

SIGNIFICANCE OF BOTH INTERNAL AND EXTERNAL BOUNDARY CONDITIONS ON HUMAN THERMAL SENSATION

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ABSTRACT

This paper describes the basic features of a new advanced human thermal model (HTM), which is integrated with a building simulation tool. The thermal sensation calculation of the model has been validated using dynamical temperature step change test results. This new methodology seems promising, and significance of both internal (metabolic rate and clothing) and external (air and surface temperature levels, air velocity, and humidity) boundary conditions can be estimated. This is beneficial, for example, when evaluating new technical concepts for future energy-efficient buildings.

INTRODUCTION

Energy-efficiency seems to become a key-driver for whole building and construction industry in the near future. Therefore, new construction and building service concepts are obviously needed. Most likely better thermal insulation levels and at least partly new heating and cooling solutions will be adopted. To avoid unpleasant indoor environment outcomes in future buildings, a more holistic approach focusing on occupant aspects is recommended. Since thermal issues seem to be dominant cause of indoor environment complaints also in the future, it is very important to really understand true nature of both complex physical and physiological phenomena, influencing human thermal sensation and comfort.

Thermal comfort can be estimated with several methods. The widely used international standards ISO 7730 (1984) and ASHRAE 55 (2003) use Fanger's PMV (Predicted Mean Vote) method for calculation of thermal comfort. Fanger's PMV method was developed based on laboratory and climate chamber studies to estimate human thermal comfort in buildings (Fanger 1970). Fanger's method is a good starting point for estimation of thermal comfort and it has been widely used in calculation of indoor environment conditions. However, the PMV method is applicable only to steady-state, uniform thermal environments. It cannot take into account time-dependant phenomena or local examination of different body parts.

The PMV method is based on a heat balance model, also referred to as a "static" or "constancy" model. While 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, heat balance models view the human being as a passive recipient of thermal stimuli. Adaptive thermal comfort approaches take into account the natural tendency of people to adapt to changing conditions in their environment. According to the adaptive principle "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" (Nicol and Humphreys 2002).

Humphreys and Nicol (2002) have examined the validity of PMV model for predicting comfort votes in every-day thermal environments. They suggest that PMV is valid for everyday prediction of the comfort vote only under severely restricted conditions. PMV progressively over-estimates the mean perceived warmth of warmer environments and the coolness of cooler environments.

To estimate accurately thermal comfort in transient conditions, an adaptive thermal comfort approach should therefore be used. Examples of adaptive methods are human thermal models, which take into account the effect of human thermoregulation on thermal sensation and comfort.

This paper presents a human thermal model connected in a building simulation environment. The new Human Thermal Model, HTM, has been developed for predicting thermal behaviour of the human body under both steady-state and more realistic dynamic indoor environment boundary conditions (Holopainen & Tuomaala 2010).

In this paper the significance of both internal (metabolism and clothing) and external (air and surface temperature levels, air velocity, and humidity) boundary conditions on thermal comfort and sensation is calculated. The aim of the paper is also to estimate the influence of different boundary conditions on human thermal sensation and comfort.

METHODS

Human thermal model integrated in a building simulation environment

Human Thermal Model (HTM) is a module of a non-commercial VTT House building simulation tool, which are both developed at VTT. VTT House

building simulation environment is used for modelling thermal interactions between the human body and the surrounding space including convective, radiation, and evaporative heat transfer (Tuomaala 2002). Both the human body and the surrounding space are described by a thermal nodal network, which consists of node capacitances and inter-nodal conductances or heat sources/sinks (e.g., net radiative heat gain components). The transient node temperatures are solved using the finite-difference heat balance method.

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: head, neck, upper arms, lower arms, hands, chest and back, pelvis, thighs, lower legs and feet. The body parts are further sub-divided typically in four realistic tissue layers (bone, muscle, fat, and skin) by concentric cylinders. 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. The passive and control system of HTM and the validation of HTM tissue temperature calculation is presented in (Holopainen & Tuomaala 2010).

The thermal sensation and thermal comfort estimation methodology by Zhang (2003) is integrated in HTM, allowing much more detailed thermal sensation and thermal comfort index estimations than traditional Fanger's methodology. This integrated method enables the quantitative analysis of the significance of both external (air and surface temperatures, air velocity, and humidity) and internal (clothing, metabolism) boundary conditions on thermal sensation and comfort.

