Title	New human thermal model integrated in a building simulation environment for a more accurate estimation of thermal comfort in transient conditions
Author(s)	Holopainen, Riikka; Tuomaala, Pekka
Citation	SB 10 Finland Sustainable Community - buildingSMART, Espoo, Finland, September 22 - 24, 2010
Date	2010
Rights	Copyright © [2010] Finnish Association of Civil Engineers RIL. This article may be downloaded for personal use only

New human thermal model integrated in a building simulation environment for a more accurate estimation of thermal comfort in transient conditions

Riikka Holopainen
Senior Research Scientist
VTT Technical Research Centre of Finland
Finland
riikka.holopainen@vtt.fi

Pekka Tuomaala
Senior Research Scientist
VTT Technical Research Centre of Finland
Finland
pekka.tuomaala@vtt.fi

Summary

This paper presents the basic features of the new VTT Human Thermal Model (HTM), the adopted heat and mass transfer models and the new way of estimating human thermal sensation and comfort. A test case with a series of stepwise changes in environmental conditions including neutral, low and high ambient temperatures has been simulated with HTM. The simulated skin temperatures have been compared to original measured values, and the calculated thermal sensation and comfort has been compared to results calculated with a traditional way of estimating human thermal comfort (Fanger method). The results show that simulated skin temperatures give a good resemblance with measured values. The calculated thermal sensation by HTM show that the Fanger method is not sufficient for estimating the human thermal comfort in transient conditions.

Keywords: thermal sensation, thermal comfort, human thermal model

1. Introduction

Increasing demand in improving energy efficiency of building and construction sector puts more and more pressure to develop new concepts for both new buildings and renovation projects. At least the typical design and dimensioning criteria of the conventional structural and building service system concepts in more energy efficient future buildings need to be verified to avoid problems in thermal indoor environment. In other words, increasing concern about building sector energy consumption and the simultaneous need for an acceptable thermal environment makes it necessary to estimate in advance what effect different thermal factors will have on occupants [1].

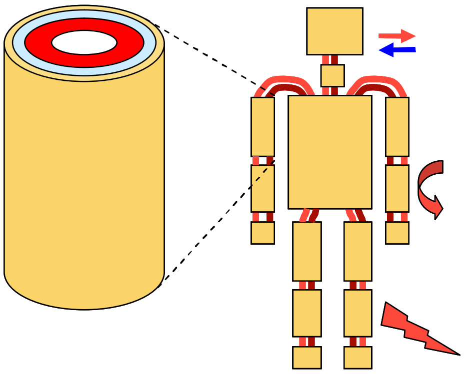
New heating and cooling system design data is needed for utilization of renewable low-temperature heating and high-temperature cooling energy in very-low energy houses. This design data must also ensure the overall thermal comfort of the building user. There is a need for a more accurate human thermal comfort calculation than the commonly used Fanger model.

A new human thermal model, HTM, has been developed at VTT for predicting thermal behaviour of the human body under both steady-state indoor environment boundary conditions. As a module of the VTT House building simulation tool, HTM can be used for estimating more accurately than before the effects that the building structures, as well as building service systems, will have on occupants under different conditions.

2. Human Thermal Model

2.1 Tissues and calculation network

Fig. 1 HTM body part composition



The new VTT Human Thermal Model, HTM, is based on true anatomy and physiology of the human body, and it estimates human body tissue and skin temperature levels. HTM divides the human body into sixteen different body parts each being further sub-divided typically in four realistic tissue layers (bone, muscle, fat, and skin) by concentric cylinders (Figure 1). The functional tissue layers are also connected to adjacent body parts by a blood circulation system, which has been used for physiological thermoregulation of the whole body.

HTM is a module of a non-commercial VTT House building simulation tool developed at VTT. Thermal interaction between the human body and the surrounding space has been modeled by including convective, radiation, and evaporative heat transfer in the model. This new approach allows true physical and physiological estimates of effects that alternative building structures, as well as building service systems, will have on occupants under different conditions.

