Modeling human thermal comfort

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SUMMARY

Thermal comfort standards determine indoor conditions in buildings as well as the energy consumption for heating and cooling purposes. Existing thermal comfort standards are based on steady-state thermal conditions, and according to recent research these standards can not describe thermal comfort accurately enough with transient boundary conditions. In this paper, a method based on Hui (2003) is presented to calculate local and overall human body thermal sensations in time dependent and non-uniform. In addition, local and overall thermal comfort predictions can be performed based on these thermal sensation values.

INTRODUCTION

Due to increasing awareness of energy consumption and environmental issues, modern buildings have better thermal insulation and ventilation heat recoveries. This lead also to other kind of demands in design phase, especially when low temperature levels are utilised. So far most human thermal comfort models are based on estimates assuming steady-state conditions. However, this often leads to underestimations of local cold or hot surfaces. In addition, that kind of models do not take into account variable conditions.

It is important for people that they feel comfortable with the environment when they are inside buildings. This is regardless of their role (employer, employee, resident) in a specific environment. Therefore, a large amount of research has been conducted in order to establish how the variables creating the environment in a building should be tuned so that the users feel comfortable.

Two widely used standards - ANSI/ASHRAE Standard 55-1992 (Thermal Environmental Conditions for Human Occupancy) [1] and ISO 7730 (Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for thermal comfort) [2] - present a necessary method (originally presented by Fanger in 1972 [3]) for evaluation of moderate thermal environment. When using this method, human's thermal sensation is related to the thermal balance of a body as a whole. This balance is influenced by occupant's physical activity and clothing, as well as the environmental parameters: air temperature, mean radiant temperature, air velocity, and air humidity (ISO 7730). The method is derived for steady-state conditions and - due to treating a human body as whole - is does not allow estimations in any spatially non-uniform conditions.

The aim of this paper is to present a method how to predict human thermal sensation and comfort under transient and non-uniform boundary conditions.
METHODS

The transient and non-uniform thermal environment as well as our body including our clothing are affecting to our thermal sensation and thus our comfort. Since neither the physiology nor the thermal comfort are not uniform to the whole human body, a detailed model is needed in order to estimate realistic thermal sensation. The model used here for estimating thermal sensation and comfort is based on Hui [4]. Basically, the model calculates local human body part’s thermal sensations and local thermal comfort, and based on that information also the overall thermal comfort can be estimated.

Human Body Model

For the estimation of thermal sensation and comfort, a human body model interacting with thermal environment is needed. The body model used here is based on Smith’s model [5]. In this model the human body is divided to 15 parts, and each body part has bone, muscle, fat and skin layers as well as blood circulation. The blood circulation and body core temperature is controlled by a human body control model which acts rather close as the real body “control systems”. For example, when human body core temperature rises above its neutral value, vasodilation occurs and cardial output increases dramatically. Nearly 100% of this increase goes to the skin tissue. For this development, a state of maximum vasodilation is achieved when core temperature reaches 37.2°C. At this state, the total skin blood flow rate may be as much as seven times its basal value. This increase in cardiac output is distributed to the individual body parts according to surface area.[5] A more detailed description of that model is presented by another paper by Tuomaala et al. in this congress.

Figure 1. The human model is divided to 15 parts.

Thermal sensation and comfort prediction model

The model used in this study is based on Hui’s study [4] which includes results from 109 human subject tests that were performed under non-uniform and transients conditions in the UC Berkeley Controlled Environmental Chamber. In those experiments, local body surfaces of the subjects were independently heated or cooled while the rest of the body was exposed to a warm, neutral or cool environment. Skin temperatures, core temperature, thermal sensation
and comfort responses were collected at one- to three-minute intervals. [4] The Figure 1 shows the flow chart how the overall thermal comfort is calculated.

Figure 1. Overall thermal comfort calculation flow chart.

