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Comfort assessment in the context of sustainable buildings: Comparison of simplified and detailed human thermal sensation methods

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ABSTRACT

This paper, based on research conducted under the EU FP7 "SuPerBuildings" project, presents current practice and approaches to comfort assessment and specification. The paper compares and discusses the results of different methods used for the calculation of thermal comfort: Fanger's PMV method, the adaptive predicted mean vote (aPMV) method, a Human Thermal Model integrated in a building simulation environment and the adaptive control algorithm ACA as an example of the adaptive comfort methods are described and applied to a test case. Results show how HTM, aPMV and ACA allow for more flexibility of the indoor conditions than the Fanger's PMV method. These flexible conditions would mean that unnecessary heating and cooling could be avoided in situations where there is still an acceptable degree of satisfaction with the indoor environment. These approaches would therefore help for an assessment in the context of sustainable building assessment, where satisfactory indoor conditions are sought, while ensuring low energy use and running costs and therefore improving environmental and economic performance of the building.

1. Introduction to thermal comfort assessment

Social, economic as well as environmental aspects relate comfort to sustainable building assessment. From a social perspective, unusually high or low indoor temperatures cause discomfort or distress for the occupants (as summarized by, for example Ref. [15]), and they can also be related to health issues, e.g. deaths from cardiovascular diseases are directly linked to exposure to excessively low indoor temperatures for long periods. Linking to an economic perspective, higher comfort levels and higher occupant satisfaction in a working environment have been shown to be directly related to productivity [25,32,33] and they also reduce maintenance costs, as the most common cause of user complain is thermal dissatisfaction. From an environmental point of view, the environmental impacts and use of resources associated to maintaining certain thermal comfort levels are mainly caused by the production, installation, operation and maintenance of HVAC systems [12]. These issues explain the validity of thermal comfort as an aspect of sustainable building [22,27]. This paper, based on research conducted under the EU FP7 "SuPerBuildings" project, compares different methods for predicting the thermal comfort of people exposed to moderate thermal environments, and based on the results discusses the suitability of these methods in design of new and refurbished energy-efficient buildings.

1.1. 'Classic' thermal comfort theory

Thermal comfort describes the synthesized feeling about the body's thermal state. Hensen (1991) [9] defines thermal comfort as "a state in which there are no driving impulses to correct the environment by behaviour". The definition by ASHRAE is "the condition of mind in which satisfaction is expressed with the thermal environment" (ASHRAE, 2004 [24]). Thermal comfort is strongly related to the thermal balance of the body, which itself is influenced by environmental and personal parameters (Fig. 1).

Widely used international standards ISO 7730 (2005) [26] and ASHRAE (2004) [24] utilize Fanger's PMV (Predicted Mean Vote) method (Fanger, 1970) for calculation of thermal comfort. The main thermal comfort standard ISO 7730 "Ergonomics of the thermal

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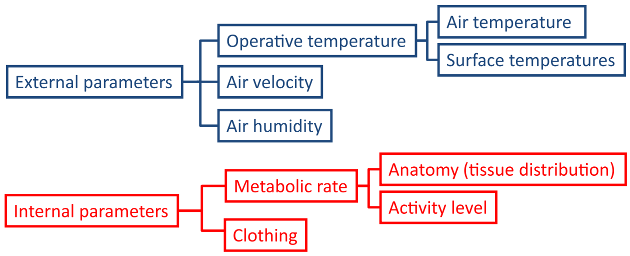

Fig. 1. Boundary conditions for human thermal sensation.

environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria" presents methods for predicting the general thermal sensation and degree of discomfort (thermal dissatisfaction) of people exposed to moderate thermal environments. It also provides methods for the assessment of local discomfort caused by draughts, asymmetric radiation and temperature gradients. The PMV (Predicted Mean Vote) index predicts the mean thermal sensation response of a large group of people according to the ASHRAE thermal sensation scale [2] presented in Table 1. PPD (predicted percentage of dissatisfied) index is a quantitative measure of the thermal comfort of a group of people in a particular thermal environment.