Table 1 HTM body part dimensions

Body part	Radius, cm	Length, cm
head	9.4	18.8
neck	5.7	8.3
chest	14.6	29.7
pelvis	16.1	29.7
upper arm	4.9	30
lower arm	4.0	25
hand	3	18
thigh	6.3	40
calf	4.2	39
foot	3.6	24.1

Table 2 HTM tissue distribution

Tissue type	Tissue mass, kg	Share of the total body mass
brains	1.4	1.8 %
viscera	11.6	14.9 %
lungs	3.0	3.9 %
bone	13.3	17.0 %
muscle	26.5	33.9 %
fat	14.8	18.9 %
skin	3.5	4.5 %
blood	4.1	5.3 %
total	**78.2**	**100 %**

A finite-difference method with free description of the thermal calculation network generation was used to develop the new thermal model. The human body is discretized into a number of smaller nodes (with thermal mass) and inter-nodal connections (thermal conductance). This network represents tissue sections, blood vessels, segment of the respiratory track, or portion of an internal organ. Energy, momentum, and mass balance equations of the human thermal model calculation network, incorporating the environmental conditions, can then be solved for calculating e.g. the skin temperatures of separate body parts.

Each body part has individual anatomic tissue distributions, and these tissue types are described by the final calculation network. Table 2 presents the HTM body part dimensions and Table 3 presents the tissue distribution.

Because of simplicity, the individual body parts are mainly approximated by concentric cylinders describing the human body tissue type distribution. The only exception is the head, which is approximated by concentric spheres. The basic idea is to model the body parts mimicking the true anatomy as a single bone core surrounded by muscle, fat, and skin layers.

2.2 Blood circulation and control system

The physiological control system of a human body uses thermal input in the form of local tissue temperatures to determine the appropriate thermoregulatory responses. Possible physiological responses include sweating, shivering, and the increase or decrease in blood flow rates to the skin. How the thermal state of the passive system changes, and to what degree, depends on the thermoregulatory responses initiated by the control system.

Between 50 % - 80 % of the tissue heat transfer occurs due to the blood circulation [2].The blood circulation system of the human body consists of macrocirculation (large vessels with diameter > 300 μm) and microcirculation (capillary bed).

Table 3 HTM skin blood flow rates, cm^3/s

Body part	Basal blood flow	Max. constrict	Max. dilate
head	1.59	1.25	3.89
neck	0.09	0	0.71
torso	1.59	0	15.33
upper arm	0.25	0	2.31
lower arm	0.14	0	1.54
hand	0.31	0.17	1.24
thigh	0.40	0	3.46
calf	0.18	0	2.29
foot	0.26	0.08	1.47
total	**6.4**	**1.8**	**44.6**

Table 4 HTM total blood flow rates, cm^3/s

Body part	Basal blood flow	Max. constrict	Max. dilate
head	15.31	14.98	17.61
neck	0.39	0.30	1.01
torso	55.05	53.04	68.79
upper arm	1.07	0.77	3.13
lower arm	0.60	0.39	2.00
hand	0.38	0.25	1.31
thigh	1.72	1.28	4.78
calf	0.76	0.45	2.87
foot	0.37	0.20	1.58
total	**80.6**	**75.0**	**118.7**

Vasodilation refers to the widening of blood vessels resulting from relaxation of smooth muscle cells within the vessel walls, particularly in the large arteries, smaller arterioles and large veins. The process is the opposite of vasoconstriction, or the narrowing of blood vessels. The thermal signals affect the quantity of blood flowing in the muscles tissue by increasing or decreasing the amplitude of the pulsating cardiac output and the skin blood flow by the mechanisms of vasodilation and vasoconstriction, which result in a higher or lower skin blood flow, respectively. The correlations depend on the mean skin temperature and on the head core temperature.

As human 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. As mean skin temperature falls below its neutral value, vasoconstriction occurs. Skin blood flow, and therefore, cardiac output, decreases. At a state of maximum vasoconstriction, assumed to occur when mean skin temperature falls to 10.7°C, the total skin blood flow rate may be as low as one eight of its basal value [3]. Tables 3 and 4 present the basal and vasomotor blood flow rates of each body part: Table 3 the skin blood flow and Table 4 the total blood flow.

If the vasodilation thermoregulatory function is not sufficient to reject the heat from the body, the sudomotor function is triggered where heat is lost by sweating. On the other hand, if vasoconstriction is not able to keep the heat in the body, metabolic thermoregulatory function takes place; the body will start shivering in order to heat the body. The sweating and shivering effects are modelled in HTM according to Smith [3].

