Building and Environment 72 (2014) 300–308

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Thermal sensation and comfort models for non-uniform and transient environments, part IV: Adaptive neutral setpoints and smoothed whole-body sensation model

Yin Zhao [a], Hui Zhang [b,*], Edward A. Arens [b], Qianchuan Zhao [a]

[a] Center for the Intelligent and Networked Systems, Department of Automation and TNList, Tsinghua University, Beijing 100084, China
[b] Center for Built and Environment, University of California, Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Received 8 August 2013
Received in revised form
23 October 2013
Accepted 5 November 2013

Keywords:
Set-points adaption
Neutral set-points
Local sensation
Whole-body sensation
Sensation jump
Sigmoid function smoothing

ABSTRACT

Models for body-segment-specific thermal sensation and comfort were put forward in 2010 in a three-part series in this journal. The models predict these subjective responses to the environment from thermophysiological measurements or simulations of skin and core temperatures, and apply to a range of environments: uniform and non-uniform, transient and stable. The models are based on unique experimental data, and formulated in a rational but piecewise structure that simplifies further validation and refinement. The models have received much attention and this experience has pointed out two issues needing improvement at the fundamental level. This paper presents solutions to these issues:

a) In the local sensation model, the neutral set-points for segment skin temperatures are sensitive to the distribution of clothing insulation provided by different clothing ensembles, and to metabolic rate. A new calculation sequence automatically creates accurate segment set-points for specific clothing and activity levels.
b) In the whole-body (overall) sensation model, the piecewise model construction produced unrealistic jumps in output at the transitions between pieces. A smoothing technique using the model's key organizational variables was developed and incorporated into the original model.

Several corrections and clarifications are listed in an Appendix.

1. Introduction

A three-part series in this journal has presented the development of models to predict, for different parts of human body, the local thermal sensation (Part I) [1], local thermal comfort (Part II) [2], and whole-body sensation and comfort for any combinations of these (Part III) [3]. The models were based on an extensive set of human subject tests conducted by the authors in 2001–2003, together with diverse findings from the literature. The subjects were engaged in sedentary activities in a range of environments, uniform or non-uniform, stable or transient.

Part I described local sensation models for 19 body parts. Human thermal sensation responses are determined by the character of thermoreceptors in the skin and core, which are sensitive to the rate of change of temperature. The models were formulated from such information together with transient tests on human subjects. The models are based on the logistic function, using as inputs: local skin temperature, mean skin (core) temperature, their derivatives, and each part's local set point, i.e. the part's local skin temperature when the sensation for the part is neutral. Impacts of whole-body thermal state, warm–cold asymmetry and dynamic responses in transient conditions are incorporated into the models. For the set point of each body part, separate 6-h-long tests under neutral conditions were performed to obtain segment-set-point temperatures.

In Part II, the local comfort models were developed from results in the literature and the authors' chamber experiments. The comfort models are based on local thermal sensation, and consider warm–cold asymmetry, the offset between comfort and neutrality which had been noticed by many researchers [4], and the effects of the overall thermal sensation on comfort magnitude [5]. Logistic-adapted linear models and exponential and quadratic equations were regressed to describe comfort for the different body parts.

Part III developed the models for both overall (whole-body) thermal sensation and for overall comfort. The overall thermal sensation model considers all the body segments' sensations by

* Corresponding author. University of California at Berkeley, Department of Architecture, 390 Wurster Hall #1839, Berkeley, CA 94720, USA. Tel.: +1 925 376 7876.
E-mail address: zhanghui@berkeley.edu (H. Zhang).

0360-1323/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.buildenv.2013.11.004

using a piecewise regression of experimental data including both uniform [6] and non-uniform tests [7]. All model coefficients were separately regressed and the results were satisfying.

The local thermal sensation models are the key to the entire series of models. During application in practice, two types of deficiencies were found in these models.

The first deficiency was in how neutral set-point was determined for calculating local sensation under different clothing levels and metabolic rates. The setpoints are the neutral skin temperatures for each body part. These temperatures depend on the local clothing and met rate of the body part, not just overall clothing insulation (clo units), as many combinations of local clo can produce the same overall clo value. The sensation model is sensitive to such differences in local clothing.

The other deficiency was caused by the discontinuity in the overall sensation model results. Across a range of environments, a sudden jump in overall sensation might appear even though the environment and local sensations was changing smoothly. This was caused by transitions in the piecewise formulation of the models described in papers Part I and Part III [1,3].

In this paper, we present improvements that deal with these two problems. The Appendix presents additional corrections and clarifications to the models that bring them up to date.

