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Thermal sensation models: Validation and sensitivity towards thermo-physiological parameters

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ABSTRACT

Thermal sensation models are commonly used to assess thermal perception in various indoor environments. However, using different models to evaluate the same environment can result in high discrepancies between the models' predictions, as they have been developed based on experimental data from various populations, use diverse input parameters, have different ranges of applicability and use different output scales. In this study, a validation of seven existing thermal sensation models has been performed based on literature data with regards to uniform steady-state and transient indoor environments. The environmental and personal parameters were selected following the experimental protocol and the needed thermo-physiological input parameters were obtained from a thermo-physiological model.

Six models showed a good performance for the analyzed range of conditions, with a mean root-mean-square deviation equal to or lower than 1 thermal sensation unit, even beyond their original range of application. A sensitivity study towards thermo-physiological parameters was also performed, showing that the models are not equally influenced by some inaccuracies in these input parameters. Since thermal sensation models are often associated with different thermal sensation scales, the possibility of applying a scaling to the predictions has been considered. However, the scaling did not consistently improve the predictions accuracy.

1. Introduction

Thermal sensation and thermal comfort are important ergonomic aspects related to the well-being, health, and productivity of occupants of indoor spaces. Thermal sensation is defined as 'a conscious feeling commonly graded into the categories *cold, cool, slightly cool, neutral, slightly warm, warm* and *hot* ' [1] and is often the first step before the estimation of thermal comfort in practice [2,3]. Thermal sensation models are convenient tools that allow the prediction of thermal sensation for various thermal environments without direct enquiry of humans. Most of the existing thermal sensation models have been developed by correlating experimental conditions and/or thermo-physiological parameters of the human body with thermal sensation votes from human subject studies.

Thermal sensation models differ in many aspects, such as conditions for which they can be applied, needed input parameters, thermal sensation scale associated to the predictions, and complexity of models' equations [4]. Although well-established models, such as the models of Fanger [3,5] or Gagge [6], have been evaluated in validation studies against various human subject data (e.g. Refs. [7,8]), some more recent models lack validation for a wide range of conditions. Published validation studies comparing thermal sensation models reported that the predictions were in agreement within one thermal sensation unit with experimental data [9–12]. A recent systematic comparison of seven thermal sensation models for a wide range of air temperatures, clothing insulation, and metabolic levels revealed much higher discrepancies between the compared models [4]. The difference between the predictions from the compared models ranged from 1.0 to even 7.0 thermal sensation units in the common range of air temperature where all models were applicable. Various issues with the comparison of predictions related to different thermal sensation scales have also been discussed. However, this study did not include a validation of the predictions against subjective responses and, therefore, the accuracy of the individual models has not been assessed and the issue of comparing various thermal sensation scales has not been resolved.

The accuracy of thermal sensation predictions, besides the accuracy of the model itself, is strictly connected with the accuracy of the input parameters. The influence of the accuracy of the environmental and

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personal variables on chosen models has been previously assessed [5,8,13,14], providing information about the sensitivity of the model to such parameters. For models using thermo-physiological input data, a sensitivity analysis towards these parameters could improve the interpretation of the results by assessing the influence of input data variability or accuracy (when provided from human subject study measurements or predicted in a thermoregulation model, respectively).

In this study, the accuracy of seven thermal sensation models has been investigated. Eighteen scenarios corresponding to office conditions have been selected from the literature and re-simulated in a model of human thermo-physiology. The accuracy of the thermo-physiological predictions was confirmed by comparing it to the reported experimental data. Then, environmental, thermo-physiological, and personal input data (metabolic activity and clothing) were fed to the seven thermal sensation models and their predictions compared to the corresponding experimental votes. The validation of thermal sensation models has been complemented with a study of the models' sensitivity towards thermo-physiological parameters.

2. Methods

2.1. Thermal sensation models

Thermal sensation predictions were calculated according to seven different models, which are as follows:

- predicted mean vote (PMV) by Fanger [3,5].
- dynamic thermal sensation (DTS) by Fiala [15,16].
- thermal sensation (TSENS) by Gagge [6,17,18].
- thermal sensation (TS) by Zhang [19–21].
- thermal sensation vote (TSV) by Takada [22].
- mean thermal vote (MTV) by Nilsson [23–25] calculated based on the heat transfer for the human body to its environment (MTV_ht) or from environmental input data (MTV_env).

Due to the adopted validation procedure (Section 2.3), adaptive models as well as models considering the influence of one's expectation on thermal sensation were not included in the study.

The PMV model was developed as an extension of the comfort equation describing the heat balance of the human body in a state of comfort [5]. It predicts the mean thermal sensation vote of a group of people using environmental and personal input parameters (Table 1). PMV is included in ISO and ASHRAE standards [1,3] and is widely used by researchers and engineers. The model was developed for steady-state conditions and for thermal sensation within ± 2 thermal sensation units.

