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The role of measurement accuracy on the thermal environment assessment by means of PMV index

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ABSTRACT

ISO 7730 Standard classifies thermal environments in three categories as a function of the PMV range value, gradually decreasing according to the need of a lower dissatisfied percentage. It is noteworthy that the PMV value is greatly affected by the changes of its independent variables (air temperature, mean radiant temperature, air velocity, relative humidity, metabolic rate and clothing insulation); therefore the accuracy requirements of sensors for the measurement of environmental quantities as well the assessment of other parameters related to the activity and clothing appear a crucial matter. This work deals with a sensitivity analysis of PMV index to the accuracy of its six independent variables. Obtained results clearly show that the widths of PMV ranges fixed for each class in 7730 are near to the PMV uncertainty related to measuring devices accuracy, making often the environment classification a random operation.
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1. Introduction

In the past few years, indoor environmental quality (IEQ), which is the combined result of acoustic, visual and thermal comfort and indoor air quality, has become a frequently debated topic mainly due to its effects on the comfort, health and productivity of occupants in workplaces [1]. In particular, it has been clearly shown that thermal comfort and indoor air quality have to be considered the most relevant facets of the issue because according to Seppänen et al. [2,3], there is a clear relationship between the air temperature and the productivity in indoor environments that is shown by a decrease in performance of 2% per °C increase of temperature in the range 25–32 °C.

Thermal comfort is also strongly related to the energy saving in buildings because it is affected by both the thermo-physical characteristics of the building envelope and the HVAC system. Also, the European Energy Performance of Buildings Directive [4] for the first time has clearly stated that "… this should contribute to avoiding unnecessary use of energy and to safeguarding comfortable indoor climatic conditions (thermal comfort) in relation to the outside temperature…". To meet these needs and harmonise the calculation methodology of the energy performance of buildings, the European Committee for Standardisation (CEN) in 2007 issued the EN 15251 Standard [5] that defines "how to establish and define the main parameters to be used as input for building energy calculation and long term evaluation of the indoor environment. Finally, this standard will identify parameters to be used for monitoring and displaying of the indoor environment as recommended in the Energy Performance of Buildings Directive".

For thermal facets, EN 15251 refers to ISO 7730 Standard [6] based on the predicted mean vote (PMV) index. This sensation index is based on the ASHRAE 7-point scale (see Table 1) and the heat balance of the human body. The Predicted Percentage of Dissatisfied (PPD) is then related to the value of the PMV index.

ISO 7730 [6] introduces a classification of thermal environments based on three levels related to the values of PMV and PPD indices (see Table 2). This classification not only directly modulates the environmental thermal quality as a function of the PMV index [5,6] but also affects indoor temperature design values that have to be used as input data for the building energetic assessment in heated and mechanically cooled buildings (EN 15251 Standard [5] also makes reference to a fourth category, for PMV < -0.7 and PMV > 0.7).

According to the ISO 7730 Standard, the PMV and PPD indices depend upon six quantities: two subjective (the clothing thermal insulation and the metabolic rate) and four physical (the air temperature, the mean radiant temperature, the air velocity and the air humidity) that have to be measured or estimated to calculate the indices that lead to the thermal environment assessment. Consequently, the need of clear procedures for the measurement of the whole of involved variables appears to be a crucial step because the

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Table 1
7-Point ASHRAE thermal sensation scale [6].

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
−1	Slightly cool
−2	Cool
−3	Cold

uncertainty could result in a "class-shift" of the environment with the consequent poor reliability of both comfort and the energetic performance of the building envelope [5,6] assessment. To measure and assess the six parameters by which PMV and PPD are affected, the ISO 7730 Standard makes explicit reference to the ISO 7726, ISO 8996 and ISO 9920 Standards, including the following:

- ISO 7726 [7] deals with the minimum characteristics (required and desired) of instruments to be used for the measurement of physical parameters. There is a certain inconsistency here especially about the mean radiant temperature measurement. In fact, the experimental recommendations only concern the accuracy of the measurement device and do not take into account the accuracy of the measurement procedure and/or other parameters that can affect the measurement reliability. This is not a trivial matter because the mean radiant temperature, as an indicator of radiative thermal flows between the subject and the surrounding environment, is obtained only by indirect measurement [7]. Consequently, making use of different measurement devices/techniques results in different accuracies that are very hard to control [8,9]. In fact, the ISO 7726 reports that if the measurement is carried out by means of a black sphere, the inaccuracy related to the mean radiant temperature can be as high as ±5 °C under comfort and up to ±20 °C under hot stress conditions [7]. This last situation makes the mean radiant temperature measurement a tricky matter because an error that is only within the prescribed accuracy range can result in a dangerous overestimation (up to 5 h) of allowable exposure time calculated according to the ISO 7933 Standard based on the Predicted Heat Strain model [10–12].
- ISO 8996 [13] specifies the methods for the assessment of the metabolic rate and their accuracy on the basis of four different levels (screening, observation, analysis and expertise) and suggests which is the most accurate. It is noteworthy that typical accuracy values are reported in the range of 5–20% according to the method (e.g., tables, heart rate measurement, oxygen consumption measurement, double labelled water method, and direct calorimetric method).
- ISO 9920 [14] deals with the assessment of thermo-physical properties of clothing ensembles devoting special care to the effect of wind action and body movements on the clothing thermal insulation. In fact, the presence of openings (e.g., collars and cuffs) results in additional air flow inside the clothing (pumping effect) that increases with increases in body movement with a consequent reduction of its thermal resistance. A similar effect occurs at high air velocities due to the reduction of clothing layers thickness. To take into account these complex phenomena, special correlations as a function of the relative air velocity and the subject walking speed have to be considered [14–16]. Unfortunately ISO 9920 does not make reference to any accuracy value. This omission appears almost singular because equations used for the correction of the clothing insulation values measured under static conditions, are nonlinear functions of both metabolic rate and air velocity values [14–16]. Therefore, the effect of measurement accuracy of both of these variables (and the others also) on the final value of PMV appears to be a matter that needs to be investigated with absolute care [6].

Table 2
The classification proposed by ISO 7730 [6] and EN 15251 [5] Standards.

Category		Thermal state of the body as a whole	
ISO 7730	EN 15251	Percentage of dissatisfied (PPD), %	Predicted mean vote (PMV)
A	I	<6	−0.20 < PMV < 0.20
B	II	<10	−0.50 < PMV < 0.50
C	III	<15	−0.70 < PMV < 0.70
–	IV	>15	PMV < −0.70 or PMV > 0.70

The role played by the measurement accuracy of physical and subjective parameters involved in the calculation of the PMV index has been rarely investigated, and the little research deals with the index sensitivity to the thermo-physical properties of the building envelope in building performance simulations (BPSs) [17]. To address this lack of research in this field, a sensitivity analysis of the PMV index to the measurement errors of its independent variables is reported in this paper. The obtained results will help to define a better measurement procedure (and/or with a better sensor) to be used and will promote an in-depth discussion on the need of an environment classification based on the narrow PMV values [6]. In our opinion, this topic is crucial because according to the recent finding by the de Dear's group based on the analysis of more than ten thousand questionnaires, A class is found to confer no relative satisfaction benefit to individuals or to realistic building occupancies. In addition, the difference between the B and C classes' satisfaction seems to be too small [18].

2. Methods

Although applied mathematics supplies very rigorous and efficient tools, such as Monte Carlo methods [19] and bifurcations theory [20] to perform sensitivity analyses of numerical models, we preferred to assess the error propagation by changing each quantity affecting PMV within its required and desired accuracy. This method allows for an easy interpretation of the obtained results and allows us to obtain a relative sensitivity scale. According to Fanger's approach [21], based on the heat balance equation of the human body, the same thermal state of a subject as a whole (e.g., the same PMV value) can be obtained for infinite sextets of subjective and physical parameters according to the symbolic equation:

$$\mathrm{PMV} = \mathrm{PMV}(t_a, t_r, v_a, p_a, M, I_{cl}) \quad (1)$$

Due to the large number of involved variables and to avoid a complex analysis and reduce the amount of numerical simulations, the sensitivity analysis was carried out under the same thermal state of the human body for a fixed PMV value. Under these conditions each independent variable involved in equation (1) within its required or desired accuracy, was first "disturbed" one at a time and then all together. This choice allowed a more coherent analysis (the sensitivity analysis can be carried out under homogeneous conditions) and favoured the graphical representation of the results because at a fixed value of $t_r = t_a$, v_a, M and I_{cl}, "iso-PMV" conditions can be depicted on a psychrometric chart. For PMV values investigated in this paper, we worked at a PMV equal to 0, ±0.35 and ±0.60. Such values were chosen to highlight the occurrence of a class shift that is very likely if the PMV value is between border values for the "A to B" categories (±0.20 and ±0.50) or "B to C" categories (±0.50 and ±0.70) transition. Numerical simulations

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