Test room and test cases

The simulation test room has a volume of 27 m³ (3 m x 3 m x 3 m) with no windows. The surrounding structures were at the same temperature as the indoor air. HTM was placed at the middle point of the test room floor. The varied internal boundary conditions were

- thermal insulation of the clothing
- operative temperature (indoor temperature and surface temperatures)
- relative humidity of indoor air
- indoor air velocity
- activity level

The clothing alternatives were shorts (0.19 clo), lighter clothing alternative (0.47 clo) and heavier clothing alternative (0.86 clo). The lighter and heavier clothing ensembles are based on Fu (1995). The garments of the lighter clothing alternative are

- short-sleeve shirt, briefs, shorts, calf-length socks and soft-soled shoes

The garments of the heavier clothing alternative are

- t-shirt, long-sleeve turtleneck sweater, briefs, jeans, calf-length socks and soft-soled shoes

The thermal and evaporative resistances of the garments are presented in Table 1.

Table 1
Thermal and evaporative resistances of garments used in simulations (Fu 1995).

GARMENT	THERMAL RESISTANCE, m ² K/W	EVAPORATIVE RESISTANCE, m ² kPa/W
Short-sleeve shirt	0.041	0.0041
t-shirt	0.030	0.0032
long-sleeve turtleneck sweater	0.112	0.0105
briefs	0.030	0.0037
shorts	0.030	0.0037
jeans	0.037	0.0066
calf-length socks	0.054	0.0104
soft-soled shoes	0.108	0.0208

Thermal Sensation Model by Zhang

Zhang (2003) has developed a new thermal sensation model to predict local and overall thermal sensation in non-uniform transient thermal environments. The overall thermal sensation is calculated as a function of the local skin temperatures and the core temperature, and their change in time.

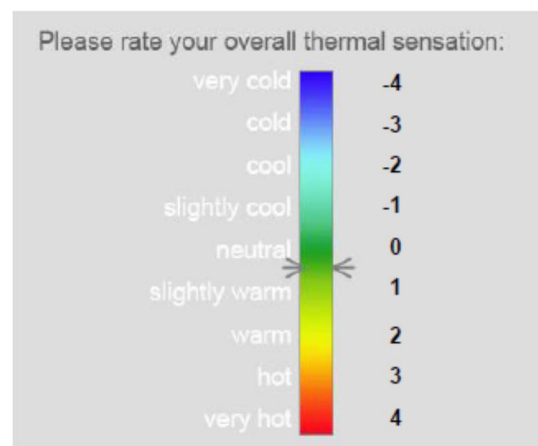


Figure 1 Thermal sensation scale by Zhang (2003).

The sensation scale by Zhang is presented in Figure 1. When the local skin temperature differs from the local skin temperature set point, the sensation reaches the sensation scale limits between +4 (very hot) and -4 (very cold). Positive index values indicate various degrees of "hot" sensation and negative values indicate "cold" sensation. The index value equal to

zero indicates thermal neutrality. The index values between -3 and +3 are comparable to the ASHRAE thermal sensation scale (ASHRAE 1993).

Zhang (2003) represents the body-part specific local thermal sensation by a logistic function of local skin temperature:

$$S_{local} = 4 \left(\frac{2}{1 + e^{-C1(T_{skin,local} - T_{skin,local,set}) - K1[\ddot{T}_{skin} - (\ddot{T}_{skin,local} - \ddot{T}_{set})]}} - 1 \right) + C2_i \frac{dT_{skin,local}}{dt} + C3_i \frac{dT_{core}}{dt} \quad (1),$$

where $T_{skin,local}$ is the skin temperature, $T_{skin,local,set}$ is the skin set point temperature, \ddot{T}_{skin} is the mean whole-body skin temperature and \ddot{T}_{set} is the mean whole-body skin set point temperature. Terms $K1$, $C1$, $C2$ and $C3$ are body-part specific regression coefficients.

In the first term on the right hand side of Eq. 1 the multiplier 4 defines the sensation range from very cold (-4) to very hot (+4), the first exponent controls the slope of the function and the second exponent represents the modifying effect of whole-body thermal status on local sensation. The body-part specific regression coefficients $C1$ are different when the local skin temperature is colder or warmer than the local skin set point temperature. The coefficients $C1$ vary from 0.15 to 1.32, depending on the body part and heating/cooling case. The body part-specific regression coefficients $K1$ vary from 0.1 to 0.18 depending on the body part.

When the derivatives of skin and core temperatures (second and third terms on the right side of the equation) are zero, the model predicts thermal sensation in a steady state condition.

The second term on the right hand side takes into account the effect of the skin temperature change to local thermal sensation. The overall response to cooling by people is much stronger than the response for heating, which is also confirmed by measurements by Zhang. The regression coefficients $C2$ are therefore provided separately for positive and negative derivatives of skin temperature. The coefficients $C2$ vary from 19 to 543, depending on the body part and heating/cooling case.

