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The use of a thermophysiological model in the built environment to predict thermal sensation
Coupling with the indoor environment and thermal sensation

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ABSTRACT

Thermal comfort, influenced by thermal sensation is an important building performance indicator. In this study we discuss the use of a thermophysiological model in the built environment to assess thermal sensation. In the context of this work, the use of CFD to simulate the thermal environmental conditions around a human is analyzed. Experimental data from two independent studies, covering both genders, are used to validate three different, currently available, thermal sensation models: (1) the Predicted Mean Vote index (PMV), (2) the UC Berkeley thermal sensation model and (3) the EN-ISO 14505 standard. Use of such a model is required to link physiological responses to thermal sensation. In this study they have been evaluated for two different steady-state non-uniform thermal environments. The results confirm that the PMV is not capable of predicting whole body thermal sensation when local effects (local skin temperatures and thermal sensation) have a significant influence. The results furthermore indicate that the use of a thermophysiological model (ThermoSEM) in combination with the UC Berkeley model or EN-ISO 14505 standard seems to be promising regarding the prediction of thermal sensation of local body parts and overall thermal sensation under steady-state non-uniform environments. The advantage of using a thermophysiological model in combination with a thermal sensation model is that thermal comfort can be assessed on a more individualized level under complex, daily encountered, thermal environments where local effects play an important role. However, both thermal sensation models need more research before they can be used in daily building design practice.

1. Introduction

Thermal comfort is regarded as one of the important building performance indicators [1]. Therefore, accurate models for predicting thermal comfort during the design phase of a building can be beneficial in avoiding malperformance in the use phase. In addition to the satisfaction of the occupant, reduction of the energy-use is an important aspect in building design, since one-third of the primary energy use in developed countries is consumed by heating, ventilating and air conditioning in residential, commercial and public buildings [2]. Non-uniform and transient thermal environments may reduce the amount of energy needed to realize an acceptable thermal environment compared to a uniform and steady-state thermal environment [3–5]. However, these kinds of thermal environments can cause thermal discomfort [6,7]. On the other hand, some combinations of local and general discomfort factors, for example draught under warm conditions, can be comfortable. Moreover, under asymmetrical thermal environments higher levels of thermal comfort can be achieved compared to uniform environments [3,4]. Thermal comfort and satisfaction with the thermal environment is a complex phenomenon, and therefore complicated to predict in the design phase. This paper discusses, based on two case studies, the use of a thermophysiological model to support and improve the comfort assessment compared to existing, more simplified, thermal comfort models.

1.1. Context

Thermal comfort can be defined in different ways. In ASHRAE [8] thermal comfort is defined as 'that expression of mind which

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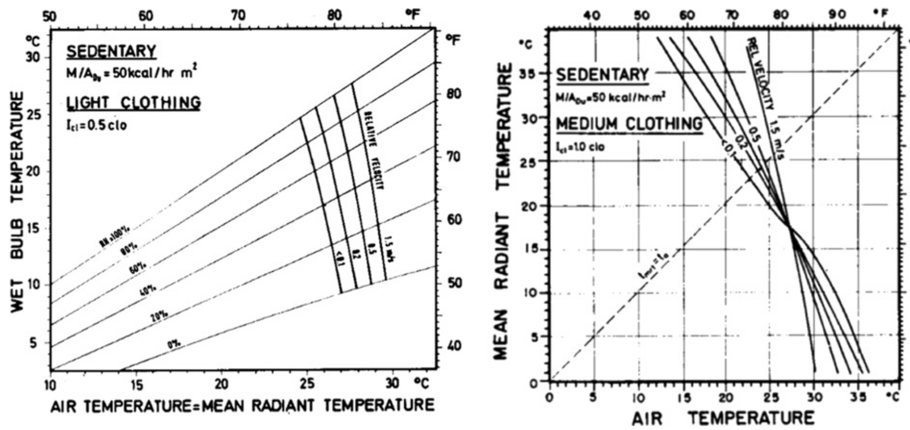

Fig. 1. Comfort lines as derived by Fanger [11].

