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Research article

Uncertainty in the evaluation of the Predicted Mean Vote index using Monte Carlo analysis

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ABSTRACT

Today, evaluation of thermohygrometric indoor conditions is one of the most useful tools for building design and re-design and can be used to determine energy consumption in conditioned buildings. Since the beginning of the Predicted Mean Vote index (PMV), researchers have thoroughly investigated its issues in order to reach more accurate results; however, several shortcomings have yet to be solved. Among them is the uncertainty of environmental and subjective parameters linked to the standard PMV approach of ISO 7730 that classifies the thermal environment. To this end, this paper discusses the known thermal comfort models and the measurement approaches, paying particular attention to measurement uncertainties and their influence on PMV determination. Monte Carlo analysis has been applied on a data series in a "black-box" environment, and each involved parameter has been analysed in the PMV range from −0.9 to 0.9 under different Relative Humidity conditions. Furthermore, a sensitivity analysis has been performed in order to define the role of each variable. The results showed that an uncertainty propagation method could improve PMV model application, especially where it should be very accurate (−0.2 < PMV < 0.2 range; winter season with Relative Humidity of 30%).

1. Introduction

Today, in building design, it is increasingly important to ensure indoor space comfort and quality (Barbulescu, 2017) in order to make the environment comfortable for the occupants (Collinge et al., 2014; Andrade and Dominski, 2018), to contain the energy consumption of Heating Ventilation and Air Conditioning systems (HVAC) (European Parliament, 2010), and to reduce GHG emissions (Heredia et al., 2018). Indeed, a considerable part of this consumption is due to indoor thermal comfort maintenance and, today it can be managed by automatic devices (Ku et al., 2015) or people can monitor it through Apps and Smartphone (D'Ambrosio Alfano et al., 2016). At the same time, ensuring thermal comfort is a fundamental parameter in given spaces, also in the framework of sustainability performance assessment (Büyüközkan and Karabulut, 2018) such as in medical operating rooms, it can influence the effectiveness and efficiency of medical procedures (Mendes et al., 2015a,b) because the medical staff, having a higher metabolic rate (Uscinowicz et al., 2015), occupy the same space as patients who have less clothing insulation (Rodrigues et al., 2015). In classrooms, thermal comfort can affect pupil performance and attendance (D'Ambrosio Alfano et al., 2013) and it can influence e performance of student' activities (Katafygiotou and Serghides, 2014; Fabbri, 2013; ter Mors et al., 2011), while in elderly care centres, the comfort can influence the health of the occupants (Mendes et al., 2015a,b). Additionally, proper indoor conditions in offices allow for higher productivity (Andersson et al., 2006), and in common houses, the conditions may contribute to a welcoming atmosphere. In this way, the role of the environmental conditions has been underlined by the 2010/31/EC European Directive on Energy Performance of Buildings that concerns the requirements of energy containment and indoor conditions for building occupants. Particularly in public buildings, users try to improve thermal comfort conditions, wherever possible, by using air-conditioning systems. To this end, due to the common absence of smart control systems, users often incorrectly use HVAC systems, causing the building to be "energy-intensive". It must be highlighted that predicting thermal comfort conditions is a very effective way to also predict potential energy saving (D'Ambrosio Alfano et al., 2014). However, as mentioned above, accurate prediction is a tough challenge, mostly when different comfort requirements occur in the same space (Maiti, 2014).

Thermal comfort is defined as a "subjective judgement or condition of mind when people have to express satisfaction with the surrounding environment" (Fanger, 1970).

Therefore, in this paper, we aim to analyse the further subdivision in

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the classification of the PMV index, proposed by UNI 7730:2006 (Standard UNI EN ISO 7730, 2006), starting from the known uncertainties and to propose uncertainty propagation analysis as a method to better define the data input of Predicted Mean Vote model. In this way, as better defined in the following sections, some modelling assumptions, previously defined by other authors, have been used in the Monte Carlo Simulations, in order to highlight the still unsolved inaccuracies in PMV calculations.