The local sensation model is a function of skin and core temperature and their rates of change (Eq. 1). The model has a sub-model to each body part, and together they capture the asymmetry of thermal conditions.

\[
S_i = f\left(T_{\text{skin}}, \frac{dT_{\text{skin}}}{dt}, T_{\text{core}}, \frac{dT_{\text{core}}}{dt}\right) (1)
\]

Local comfort is predicted from local sensations and average of all body's local sensations, and the overall sensation model integrates the local sensations. The whole body comfort model integrates the local comfort values. Overall thermal sensation is modelled as a weighted average from the local sensations:

\[
S_o = \frac{\sum \text{weight}_i \cdot S_{ij}}{\sum \text{weight}_i} (2)
\]

where \text{weight} is a function between the difference of local sensation and geometrical average of all sensations.

\text{weight} can be calculated for each body part:

\[
\text{weight}_i = a \cdot (S_{ij} - \overline{S}_j) (3)
\]

where \(a\) is a factor depending on local and overall sensation, \(\overline{S}_j\) average value from all local thermal sensation factors.

For some body parts (e.g., chest and back) the weight is higher than for other parts. The weight is higher either due to body part size or sensitivity. Some body parts are not behaving similarly if the local sensation is higher or lower compared to average thermal sensation. One body part may be more important to determine cold than warm sensation. As the \text{weight} is a function between the difference of local and geometrical average of all sensations it assigns
larger weights when the local thermal sensation is opposite to rest of the body's thermal sensation.

Sensation can have values from -4 to 4. Value 4 corresponds very hot, 3 hot, 2 warm, 1 slightly warm and 0 neutral.

Local comfort is a function of local sensation and overall sensation:

$$ C_h = f(S_{lj}, S_o) \quad (4) $$

and overall thermal sensation is a function of local thermal comfort. Overall thermal comfort is evaluated from two rules:

• Rule 1: Overall comfort is the average of the two minimum local comfort votes unless Rule 2 applies.

• Rule 2: If the following criteria are met the overall thermal comfort is average of the two minimum and the maximum comfort vote.
  Criteria are:
  • the second lowest local comfort vote is higher than -2.5
  • the person has some control over his/her thermal environment or the thermal conditions are transient

If both hands or both feet comprise the two most uncomfortable body parts ignore the second lowest hand or foot comfort value, and use the third lowest comfort vote as the second lowest vote in both Rules 1 and 2.

Comfort can have values from -4 to 4 and value 4 corresponds to very comfortable, 2 comfortable and 0 neutral.

RESULTS

When the body surface temperatures and core temperature are close to neutral conditions, local thermal sensations are close to zero, thus no big thermal sensations. The local and overall comfort values are close to 2, indicating comfortable thermal conditions, Figure 2. It should be noted that according to [4] the very comfortable conditions (value 4) was only recorded in transient conditions when thermal stress is suddenly removed.
When body temperatures are decreasing in cold environments, the sensation and comfort values are negative. If body part temperatures are decreasing by 4 degree the local thermal comfort is lower than -2 indicating uncomfortable cold, Figure 3. In calculations for Figure 3 it was assumed that the core temperature is not changed.

Figure 2 Local sensations and comfort values close to thermal neutral area.

Figure 3 Local sensations and comfort values when body surface temperatures are in average 4 degrees lower than thermal neutral area. Core temperature was not changed.
Head of human body is sensitive to temperature changes. If all other body parts are kept in thermal neutral area, but head, face, breath and neck temperature is decreasing 2°C lower than thermal neutral temperatures it is affecting overall comfort dramatically, Figure 4.

Figure 4 Local sensations and comfort values when head are is 2 degrees Celsius lower than the thermal neutral area, other body parts remained close to thermal neutral conditions. Core temperature was not changed.

DISCUSSION

The model based on Hui’s study [4] gives new understanding about the thermal comfort and how changes in thermal environment are effecting on human thermal sensation. The new knowledge is valuable in designing and developing new indoor environments. It would also help us to find out the most suitable renovation alternatives for old buildings in respect to indoor environment comfort.

REFERENCES

2. ISO 7730:1994 (E), Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for thermal comfort, International Organization for Standardization, Switzerland.