The DTS model was developed by correlating experimental thermal sensation votes to various thermo-physiological parameters obtained from simulations with a thermoregulation model [16]. The experiments included both steady-state and transient conditions, therefore, the model integrates both static and dynamic components of thermal sensation predictions. Moreover, the model is suitable for sedentary and exercising scenarios (the experiments underlying the model included metabolic activity up to 10 met).

The TSENS model was rooted to the thermoregulation model by Gagge developed at the Pierce Foundation Laboratory [6]. The TSENS model consists of three parts, i.e. three different equations, with the one effectively chosen based on the relationship between the predicted body temperature and the cold and warm set-points (calculated in the thermoregulation model). Since the most cited reference of the TSENS model is not describing the details of the model development [6], it is not clear what conditions fall within the model's range of applicability.

The TS model developed by Zhang [19–21], also known as the UCB-model (University of California, Berkeley) predicts whole-body thermal sensation based on the local thermal sensations of individual body parts. The experimental data from which the model was derived have

Table 1
General information about the thermal sensation models: range of applicability with respect to air temperature and clothing insulation, type of scale used by the model, and detailed references to equations.

Model	Range of applicability		Type of scale	References to equations
	ta (°C)	Icl (clo)		
PMV	19–28	0.6 (0.0–2.0)	7-point	Fanger [5], chap. 4, eqns. (25), (40) and (41)
DTS	10–48	0.1–1.2	7-point	Fiala et al. [16], eqns. (1)–(10)
TSENS	–	–	11-point	Schweiker et al. (R package „comf") [18]
TS	20–32	0.3 (–1.0)	9-point	Zhang et al. [20], eqn. (5) Zhang et al. [21], section 1.3.1 ("no-opposite model" only) Zhao et al. [31], section 2, appendix part A and C
TSV	20–38	0.3 (–0.5)	7-point	Takada et al. [22], eqn. (1)
MTV_ht	19–29	1.3–1.5	7-point[a]	Nilsson [24], eqn. (2) Nilsson [23], eqn. (6)
MTV_env	19–29	1.3–1.5	7-point[a]	Nilsson [24], eqn. (2) Nilsson [23], eqn. (10a)

PMV – predicted mean vote by Fanger, DTS – dynamic thermal sensation by Fiala, TSENS – thermal sensation by Gagge, TS – thermal sensation by Zhang, TSV – thermal sensation vote by Takada, MTV_ht – mean thermal vote by Nilsson calculated from heat transfer, MTV_env – mean thermal vote by Nilsson calculated from environmental parameters, ta – air temperature, Icl – clothing thermal insulation.

[a] Models based on the modified Bedford scale instead of the ASHRAE 7-point scale.

been collected in tests with cooling/heating applied locally by custom-made air-sleeves. Although originally the TS whole-body thermal sensation was calculated as a weighted average of local sensations [19], a more complex way of calculating the whole-body TS was published afterwards [21]. The model consists now of different sets of equations to be applied when specified conditions are met (e.g. when local thermal sensations are within ± 2 thermal sensation unit or outside this range).

The TSV model was developed as an attempt to assess scenarios with transient conditions based on skin temperature only, using regression coefficients. Although the experimental data underlying the model are limited, the TSV predictions were shown to be accurate for the validation cases presented by the authors of the model for sitting and walking activities [22].

The MTV_ht and MTV_env models are based on the same approach, that is, the equivalent temperature, which is 'the temperature of an imaginary enclosure with the mean radiant temperature equal to air temperature and still air in which a person has the same heat exchange by convection and radiation as in the actual conditions' [23]. The equivalent temperature was correlated with thermal sensation votes from human subjects to enable the assessment of the perception of the environment. The two versions of the model, namely MTV_ht and MTV_env, differ in how the equivalent temperature is calculated. MTV_env is based on environmental parameters only which are often the easiest to define. In the case of MTV_ht, the equivalent temperature is calculated based on the heat transfer between the human body and its surroundings, therefore, it can be regarded as more complex.

Apart from PMV, all chosen models allow the assessment of both steady-state and transient conditions. We computed PMV predictions also for exposures with transient conditions in order to check the accuracy of this model for conditions for which it was not originally developed, as its validity for air temperature ramps has been previously investigated by Schellen et al. [26] and Kolarik et al. [27]. Although the MTV model was developed based on scenarios with steady-state and non-uniform conditions, the author did not specify that it should be used only for steady-state conditions [23]. Moreover, examples of applications of the MTV_ht model in ISO 14505-2 [25] include warm-up and cool-down tests; thus we assumed the model can be used to evaluate transient conditions. The applicability of the TSENS model in

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