According to Zhang, the core temperature responds to local cooling of most influential body parts (face, chest, back and pelvis) with an immediate increase. This is reflected in the third term on the right hand side with coefficient $C3$ varying from -2135 to -5053.

The overall thermal sensation is calculated as a weighted average of all the local sensations. The weighting factors for different body parts are presented by Zhang (2003) in Table 2.

Table 2
Overall thermal sensation weighting factors by Zhang (2003)

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
sum	1.0

SIMULATION

HTM dynamical thermal sensation calculation compared to experimental values and Fanger method

Nevins et al. (1966) has measured the thermal sensation of college students, who were exposed to each thermal condition in groups of ten persons (five males and five females). The exposure period was 3 hours. The students were clothed in cotton shirts and trousers and woollen socks; the insulating value of the clothing was 0.52 clo. The students were seated during the test and their average metabolism was 1 Met. Simulated thermal sensations in nine steady state temperatures between 18.9 °C and 27.8 °C with the relative humidity of 45 % were compared to the experimental series by Nevins et al. Figure 2 shows the measurement results of male test persons and simulated values with HTM method and Fanger PMV method.

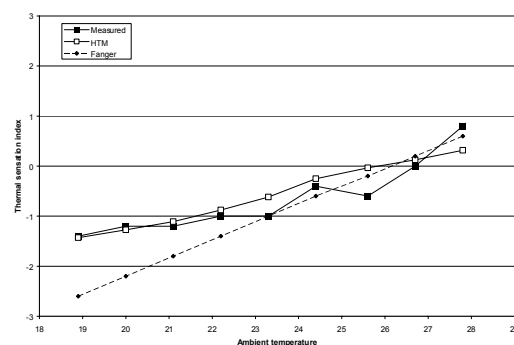


Figure 2 Measured and simulated thermal sensation of sedentary subjects in different temperatures.

Gagge et al. (1967) have measured temperature step change responses of three male subjects. In a cold exposure test the subjects were exposed for one hour in a neutral environment of 29 °C. The subjects were then transferred to a colder room in 17.5 °C, where they stayed for 2 hours. After the cold room the subjects moved back to the neutral room for one hour. The activity level was 1 Met, and the clothing insulation was 0.1 clo (shorts). The relative

humidities of the experiment rooms were not reported, in simulations they were assumed to be 40 % in both rooms. Figure 3 shows the thermal sensation measurement results and simulated thermal sensations with HTM method and Fanger PMV method for the cold exposure test case.

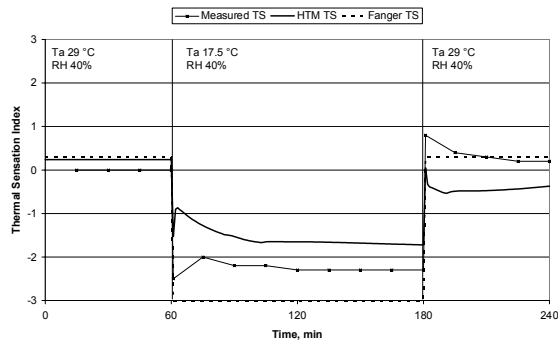


Figure 3 Measured and simulated thermal sensation during the cold exposure test by Gagge (1967).

In a hot exposure test the temperatures of the test rooms were 28 °C, 48 °C, and 28 °C. The exposure times, activity levels and clothing were similar to the cold exposure test. The relative humidities in the test rooms were not reported. In simulations the relative humidity was assumed to be 40 % in the 28 °C test room and 30 % in the 48 °C test room. HTM simulations were made with the original Zhang local thermal sensation equation and a modified equation without the term representing the effect of core temperature change (Figure 4).

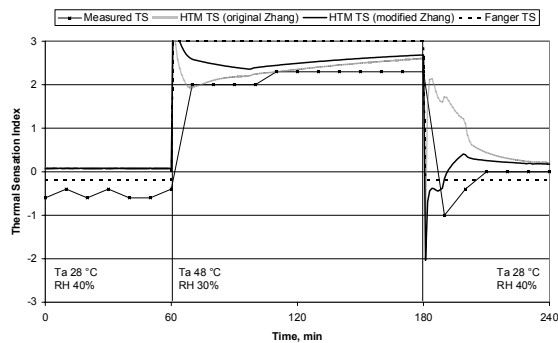


Figure 4 Measured and simulated thermal sensation during the hot exposure case by Gagge (1967).