expresses satisfaction with the thermal environment'. This statement is widely accepted and most used as definition for thermal comfort. Due to the large differences between persons, both psychological and physiological, it is difficult to satisfy everyone in the same room even if the individuals are allowed to change their personal behavior accordingly. In the past many researchers carried out laboratory and field studies to investigate the parameters which affect thermal comfort. The objective was, by using the results, to define conditions which are comfortable and/or acceptable for a major part of the occupants. One of the first studies related to this field was conducted by ASHVE (nowadays ASHRAE) in 1925, resulting in an index for the effective temperature (ET) [9]. In another study conducted by Vernon and Warner [10], the corrected effective temperature (CET) was developed. The purpose of the study of Vernon and Warner was to take the effect of radiation into account. Both methods were used worldwide as an index for thermal comfort [9].

1.2. The PMV model

The most well-known and probably most referred research in the field of thermal comfort was carried out by Fanger in the 1970s [11]. He developed an empirical model which was capable of predicting the overall thermal comfort (whole-body) for a group of occupants. This model was based on regression equations that were derived from subjective responses. Fanger developed a method that could be used by HVAC engineers to determine the optimum environmental conditions (combination of air temperature, mean radiant temperature, relative humidity and mean air velocity) under given boundary conditions (activity level and clothing) to satisfy most persons of a given group of occupants. He defined that if a person is in a thermal neutral condition, that this is also the most comfortable condition. A thermal neutral condition was assumed as the condition wherein a person does not prefer either a colder or warmer environment. In physiology the thermoneutral zone is defined as the range of ambient temperatures without regulatory changes in metabolic heat production or evaporative heat loss [12]. For practical use Fanger composed comfort diagrams; two examples are shown in Fig. 1. The comfort lines are represented by the lines in the diagrams, each point on these lines corresponds with the conditions which are necessary to achieve thermal comfort.

Fanger developed a model that predicts the mean thermal sensation vote (PMV, predicted mean vote), and linked this vote to thermal comfort through the percentage of people who will be dissatisfied with the thermal environment (PPD, predicted percentage dissatisfied). Results of the PMV model are expressed on the 7-point ASHRAE thermal sensation scale (Table 1), consisting of a range from −3 to +3, where negative values correspond to a cold sensation and positive values to a warm sensation. Currently, this scale is widely accepted and used. The PMV model is nowadays the most commonly used model in practice to predict thermal comfort in the design process of a building. Furthermore, the model is often used to evaluate discomfort in an existing situation.

1.2.1. Limitations of the PMV model

Several studies show a good agreement between the predicted mean vote (PMV) and actual mean vote (AMV), where the actual mean vote is the subjective response regarding thermal sensation expressed on the 7-point thermal sensation scale (Table 1). The good agreement is, particularly, found for uniform and steady-state environmental conditions (typical HVAC conditions) [13,14]. Other studies, however, found discrepancies between PMV and AMV due to limitations of the model regarding differences in different subpopulations (e.g. young versus elderly, males versus females) [6,9,15,16]. Since preferences for non-neutral thermal sensations are common and can change over the season, the optimal thermal condition is not necessarily equal to thermal neutrality [17–19]. At the same time, low and high PMV values do not always represent discomfort [15]. Van Hoof et al. [20] conducted an extensive literature survey on the validity of the PMV/PPD model. They compared the PMV/PPD model relation to the actual percentage of dissatisfied. In Fig. 2 the outcomes are presented. They found for naturally ventilated buildings and air-conditioned buildings and in climate chamber settings relations between PMV and PPD that were different from the ones derived by Fanger. One of the deviations found concerns the symmetrical distribution of the model; on the warmer side fewer dissatisfied subjects were found than based on Fanger's model.

Furthermore, van Hoof et al. [20] compared the outcomes of the PMV model with the AMV of test subjects in several different

Table 1
7-point ASHRAE thermal sensation scale [8].

Thermal sensation	Corresponding term
−3	Cold
−2	Cool
−1	Slightly cool
0	Neutral
+1	Slightly warm
+2	Warm
+3	Hot