2. Method: Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) mathematical models

The methods able to evaluate thermal comfort have been developed using a robust theory established more than 40 years ago and applied according to the international and European standards requiring very highly skilled people.

To determine comfort, it is possible to use Fanger's method, which has inspired many researchers, who have developed (Höppe, 2002) and applied (Nian and Wang, 2017; Hussin et al., 2015) the method to different conditions and climates (Li et al., 2016; von Grabe, 2016; Bertetto et al., 2014).

The method is based on the energy balance of the human body, as people feel a comfortable environment when the thermal energy generated by their body is equal to that dissipated in the indoor environment. In this way, the widely known Predicted Mean Vote (PMV) index combines the thermal sensation experienced by people with a graduated scale of 7 points, from −3 to 3 (cold = -3; cool = -2; slightly cool = −1; neutral = 0; slightly warm = 1; warm = 2; and hot = 3), that identifies the relative thermal sensations. PMV also considers the percentage of the people who are dissatisfied in the same room through the Predicted Percentage Dissatisfied (PPD), which is discussed in detail in the following section.

The Fanger method has also been adopted by UNI EN ISO 7730:2006 and ASHRAE 55 (Standard ASHRAE, 2013) reference standards, and to better evaluate the indoor spaces. More in particular, the UNI EN ISO 7730 classifies the thermal environment within the three quality categories A, B and C. For each category it should be verified all the criteria at the same time. The classes (A, B and C) are characterised by increasingly restrictive requirements for correspondingly smaller quality indices: Class A: −0.2 ≤ PMV ≤ +0.2; PPD < 6%; Class B: -0.5 ≤ PMV ≤ +0.5; PPD < 10%; Class C: - 0.7 ≤ PMV ≤ +0.7; PPD < 15% (Fig. 1).

Indeed, the comfort classes aim to better define the PMV limits relating to PPD around the neutral zone (0).

In the known Fanger model, the environmental parameters are as follows: air temperature (t_a), mean radiant temperature (t_r), relative humidity (*RH*), and air velocity (v_a). Furthermore, the parameters are necessary to directly measure the characteristics of the confined environment, according to UNI 7726 (Standard UNI EN ISO 7726, 2002).

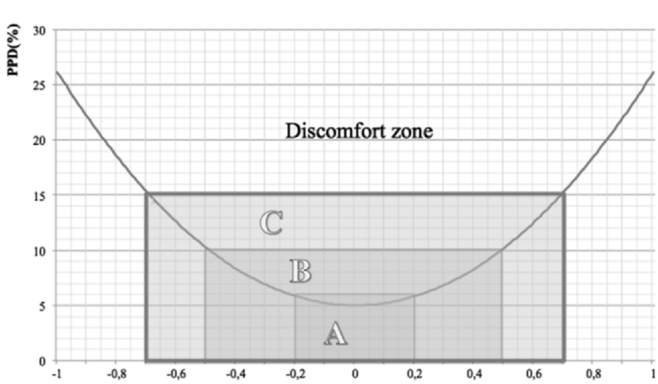

Fig. 1. Comfort class schema according to 7730:2006.

Finally, by using the two parameters tabulated in UNI 7730, related to the metabolic energy (Met) and the clothes thermal insulation (Clo), it is possible to obtain the unknown PMV index.

More in detail, the Met and I_{cl} quantities are strongly linked to the typical physical activity (i.e., office work, theatre, hard work) in confined environments and seasonal clothing, respectively.