Significance of internal and external boundary conditions on steady state thermal sensation

The effect of relative humidity, operative temperature, activity level and clothing on thermal sensation was simulated. The base case was defined as:

- relative humidity 40 %
- operative temperature 20 °C
- activity level 58 W/m² (1 Met)

The operative temperature of a space is approximately the average of the air and mean radiant temperature a person is experiencing. The effect of relative humidity and operative temperature on thermal sensation was simulated between relative humidities of 0 % and 100 % with steps of 20 %, and operative temperatures between 18 °C and 28 °C with steps of 2 °C (Figures 5 -7).

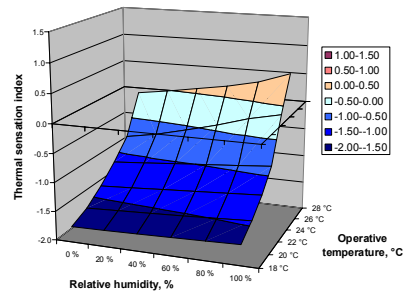


Figure 5 Effect of relative humidity and operative temperature on thermal sensation, clothing 0.19 clo.

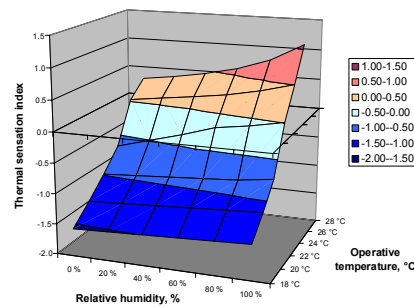


Figure 6 Effect of relative humidity and operative temperature on thermal sensation, clothing 0.47 clo.

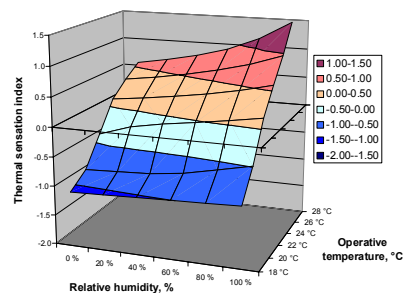


Figure 7 Effect of relative humidity and operative temperature on thermal sensation, clothing 0.86 clo.

The simulated activity levels were as defined in ISO 7730 (ISO 1984)

- 46 W/m² (0.85 Met): resting
- 58 W/m² (1.0 Met): relaxed sitting

- 70 W/m² (1.2 Met): sedentary activity (office, dwelling, school, laboratory)
- 93 W/m² (1.6 Met): standing, light activity (shopping, light industry)
- 116 W/m² (2.0 Met): standing, medium activity (shop assistant, domestic work, machine work)

Figures 8 -10 show the effect of activity level and operative temperature on thermal sensation.

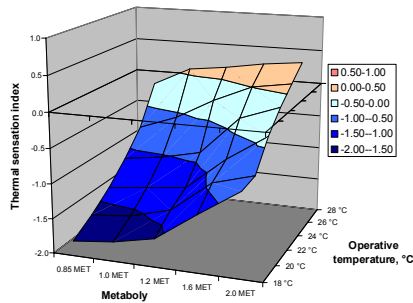


Figure 8 Effect of activity level and operative temperature on thermal sensation, clothing 0.19 clo.

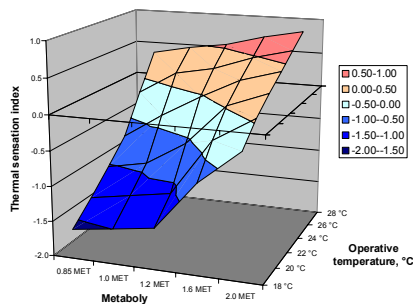


Figure 9 Effect of activity level and operative temperature on thermal sensation, clothing 0.47 clo.

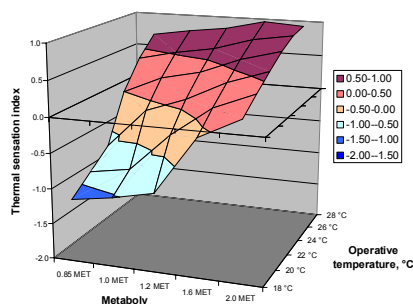


Figure 10 Effect of activity level and operative temperature on thermal sensation, clothing 0.86 clo.

The combined effect of metabolism, relative humidity and clothing on thermal sensation is presented in Figures 11-13 for a cold, neutral and hot room with operative temperatures as 18 °C, 21 °C and 25 °C, respectively.

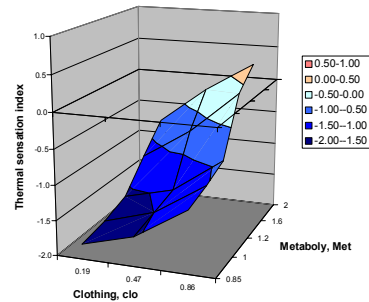


Figure 11 Effect of metabolic rate and clothing on thermal sensation in a cold room (operative temperature of 18 °C).