2.3 Thermal sensation and comfort calculation

Table 5 Thermal Sensation index by ASHRAE

Index	Thermal sensation
3	hot
2	warm
1	slightly warm
0	neutral
-1	slightly cool
-2	cool
-3	cold

The commonly used Fanger’s PMV (Predicted Mean Vote) model combines four physical variables (air temperature, air velocity, mean radiant temperature, and relative humidity), and two personal variables (clothing insulation and activity level) into an index that can be used to predict the average thermal sensation of a large group of people in a space. The PMV index predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale
(Table 5).

PPD (Predicted Precentage of Dissatisfied) is a quantitative measure of the thermal comfort of a group of people at a particular thermal environment. Fanger related PPD to PMV as follows:

$$\mathrm{PPD} = 100 - 95e^{-\left(0.03353\,PMV^4 + 0.2179\,PMV^2\right)} \tag{1}$$

Fanger’s thermal model is applicable only to steady-state, uniform thermal environments. It also does not take into account which body parts have a clothing layer.

Table 6 Thermal Sensation index by Zhang Hui

Index	Thermal sensation
4	very hot
3	hot
2	warm
1	slightly warm
0	neutral
-1	slightly cool
-2	cool
-3	cold
-4	very cold

Zhang Hui et. al [5] have developed a new thermal sensation model to predict local and overall sensations, and local and overall comfort in non-uniform transient thermal environments. Zhang Hui represents the local thermal sensation by a logistic function of local skin temperature. When the local skin temperature differs from the local ski temperature set point, the sensation reaches the sensation scale limits +4 and -4 (Table 6). The overall thermal sensation is a weighted average of all the local sensations:

$$\text{overall thermal sensation} = \frac{\sum\left(weight_i S_{local.i}\right)}{\sum weight_i}\ , \tag{2}$$

where $S_{local,I}$ represents the local sensation for segment *i*, and $weight_i$ is the weighting factor for that segment (see Table 7). PPD-calculation of HTM is based on the thermal sensation on each skin surface.

The local comfort is a function of local and overall thermal sensations. The overall comfort is the average of the two minimum local comfort votes or unless if the following criteria are met:

i) the second lowest local comfort vote is > -2.5
ii) the subject has some control over his/her thermal environment or the thermal conditions are transient,

then the overall comfort is calculated as the average of two minimum votes and the maximum comfort vote. Table 8 gives the used grading of the thermal comfort.

The thermally neutral set point temperatures for each body part by Zhang Hui were calibrated for a naked HTM with simulated skin temperatures in a thermoneutral environment (temperature 29 °C, relative humidity 45 %). The original and calibrated set point temperatures are presented in Table 9.

Table 7 Thermal Sensation weighting factors

Body part	Weighting factor
head	0.07
chest	0.35
lower arm	0.14
hand	0.05
thigh	0.19
calf	0.13
foot	0.07

Table 8 Thermal Comfort index by Zhang Hui

Index	Thermal comfort
4	very comfortable
+0	just comfortable
-0	just uncomfortable
-4	very uncomfortable

Table 9 Original and for HTM calibrated set point temperatures for calculation of thermal sensation

Body part	Zhang Hui set point temperature	HTM set point temperature
face	35.2	35.2
head	35.8	35.3
neck	35.8	35.1
chest	35.1	34.0
back	35.3	34.2
pelvis	34.3	34.1
upper arm	34.2	34.1
lower arm	34.6	33.8
hand	34.4	33.7
thigh	34.3	33.4
calf	32.9	33.1
foot	33.3	32.1