Moreover, it is possible to obtain the metabolic rate (Met) using UNI EN ISO 8996 (Standard UNI EN ISO 8996, 2005) and thermal insulation (Clo) using the UNI EN ISO 9920 standards (Standard UNI EN ISO 9920, 2009). However, the recommendations are difficult to apply by building designers because the UNI standards are mostly targeted to medical applications. Thus, the deterministic approach to evaluate the PMV index by UNI EN ISO 7730 is reported in Equation (1).

$$
\begin{aligned}
&PMV = [0.303\cdot\exp(-0.036\cdot M) + 0.028]\,.\\
&\left\{\begin{matrix}(M-W) - 3.05\cdot10^{-3}\cdot[5733 - 6.99\cdot(M-W) - p_a] - 0.42\\ \cdot[(M-W) - 58.15]\\ -1.7\cdot10^{-5}\cdot M\cdot(5867 - p_a) - 0.0014\cdot M\cdot(34 - t_a)\\ -3.96\cdot10^{-8}\cdot f_{cl}\cdot[(t_{cl}+273)^4 - (\bar{t}_r + 273)^4] - f_{cl}\cdot h_c\cdot(t_{cl} - t_a)\end{matrix}\right\}\\
&t_{cl} = 35.7 - 0.028\cdot(M-W) - I_{cl}\cdot\{3.96\cdot10^{-8}\cdot f_{cl}\cdot[(t_{cl}+273)^4 - (\bar{t}_r+273)^4]\\
&\quad + f_{cl}\cdot h_c\cdot(t_{cl} - t_a)\}\\
&h_c = \begin{cases} 2.38\cdot|t_{cl} - t_a|^{0.25} & for \quad 2.38\cdot|t_{cl} - t_a|^{0.25} > 12.1 \cdot\sqrt{v_a}\\ 12.1\cdot\sqrt{v_a} & for \quad 2.38\cdot|t_{cl} - t_a|^{0.25} < 12.1\cdot\sqrt{v_a}\end{cases}\\
&f_{cl} = \begin{cases} 1.00 + 1.290 I_{cl} & for \quad I_{cl} \le 0.078 m^2\cdot K/W\\ 1.05 + 0.645 I_{cl} & for \quad I_{cl} > 0.078 m^2\cdot K/W\end{cases}
\end{aligned}
\tag{1}
$$

Each vote around PMV is useful to identify people who could consider the room “uncomfortable”. Indeed, the Predicted Percentage Dissatisfied (PPD) is an index depending on PMV only, and it can predict the thermally dissatisfied people percentage. The PPD index is calculated according to Equation (2).

$$PPD = 100 - 95\cdot e^{-(0.3353\cdot PMV^4 + 0.2179\cdot PMV^2)} \tag{2}$$

In this regard, it could be very useful to accurately analyse the effect of changing one aspect of the variables on the indoor thermal comfort prediction.

According to other authors, in the PMV calculation, the weight of each parameter must be highlighted. Indeed, although this method is adopted worldwide, as affirmed by Ribeiro et al. (2015), much work must be done to establish measurement uncertainties associated with their use because given measured tabulated values have limited numerical accuracy and uncertainty knowledge is fundamental (Dell'Isola et al., 2012). Furthermore, D'Ambrosio Alfano et al. (D'Ambrosio Alfano et al., 2011) found that the correct evaluation of the operative temperature (t_o), relative humidity (RH) and clothing insulation (I_{cl}) is important due to their strong effect on HVAC design and building energy consumption. In this way, the authors demonstrated how measurement or protocol errors can cause significant mistakes when PMV values are within the range of −0.20 and + 0.20; furthermore, the authors also highlighted how the evaluation of the subjective uncertainty parameters is very significant. In this context, Chaudhuri et al. (2016) demonstrated that the main error in PMV calculations is to make t_r equal to t_a. The weight of the uncertainty contribution caused by t_r was also confirmed by Ekici (2016).

Moreover, as highlighted by van Hoof (van Hoof, 2008), Fanger derived the PMV model based on the concept that the neutral temperature of a large group of people is independent of age, body size, gender, day, geographic location, etc., so the PMV index can only be applied in certain conditions. In the following section, the main uncertainty measure approaches are described.