of the clothes. The basal metabolic rate is the minimum energy or the quantity of calories that the human body utilizes, in the rest state, to keep the vital functions of all organs such as the heart, the brain, the lung, and others. The metabolic rate is the conversion of chemical substance in mechanical and thermal energies and presents the numerical index for the human body´s activity. The unity of metabolic rate is represented in W/m^2 and in met (1 met = 58.2 W/m^2), or unity of quantity of heat produced by the organism. With the didactic aim transcribe from [5] some values according to the activities carried out by one man:

- walking 5.15 met = 300 W/m^2;
- typing 2.23 met = 130 W/m^2;
- in heavy work of lift and transport weight 8.08 met = 470 W/m^2.

The tables included in the International standards mentioned, regards to the common person: the man of 30 years old weighing 70 kg and 1.75 m of height that has surface area of the body of 1.80 m^2, also named as surface of skin. The equation of the estimation of the surface of the skin was developed by the French scientist called DuBois which is presented in the Equation 2.

$$A_{Du} = 0.202.^{m0.425}.l^{0.725} \qquad (2)$$

- A_{Du} - superficial area of the naked body, in (m^2);
- m - mass of the body, in (kg);
- l - height of the body, in (m).

The body to be in thermal neutrality, the condition is that the rate of the sweat be within the boundaries.

The rate of the sweat is analyzed in function of the area of the skin, thus, the analysis of the boundaries is given the expressions 3 and 4:

$$a < t_{sk.m} < b \quad (3)$$

$$c < E_{sw} < d \quad (4)$$

- $t_{sk.m}$ - average temperature of the skin, in (^oC);
- E_{sw} - rate of secretion of the sweat, in (W/m²);
- a, b, c, d - empirical parameters, regarding to activity carried out.

$$T_{sk.m} = 35.7 - 0.0275M \quad (5)$$

$$E_{sw} = 0.42(M - 58.15) \quad (6)$$

- M - Metabolic rate, by means of the activity carried out, in (W/m²).

The mechanical efficiency of the muscle work or useful work represented by W, the majority of types of industrial works presents negligible value and not interferes in the metabolic rate. Thus, assumes that the metabolic rate is equal to the production rate of the heat in the body whose activity carried out by the person determines the quantity of the heat generated by the organism.

The utilization of thermal insulated clothing interacts with the environment and, it takes up an essential role in the sensations of thermal comfort and discomfort. To the purpose of quantifying this variable, [10] introduced an index of thermal resistance for clothing thermal insulation (Icl) expressed in "clo". The "clo" is equal to 0.155 m^2 k/W which defines the insulation required for a complex of clothes to provide an individual with a thermal comfort in the sitting and resting positions along the hours that he is confined in an environment under an air temperature of 21^oC with a relative air moisture of 50%, and air speed of 0.1 m/s [11].

The total "clo" values of each piece composing the individual clothing is represented by the final thermal resistance index (lcl). The thermal insulation of clothes is determined by the measuring heat dummies or determined directly by the figures provided in specific tables.

3.3. Indexes of thermal comfort

The indexes of thermal comfort were developed upon the needs of becoming known the thermal sensation experienced by individuals exposed to personal and environmental variables. One of them is the effective temperature index (te) which is the temperature calculated in accordance with the temperature of the dry bulb, as well as the temperature of the damp bulb and the air speed. It is used to assess the heat in a work environment, and its value is obtained through abacus. Author [2] used the details of figures obtained from laboratory experiments with around 1,300 persons to determine an equation that, upon the environmental and personal variables, allows that the average thermal sensation of a group of persons (PMV) when exposed to a specific combination of those variables are estimated.

Fanger method was a basis for the development of an International Norm specifically for the thermal comfort conditions in thermally moderate environments [9], its latest version updated in November 15th, 2005.

Table 2. Values of the thermal sensation.

Value	Thermal Sensation
+3	Too hot
+2	Hot
+1	Slightly hot
0	Neutral
-1	Slightly cold
-2	Cold
-3	Too cold

Source: Adapted of Fanger (1970 p.110)

This study uses the Equation 7 for the calculation of the PMV.

$$PMV = (0.303.\ \exp(-0.036M) + 0.28)\ L \quad (7)$$

- PMV - Predicted Mean Vote or Mean Estimate Vote
- M - Metabolic rate, in W/m^2
- L - Thermal charge acting over the body.

After calculating the PMV indexes, [10] researches have utilised 20 studies which proposed that the PMV model is extended to hot environments in non-acclimated buildings, by the use of an expectation factor "*e*" to be multiplied to the PMV in conformity with a low degree (0.5 and 0.7), as well as moderate (0.7 and 0.9) and high degree (0.9 and 1.0), thus obtaining the final results of the PMV. The PPD index determines the estimated quantity of persons non-satisfied thermally with the environment. He found grounds in the percentile of a large group of persons who would like that their environment were hotter or cooler, voting + 3, +2 or 3 and -2 in the seventh scale of sensations. The PPD can be determined analytically in conformity either with the Equation 8 and the PMV.

$$PPD = 100 - 95.\exp[-(0.03353PMV^4 + 0.2179PV^2)] \quad (8)$$

- PPD - Percentile of Persons non-satisfied, in %;
- PMV - Estimated Average Vote, dimensionless.

