International Journal of Industrial Ergonomics 69 (2019) 1–8

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

# The approximation between thermal sensation votes (TSV) and predicted mean vote (PMV): A comparative analysis

Evandro Eduardo Broday[a,*], Jéferson Aparecido Moreto[b], Antonio Augusto de Paula Xavier[a], Reginaldo de Oliveira[a]

[a] Federal University of Technology of Paraná (UTFPR), Ponta Grossa, Paraná, Brazil
[b] Federal University of Triângulo Mineiro (UFTM), Uberaba, Minas Gerais, Brazil

ARTICLE INFO

*Keywords:*
Thermal comfort
Predicted mean vote
Clothing surface temperature
Welders
Army officers

ABSTRACT

The Fanger's predicted mean vote (PMV) model is used to evaluate thermal comfort. However, when PMV is compared to people's real thermal sensations, collected in field studies, some discrepancies are verified. One of the components for the calculation of PMV is clothing surface temperature ($t_{cl}$), which can be a factor that contributes towards these discrepancies. The aim of this study was to propose alternative methods for predicted mean vote, seeking to reduce these discrepancies. The mathematical Newton's method was applied to obtaining $t_{cl}$ values. The $PMV_1$ was determined by replacing the $t_{cl}$ values in the traditional equation of PMV as described by ISO 7730 (2005). The second model of thermal prediction, named as $PMV_2$, was obtained by a multiple linear regression considering the thermal sensation votes, the metabolic rate and the six heat exchange mechanisms. Two groups (welders and army officers) were used to verify the accuracy of the methods used in this research. The results show that both methods were able to describe the thermal sensation votes. For the welder group, both $PMV_1$ and $PMV_2$ overestimated the results: when people voted TSV = 0, $PMV_1$ = 0.64 and $PMV_2$ = 0.23. In the case of the army officers group, applying $PMV_1$, when TSV = 0, $PMV_1$ = 1.47. The application of the multiple regression increased the potential of $PMV_2$ to obtain responses closer to those provided by the occupants of the thermal environment studied: when TSV = 0, $PMV_2$ = 0.0068, demonstrating a greater effectiveness of this method.

## 1. Introduction

Ergonomics has been gaining more space in the industry in recent decades. Since its emergence, the central focus has always been on adapting the work environment to man. According to Iida (2005), it is extremely important to obtain the well-being of the human being indoors, in order to guarantee the basic objectives of Ergonomics: health, safety, satisfaction and efficiency. Among the concerns with the work environment it is possible to cite noise, luminosity, air quality and temperature as factors of influence in the development of activities. The temperature is related to Thermal Comfort, object of this research.

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 55, 2013), Thermal Comfort is defined as the "condition of the mind that expresses satisfaction with the thermal and is assessed by subjective evaluation". Studies in thermal comfort area are becoming more widespread because there is a need to create a thermically comfortable environment. In these environments, people spend most of their time every day. According to Sales et al. (2017), obtaining personal comfort is important because it is responsible for keeping people's quality of life.

Generally speaking, a sense of comfort occurs when body temperature is kept within narrow limits, skin humidity is low and the physiological effort of regulation is minimized. Comfort also depends on behavioral actions such as changing clothes, activities, changing body posture or place, altering the adjustment of the thermostat, opening a window and complaining about a room because of its temperature (Djongyang et al., 2010).

The most popular method to evaluate thermal sensation of a group of people is the one created by Fanger: the *Predicted Mean Vote* (PMV). However, when the PMV index is compared to real thermal sensations collected in field studies, it presents significant discrepancies. Rupp and Ghisi (2017) claim that with the adaptive models of thermal comfort, the limitations of Fanger's PMV became clearer.

During the past few years, several researches studied the differences between thermal sensation votes, collected in field studies and PMV: Humphreys and Nicol (1996), De Dear and Brager (1998), Jones

* Corresponding author.
*E-mail addresses:* broday@utfpr.edu.br, evandrobroday@gmail.com (E.E. Broday).

https://doi.org/10.1016/j.ergon.2018.09.007
Received 22 August 2017; Received in revised form 11 September 2018; Accepted 18 September 2018

(2002), Havenith et al. (2002), Peeters et al. (2009), Mors et al. (2011), Maiti (2014), Broday et al. (2014), Yun et al. (2014), Almeida et al. (2016), Gilani et al. (2016), Li et al. (2017) and Broday et al. (2017) state that the calculated value of the PMV does not match the answers obtained in field studies.

The PMV model may underestimate or overestimate the answer provided by people. The result in which the PMV equation predicts more heat than people actually feel, was found by Feriadi and Wong (2004) in residences, Indraganti et al. (2013) in university classrooms, Maiti (2014) in a controlled environment and Kim et al. (2015) in offices. Other studies suggest that the PMV underestimates the actual thermal sensations of people. Al-Ajmi (2010) in a field study in a mosque and Simone et al. (2013) in a supermarket, found that the PMV underestimates the actual thermal sensation, indicating that they are colder than they are really feeling.

These discrepancies mentioned above between real thermal sensation and the PMV may be connected with the incorrect estimation of clothing surface temperature ($t_{cl}$). Studies on people's clothing by using thermal manikins have been developed over the past few years: McCullough et al. (1985), Holmér (1999), Fan et al. (2005), Huang et al. (2014), Nilsson (2007), Wang et al. (2010), Zolfaghari and Maerefat (2010), Bogerd et al. (2012) and Pang et al. (2014). These studies, however, do not show a method for determining the clothing surface temperature ($t_{cl}$).