3. HTM Simulation results

3.1 HTM tissue temperature simulation

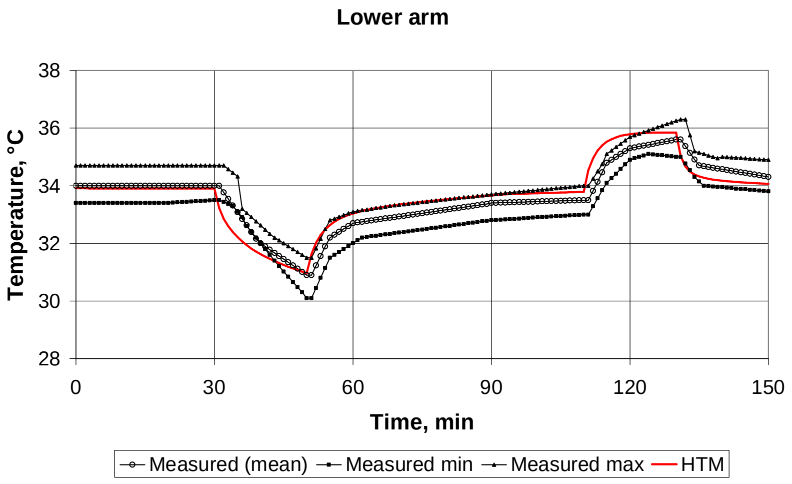


Fig. 2 Simulated and measured lower arm temperatures during Munir test schedule

Munir et al. have examined transient skin and rectal temperature variations under a series of stepwise changes in environmental conditions including neutral, low and high ambient temperatures. The measurements were made with fifteen healthy male students, whose average age was 23.5 years, average weight 66.6 kg and average height 1.70 m. The students were exposed to a series of conditions: 1) a thermally neutral condition (29.4ºC) for 30 minutes, 2) 20 minutes in a low surrounding temperature (19.5ºC), 3) a neutral condition for 60 minutes, 4) 20 minutes in a high surrounding temperature (38.9ºC), and 5) 20 minutes in a neutral condition. All subjects wore only trunks (undershorts) and remained sedentary under a thermally neutral condition (29.4 ºC, 47% rh) for 1 hour before the experiment began. During the experiments, the core and skin temperatures and the environmental conditions (air temperature, relative humidity, globe temperature, and wind velocity) were measured continually at intervals of 10 s. [4]

The test schedule was simulated with HTM. The average mean relative second norm of difference between measured and simulated skin temperatures was 1.45 %. As an example, Figure 2 shows how the simulated HTM lower arm skin temperatures (HTM) correspond with the minimum, maximum and average measured values.

3.2 Thermal sensation and comfort

Figure 3 shows the thermal sensation and Figure 4 shows the thermal comfort during Munir's test case. In Figure 5 the Predicted Precentage of Dissatisfied, PPD, by Fanger's method is compared to HTM PPD calculation.