Different categories for the thermal environment can be proposed based on the PMV and PPD values (with some additional factors for local discomfort), for example as described in Table 2. The three different comfort categories A–C proposed in ISO 7730:2005 offer the possibility of being flexible on some of the comfort parameters (air temperature, air velocity, humidity, etc.) depending on the comfort requirements for a particular building or for particular rooms. The higher comfort requirements of a building or living space are, the narrower comfort bands are proposed. The comfort classification in categories is also considered in standard EN 15251:2007 [6] *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*, although the standard tries to distance itself from the implication of closer control being superior, and to avoid the penalization of buildings with less control. However, it is suspected that categories are still used as quality indicators [31], and are in cases used as criteria for thermal comfort in sustainable building assessment methodologies.

Fanger's PMV method is a heat balance model, which views the human being as a passive recipient of thermal stimuli, assuming that the effects of the surrounding environment are explained only by the physics of heat and mass exchanges between the body and the environment. A real human being adapts into changing conditions in the surrounding environment by means of the thermoregulation system. There is currently an international discussion regarding how strict the heat balance theory applies to the evaluation of thermal comfort.

Fanger's PMV method is also applicable only to steady-state, uniform thermal environments. It does not take into account which body parts have a clothing layer. Humphreys and Nicol (2000) [37] have shown that PMV is less closely correlated with the comfort votes than with the air temperature or globe temperature. Humphreys (2000) has also shown that the discrepancy between PMV and the mean comfort vote is related to the mean temperature of the accommodation. In Humphreys and Nicol (2002) [43] the validity of ISO-PMV for predicting comfort votes in everyday thermal environments is examined. This comprehensive exploration shows for example that

Table 1
ASHRAE thermal sensation scale.

Index	Thermal sensation
3	Hot
2	Warm
1	Slightly warm
0	Neutral
−1	Slightly cool
−2	Cool
−3	Cold

- PMV overestimates the warmth sensation at room temperatures above about 27 °C and at higher temperatures the bias becomes severe
- PMV underestimates the cooling effect of increased air movement
- with increased activity corresponding to 1.8 Met, PMV overestimates the sensation of warmth by one scale unit
- PMV overestimates the warmth of people in heavier clothing (over 1.2 clo)

The overall conclusion of Humphreys and Nicol (2002) is that PMV is valid for everyday prediction of the comfort vote only under severely restricted conditions. PMV progressively overestimates the mean perceived warmth of warmer environments and the coolness of cooler environments. In the context of the effect of thermal comfort on sustainability performance, overestimation of PMV can indeed represent an increase on environmental impacts and costs.

1.2. Adaptive thermal comfort theory

Other more recent approaches to comfort evaluation include the adaptive comfort concept, which considers that people are able to adapt to surrounding climatic conditions. The adaptive comfort theory suggests that humans consciously or unconsciously modify constantly our behaviour to adapt to thermal conditions, so the thermal balance equations cannot be strictly applied. There are also researchers that argue that there are cultural and symbolic thermal sensibilities, which cannot be homogenized by standard levels [11]. The adaptive approach to thermal comfort is based on the natural tendency of people to adapt to changing conditions in their environment.

The adaptive comfort concept is based on the findings of field surveys on thermal comfort (Nicol and Humphreys, 2002). According to these studies rational indices such as temperature, humidity, air velocity, clothing and activity are poor indicators of comfortable conditions in buildings. Instead, the comfort temperature has been found to be closely correlated to the mean measured temperature. Different ways of adaptation are e.g. changing the clothing, posture and activity level. The adaptive principle can be expressed as "*if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*"(Nicol and Humphreys, 2002). The adaptive comfort concept is particularly interesting for naturally ventilated buildings, and it is included in standards such as ASHRAE 55:2010 or EN 15251:2007 [6]. Fig. 1

Table 2
Categories of the thermal environment. (ISO 7730:2005).

Category	PPD (%)	PMV
A	<6	$-0.2 < PMV < +0.2$
B	<10	$-0.5 < PMV < +0.5$
C	<15	$-0.7 < PMV < +0.7$