By using the mathematical Newton's Method, which determines the value for $t_{cl}$ with a minimized error (Broday et al. (2017)), the aim of this study was to propose alternative methods for predict thermal sensation votes, in two ways: $PMV_1$ was determined by replacing the $t_{cl}$ values in the traditional equation of PMV as described by ISO 7730 (2005) and $PMV_2$ was obtained by a multiple linear regression considering the thermal sensation votes, the metabolic rate and the six mechanisms of heat exchange. The effectiveness of $PMV_1$ and $PMV_2$ was verified by comparing the thermal responses calculated by both methods with the responses provided by people.

## 2. Material and methods

The interaction between humans and the thermal environment that surrounds them can only be well characterized if there is an understanding about the necessary variables to describe this interaction. The variables that influence human Thermal Comfort are the environmental and personal ones. The environmental variables are those which relate to the clime conditions in the environment. They include the air temperature ($t_a$), mean radiant temperature ($t_{rm}$), air velocity ($v_a$), and relative humidity (HR).

The personal variables are those pertaining to the individual under study, being the metabolic rate and the clothing thermal insulation. During the actual performance of the volunteers' tasks of this research work, the data on Thermal sensation was collected, pursuant to the scale of 7 points presented within ISO 7730 (2005).

### 2.1. Selection, size-gauging and characterization of the sample

This study was carried out in two different countries, Brazil and Portugal, and counted on two different populations of participants. The first group (G1) was composed of welders, being a 100% male population, whose data were collected in 2013 and previously analyzed in Broday et al. (2017). Nine workers participated voluntarily in this research. These workers represent all workers at the location, and there wasn't calculation of the sample size. A set of 31 environmental and personal data from Thermal Comfort in a naturally ventilated environment were collected.

As 31 measurements were taken and 9 workers were available, three complete measurements were performed with all, and data collection was repeated until the 31 measurements were completed. It was chosen to perform 31 measurements to meet the data normality assumption. When $n > 30$, from a continuous population, the distribution of data is well approximated by normal distribution (Montgomery, 2009).

The research with the second group (G2) was performed in a climatic chamber in Oporto, Portugal, namely at the Occupational and Environmental Risks Prevention Laboratory of the Department of Engineering of the University of Porto (UP), with a population of 100% males, all military personnel in the Army. Six volunteers from the Portuguese Army participated in this research. There wasn't a calculation of the sample size, because all the volunteers provided by the Portuguese Army were analyzed.

In a controlled setting, they performed running tasks, marched carrying loads and without loads inside a climatic chamber with the use of a treadmill that was placed inside the climatic chamber. With this group, a set of 48 measurements was collected, eight times with each volunteer. It is worth observe that all the measurements performed followed the precepts of the International Standardization [ISO 8996, 2004; ISO 9920, 2007; ISO 7726, 1998, and ISO 10551, 1995].

### 2.2. Acquisition of the environmental and personal variables

The G1 measurements were carried out with a group of welders and this procedure is already published in "Comparative analysis of methods for determining the clothing surface temperature ($t_{cl}$) in order to provide a balance between man and the environment" (Broday et al., 2017.) The data collection with G2 (Army Officers) was performed by using a climatic chamber Model *FitoClima 25000*, with the possibility for temperature control between −20 °C to +50 °C and relative humidity up to 98% at Oporto University (UP). Tests were conducted at temperature 22 °C and 40% of RH. This condition was chosen because these two parameters are far close to the temperature and average humidity conditions in Continental Portugal. The climatic chamber had a treadmill, on which the three types of tests were performed: marching without any loads, marching with loads, and running. Fig. 1 shows the Climatic Chamber used in this research.

In marching without any loads, an army officer would walk on the treadmill at a speed of 6 km h$^{-1}$ wearing the military (army) attire. In marching with a load, a backpack would be added, weighing on average 30 kg, which contained all the pieces of equipment that a soldier needs in case he goes to the battle field. Marching with load would include the possession of a weapon. Lastly, the running test was comprised of running on the treadmill. All these types of trials (tests) were commonplace situations to which military officers were subjected to, in the field. Six officers of the Portuguese Army volunteered and each test lasted for about 30 min.

Although all three types of tests were performed, totaling 48 measurements, only 18 measurements were used. The only situation used in

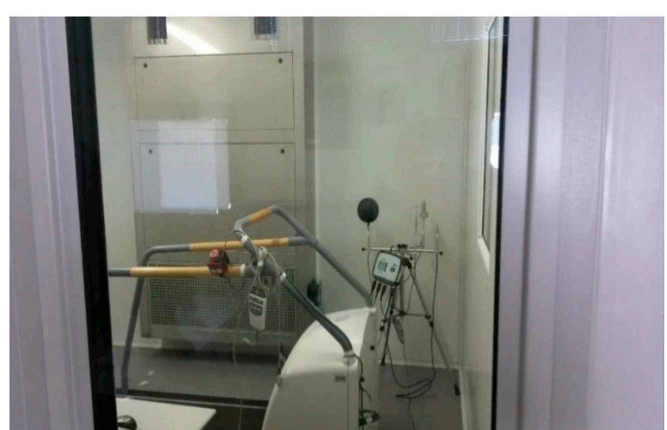

**Fig. 1.** Climatic chamber *FitoClima* 25000, Oporto university.