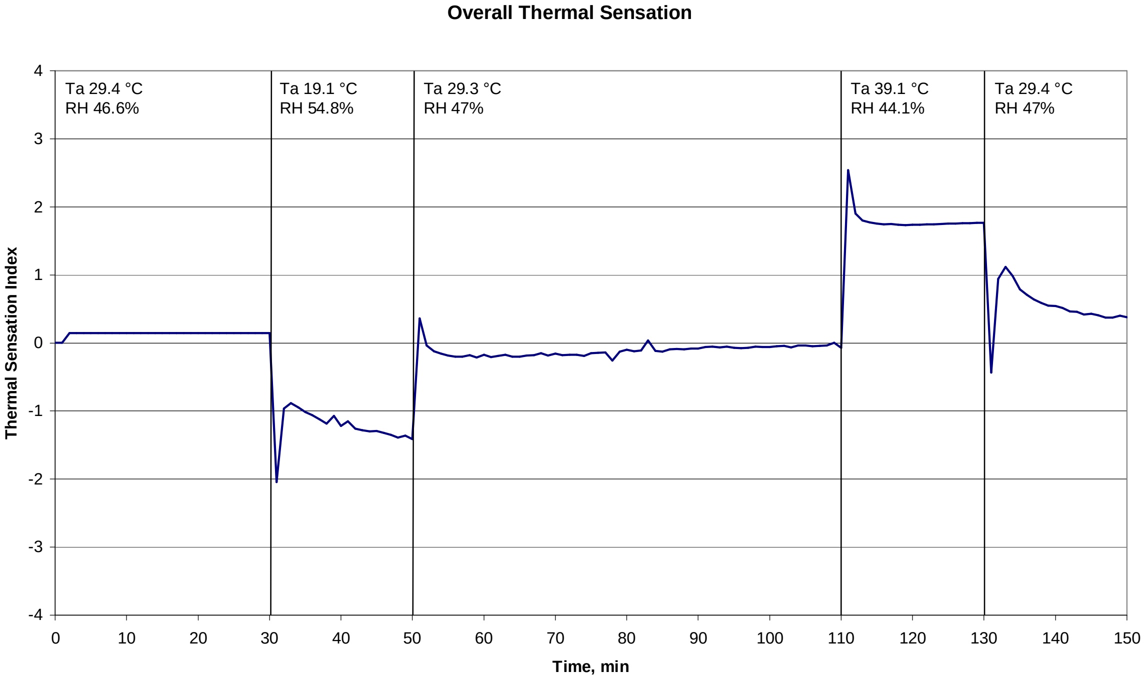


Fig. 3 Simulated thermal sensation during Munir test schedule

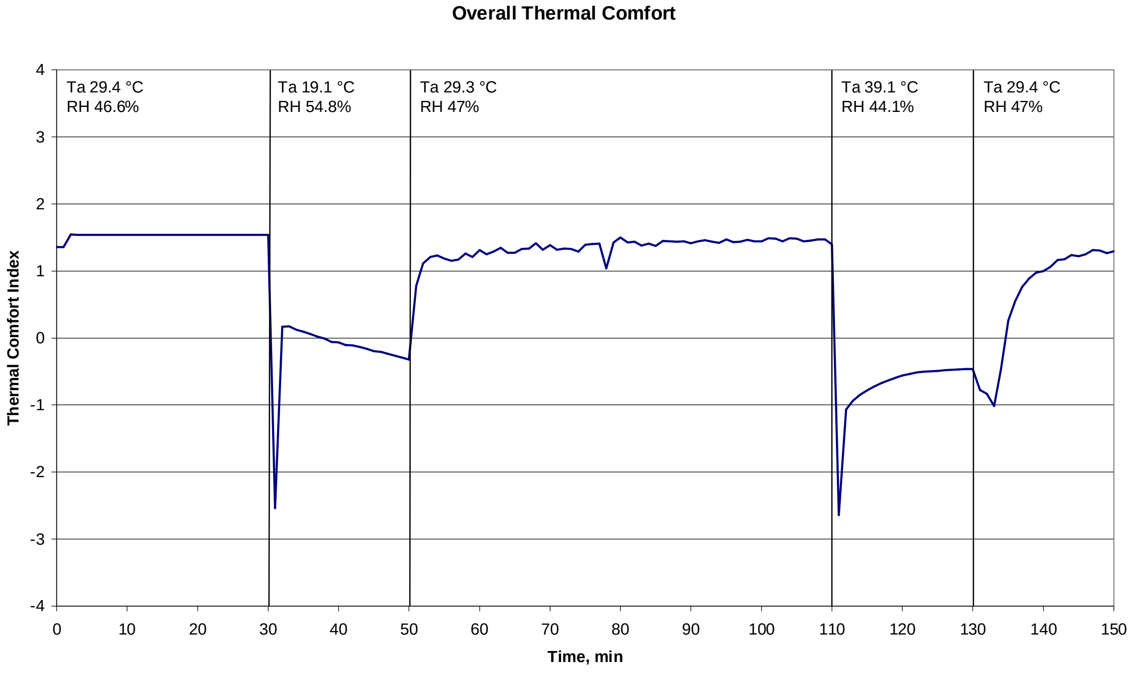


Fig. 4 Simulated thermal comfort during Munir test schedule

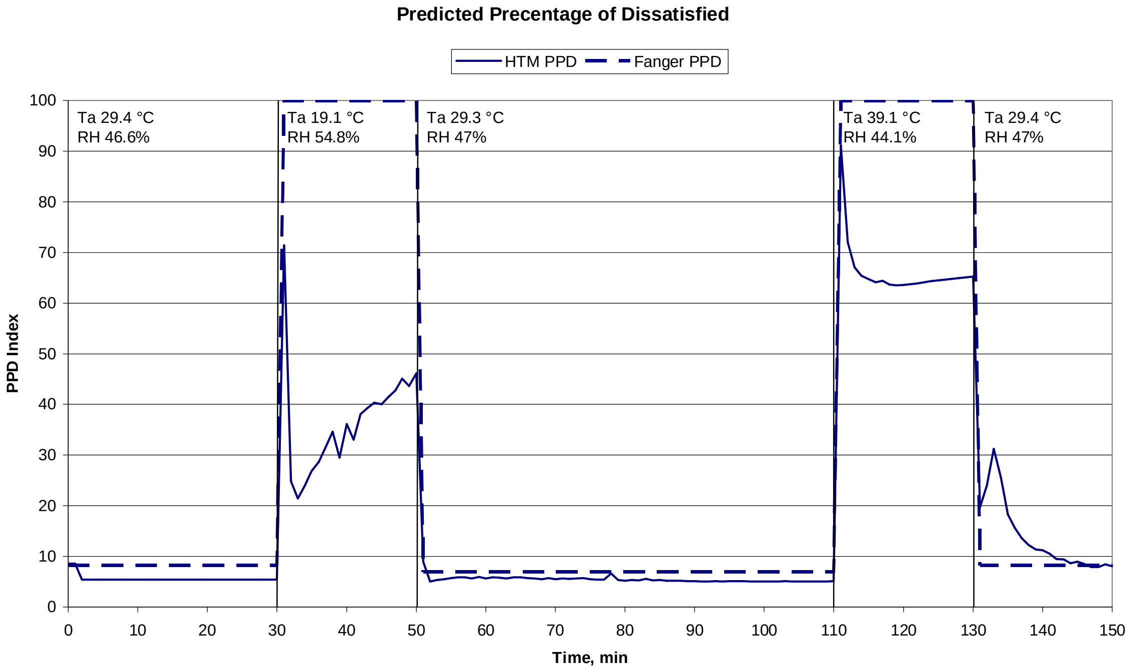


Fig. 5 PPD by Fanger and HTM during Munir test schedule

4. Discussion and conclusions

HTM tissue temperature calculation has been validated with measurements by Munir. The results show that HTM simulations give a good resemblance with measured skin temperatures.

The simulated overall thermal sensation during the Munir test schedule (Figure 3) shows how the thermal sensation index changes between 1.5 – 2.5 units immediately after the surrounding temperature is either rised or decreased by 10 °C. The body adapts to the changed temperature in approximately 1-2 minutes by means of vasodilation and sweating (temperature increase) or vasoconstriction (temperature drop). The heat loss by sweating increases during the hot phase (29.3 °C) from 19 W to 94 W. The cold phase (19 °C) is too short for the shivering effect to fully start, at the end of the phase the heat produced by shivering is just 0.01 W.

As the thermal comfort is calculated as a function of the local and overall thermal sensations, the thermal comfort curve follows logically the thermal sensation. The maximum thermal comfort index 1.5 is reached during the neutral surrounding temperatures (29.3 – 29.4 °C). The minimum thermal comfort is -2.5 at the beginning of the cold and hot phases. During the cold phase the average thermal comfort index is -0.2 and during the hot phase -1.