The minimum expected percentile of non-satisfied, is of 5%. The curve is symmetric regarding to the point of neutrality, PMV = 0 and can expect the percentile equal of persons non-satisfied with the thermal environment studied regarding to sensations of cold and hot.

3.4. Thermal environment acceptance with the aim of comfort

Due to the diversified features of individuals, it is difficult to design a thermal environment model which comes to fully satisfy all of its occupants at the same time. As shown by the Table 3, the desired thermal environment can be analysed by the Categories A, B or C, however, the criterions concerning the values of PMV and PPD must be simultaneously of satisfaction for each of those categories.

Table 3. Categories of thermal environments.

Thermal state of the body as a whole		
Categories	PPD (%)	PMV
A	6	- 0.2 PMV + 0.2
B	10	- 0.5 PMV + 0.5
C	15	- 0.7 PMV + 0.7

Source: Adapted from ISO 7730 (2005).

The category B holding a thermal acceptability of 90% of its occupants, limits to a maximum of 10% the percentile of non-satisfied (PPD) with the environment be considered thermally acceptable by its occupants, emphasizing that the PMV values must be within $-0.5 < PMV < +0.5$. The category B reflects the requirements of the prior version of the [13] also denominated Fanger´s Model (1970). There will be 5% of non-satisfied persons with the thermal environment when the thermal satisfaction PMV is equal to zero condition of plain comfort [14].

4. The research work

This research work has assessed the percentile of non-satisfied individuals by four distinct ways denominated non-satisfied ones: 11, 12, 13 and 14, taking into account four distinct interpretations of the votes: + 1 and - 1 in the thermal sensations scale [2] described the ranking of non-satisfied as follows:

1. The Votes of thermal sensations equals to + 1, 0, and -1 do not represent any portion of non-satisfied persons. The remaining Votes + 3, +2, -3, and -2, represent the non-satisfied persons (%).
2. All of the remaining votes +3, +2, +1, -3, -2, -1 represent non-satisfied persons (%).
3. The Votes of thermal sensations equal to +1, and -1 represent 50% of non-satisfied persons, which are summed up to the remaining Votes + 3, + 2 and - 2 representing the non-satisfied persons (%).
4. The Votes + 1 and -1 had the following understanding: "they are considered to be non-satisfied the persons voting + 1 or -1 in the sensation scale and, kept the same Votes in the scale of thermal preferences. Those persons voting + 1 or -1 in the scale of sensations and voted 0 (zero) in the thermal preference scale, shall not be considered to be non-satisfied persons, i. e., they do not desire that the environment parameters are changed" .

As the curve in its minimum scale has shown approximately 47.5% of non-satisfied which corresponds to a PMV = 0, in this research adopted the same scale of sensation utilized by Fanger to represent the PMV, i.e., changing to -2 (cool) a + 2 (hot). Figure 2 shows the percentile of non-satisfied as instructed by the PMV.

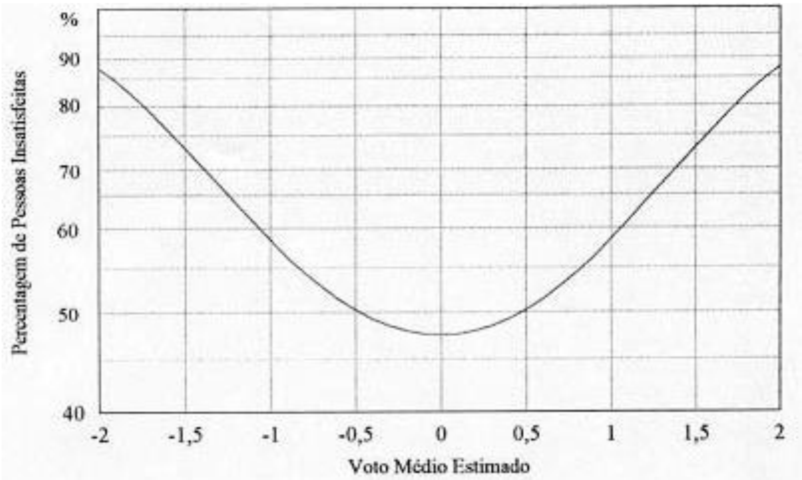

Fig. 2. Percentile of non-satisfied regarding to PMV; Source: Araujo (1996).

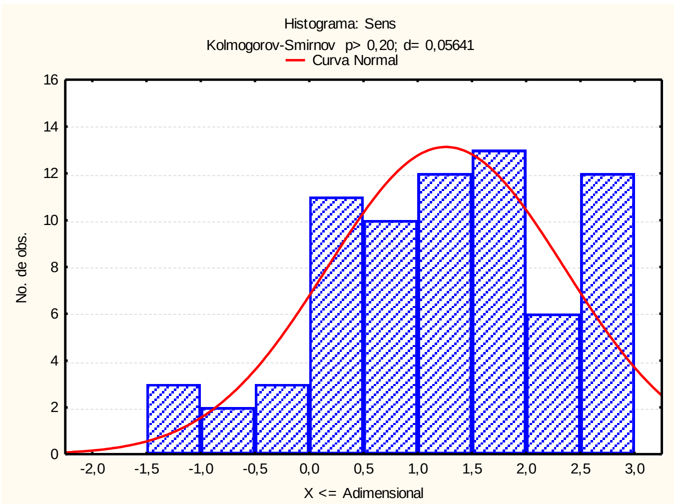

Fig. 3. Distribution of the frequency of comfort sensation [15].