2. Set-point adaption

The neutral setpoints can be brought closer to reality through two steps: 1) determine the environmental temperature for a uniform environment that produces a neutral overall sensation for the clothing ensemble's overall clothing insulation. The PMV model [8] may be used for this. 2) Obtain the local skin temperatures that occur in that uniform neutral environment under the actual distribution of local clothing. A multi-segment physiological model is used for this. A description how to perform the two steps is provided below.

A given clothing ensemble will consist of several local insulation levels, which have been traditionally averaged into an overall clo value. Overall clo is used in models such as PMV and 2-node [9]. Table 1 contains the neutral-sensation air temperatures calculated by the PMV model for specific combinations of overall clo and met values. Intermediate values may be interpolated.

The multisegment physiological model then uses that neutral air temperature, and the ensemble's real distribution of segment-specific clothing values, runs for several hours to obtain the local neutral skin temperature for each body segment. The local sensation model uses these neutral skin temperatures as setpoints for predicting the local sensations for the given clothing ensemble under any combination of environmental conditions.

The above explanation is in terms of clo distribution. Metabolic heat generation will also not be distributed uniformly across the whole body and may differ by activity (e.g., walking liberates proportionally more heat in leg muscles than do sedentary activities). The structure of the sensation model as currently formulated may not account for activities that differ appreciably from sedentary. The empirical data upon which the model is based were obtained under sedentary test conditions, in which metabolic heat generation fits a certain pattern. For predicting local setpoints and thermal sensation under other exercise states, new empirical data will be needed [10].

Table 1
Ambient temperatures (°C) producing neutral sensation for given metabolic rates (met) and levels of overall clothing insulation (clo), calculated using the PMV model.

Met/clo	0.5	0.6	0.7	0.8	0.9	1
0.8	28.30	27.90	27.45	27.00	26.60	26.20
0.9	27.35	26.80	26.30	25.80	25.20	24.70
1.0	26.00	25.50	24.95	24.40	23.85	23.30
1.1	25.40	24.80	24.20	23.60	23.00	22.40
1.2	24.75	24.05	23.45	22.80	22.20	21.55
1.3	24.05	23.35	22.70	22.00	21.35	20.70

3. Smoothed overall sensation model

The overall sensation model consists of 7 sections (Table 2). During the development of the model, each section's parameters and accuracy were intensively validated. However, during simulations with the combined model, unrealistic jumps would appear in the output: when the environment is changing smoothly, the overall sensation might exhibit a sudden jump. In this section, we present a smoothing method to solve this problem without modifying the main parts of the original model.

Note that the Appendix describes small corrections to the model that are incorporated in the discussion below. They should be noted when comparing against Part III [3] and Part I [1].

3.1. "Jumps" in the model

The sudden jumps are caused by the discontinuity of the model. The continuity of a function is defined as follows, in epsilon delta language:

Given a certain c in the function domain, for any number $\varepsilon > 0$, there always exists some number $\delta > 0$ such that for all x in the domain of f with $||x - c|| < \delta$, the value of f satisfies $||f(x) - f(c)|| \le \varepsilon$.

The jump in the model means no matter how small $\delta > 0$ is, there is a scalar $M > 0$, such that $||f(x) - f(c)|| \ge M$. These cases generally exist when conditions change from one piece of a model to another, which will be analyzed below. In addition, we intend the proposed overall sensation model to be C-1 continuous, meaning the first derivatives of the model should also be continuous. This condition is stricter than the continuity defined above. Intuitively, C-1 continuity means the model is not only continuous but smooth. It is reasonable to expect that the overall thermal sensation should change smoothly with smooth changes in the local sensations.

We categorize the reasons of the sudden jump into two types: jumps **between** pieced models and jumps **within** a pieced model. The main idea in smoothing is to find key continuous variables and conditions that determine the jumps between pieces of model and to smooth the jumps by a smoothing function of these variables and conditions.

We first denote the model in a concise way, i.e. model index shown in Table 2, to reference them. The model 1–4 represent situations when all body parts feel warm or cool. They are presented in Fig. 1. Model 5–7 represent situations when the opposite sensations (warm and cool) for different body parts exist simultaneously. Term "dominant" or "dominate body parts" referred later indicate dominant body parts, i.e. chest, back, and pelvis. More detailed descriptions for these 7 models are presented in [3].

Table 2
Representation of the model.

Model index	Name of each pieced model
1	No-opposite-sensation high-level warm
2	No-opposite-sensation high-level cold
3	No-opposite-sensation low-level warm
4	No-opposite-sensation low-level cold
5	Opposite-dominated cold
6	Opposite warm
7	Opposite cold