The calculated PPD by Fanger and HTM (Figure 5) show that the Fanger method is not sufficient when estimating the human thermal comfort in transient conditions. During the phases with a cold temperature (19.1 °C) and hot temperature (39.1 °C) Fanger method gives a constant PPD of 100 %, whereas the average PPD estimated by the thermal sensation of HTM is only 37 % and 66 %, respectively.

5. References

[1] NILSSON H, *“Comfort Climate Evaluation with Thermal Manikin Methods and Computer Simulation Models”*, Doctoral Dissertation, University of Gävle, Sweden, 2004

[2] SHITZER A, EBERHART R C, *“Heat Transfer in Medicine and Biology, Analysis and Applications”*, Vol. 1., Plenum Press, New York, 1985.

[3] SMITH C, *“A Transient, Three-Dimensional Model of the Human Thermal System”*, Doctoral Dissertation, Kansas State University, USA, 1991.

[4] MUNIR A, TAKADA S, MATSUSHITA T, “Re-evaluation of Stolwijk’s 25-node human thermal model under thermal-transient conditions: Prediction of skin temperature in low-activity conditions”, *Building and Environment* 44, 2009, pp. 1777-1787.

[5] HUI Z, *“Human Thermal Sensation and Comfort in Transient and Non-Uniform Thermal Environments”*. Doctoral Dissertation, University of California, Berkeley, USA, 2003.