The votes over thermal sensation and thermal preferences were processed for the Kolmogorov-Smirnov test to get the distribution histogram of the frequency of the comfort sensation resulted from the measurement performed in the present survey, as shown in the Figure 3.

Figure 3 shows the frequency of average response on thermal comfort sensation falls within 1.25 indicating the existence of non-satisfied workers in their working environment which calls for further improvement. Results concerning the metabolic rate, thermal isolation of clothes, the temperature of the air, humidity, frequency of PMV and PPD were found and reported in [15] to be utilized as a reference for decision taking.

5. Conclusion

The conclusive results show that high temperatures prevailed in the surveyed environments which may bring about health problems which interfere with the individual productive performance exposing to eventual serious labour accidents. This study surveyed the existing environment thermal comfort within an industry sectors working in the field of steel products manufacturing, however, analysis over other issues such as the deriving thermal stress and whether existing or not salubrious conditions to be the purpose of other forthcoming researches.

In 73.62% of the measurements, the employees reported their sensations as follows: slightly hot; hot and very hot, which may be considered to be reason for some discomfort in the practice of labour activities, this in general, turns the persons dissatisfied and the work environment thermally discomfort. The reportedly stated sensations which were not compatible to the PMV Model, may be resulted from the differential scales, having in mind that the thermal sensation vote obtained from the diagnosing questionnaire is under a scale with unitary variation while the assessed PMV has a continuous variation within the interval of -3 to +3.

The results of the survey points out to the possibility of large errors in the use of international values of metabolic rate and confirms the need for studies according to the characteristics of the Brazilian ethnical population.

References

[1] F. C. Hougthen; C. P. Yaglou, Determining lines to equal comfort and determination of the comfort zone. In: ASHRAE Transactions, v.29, 1923.

[2] P. O. Fanger, Thermal comfort: analysis and applications in environmental engineering. New York: McGraw-Hill Book Company, 1970.

[3] M. Barbiero, Evaluation of perceptions regarding thermal environment in metallurgical industry: the case study. 239 f. Dissertation (Practice Oriented Master Degree – Emphasis in Ergonomics) – Engineering School, Federal University of Rio Grande do Sul, Porto Alegre, 2004. (in Portuguese).

[4] R. Lamberts, A. A. P. Xavier, Thermal comfort and thermal stress. Laboratory of Energy Efficiency in Buildings. Florianopolis – SC, 2011. (in Portuguese).

[5] International Organization for Standardization. Moderate thermal environments - Determination of the PMV and PPD index and specification of the conditions for thermal comfort, ISO 7730. Geneva, 1984.

[6] A. M. Hackenberg, Comfort and thermal stress in industries: surveys in the Joinville, SC and Campinas, SP regions. 270 f. Doctorate Thesis in Mechanical Engineering. State University of Campinas, SP. 2000. Ler foneticamente

[7] B. W. Olesen; K. C. Parsons, Introduction to thermal comfort standard and the proposed new version of EN ISO 7730. Energy and Buildings, Amsterdam, v.34, n.6, p. 537-548, 2002.

[8] International Organization for Standardization. Moderate thermal environments - Moderate thermal environments - Determination of the PMV and PPD index and specification of the conditions for thermal comfort, ISO 7730. Geneva, 1994.

[9] Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions of thermal comfort, ISO 7730. Geneva, 2005.

[10] M. A. Humphreys; J. F. Nicol, Understanding the adaptive approach to thermal comfort. In: ASHRAE Transactions: Symposia. V.7, n.1, p. 991-1004,1998.

[11] M. S. Al-Homoud; A. A..Abdou; I. M. Budaiwi, Assessment of monitored energy use and thermal comfort conditions in mosques in hot-humid climates. Energy and Buildings, Amsterdam, v. 41, n. 6, p. 607-614, 2009.

[12] International Organization for Standardization. Ergonomics of the thermal environments - Instruments for measuring physical quantities, ISO 7726. Geneva, 1996.

[13] P. O. Fanger; J. Toftum, Extension of the PMV model to non-air-conditioned buildings in warm climates. Energy and Buildings, Amsterdam, n.34, v.6, p. 533-536, 2002.

[14] V. M. D. Araujo, Parameters of thermal comfort for users of school buildings in the Brazilian northeastern seashore. Doctor thesis. Faculty of Architecture and Urbanization of the Sao Paulo University. São Paulo,1996.(in Portuguese).

[15] N. M. Pinto, A. A. P. Xavier, K. Hatakeyama, Thermal comfort: analysis in industrial environment. Publit Soluções Editoriais, Rio de Janeiro, 2014. (in Portuguese).