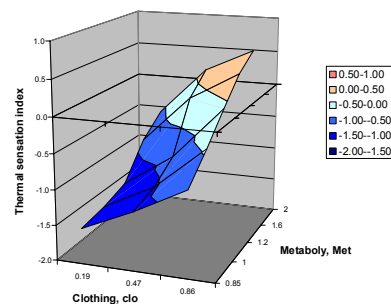


Figure 12 Effect of metabolic rate and clothing on thermal sensation in a neutral room (operative temperature of 21 °C).

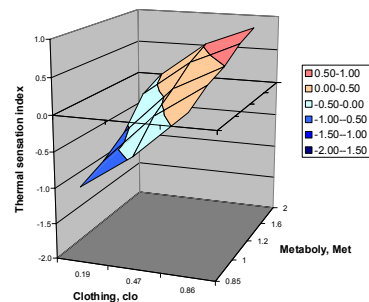


Figure 13 Effect of metabolic rate and clothing on thermal sensation in a warm room (operative temperature of 25 °C).

HTM takes into account the effect of air velocity by means of body part-specific convective heat transfer coefficients. deDear has defined body part-specific convective heat transfer factors based on laboratory measurements with a thermal manikin (deDear et al. 1997). A general-purpose forced convection equation was generated for the whole body

$$h_c = 10.3 \cdot v^{0.6} \quad (1)$$

where h_c is the convective heat transfer factor and v is the air velocity. Similar equations were generated

for individual body segments in both seated and standing postures.

In the simulations, the body part-specific convective heat transfer coefficients for a seated person were calculated according to deDear by taking the higher value of either the calculated forced convective heat transfer factor or the free convective heat transfer factor of each body part (Table 3).

Table 3
Convective heat transfer coefficients h_c (W/m^2K) for different air velocities, coefficients based on forced convection in bold.

BODY PART	AIR VELOCITY, m/s					
	<0.1	0.10	0.15	0.20	0.25	0.30
Head	3.7	3.7	3.7	3.7	3.7	3.7
Chest	3.0	3.0	3.0	3.5	4.0	4.5
Back	2.6	2.6	2.7	3.2	3.7	4.2
Pelvis	2.8	2.8	2.8	2.9	3.3	3.7
Upper arm	3.4	3.4	3.4	4.1	4.7	5.3
Forearm	3.8	3.8	3.8	4.4	5.0	5.6
Hand	4.5	4.5	4.5	5.1	5.8	6.5
Thigh	3.7	3.7	3.7	3.7	3.9	4.3
Calf	4.0	4.0	4.5	5.3	6.0	6.6
Foot	4.2	4.2	4.6	5.4	6.1	6.7

As the convective heat transfer factors based on forced convection were calculated in an ambient temperature of 20 °C the effect of air velocity on thermal sensation was simulated only in an operational temperature of 20 °C. The indoor air velocity was varied between 0 and 0.3 m/s with steps of 0.05 m/s. Figure 14 shows the simulation results with different clothing alternatives.

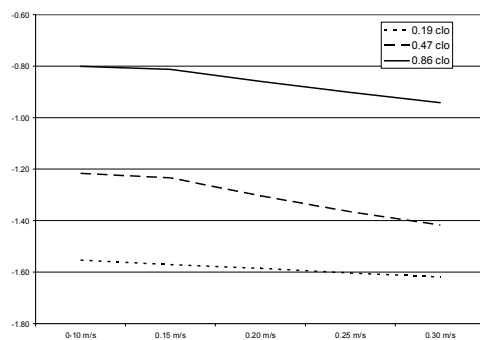


Figure 14 Effect of air velocity on thermal sensation in an operative temperature of 20 °C.

DISCUSSION AND RESULT ANALYSIS

When compared to the original results presented by Nevins et al. (1966), promising estimations of human thermal sensation were obtained by the new Human Thermal Model (HTM). According to this test case,

HTM is able to show a better resemblance with measured values than Fanger's PMV method.

The original Zhang's local thermal sensation equation gives inconsistent results in downward temperature step changes when compared to measured thermal sensation values. The simulated thermal sensation index showed a steep drop downward followed by a steep rise upward after changing from the 48 °C room to 28 °C. This effect differed from the measured thermal sensation. When the third term was left out from the thermal sensation equation (Eq. 1), the simulated thermal sensations followed measured values after the temperature drop. After the temperature rise from 28 °C to 48 °C the original Zhang's equation gave better resemblance with the experimental values than the modified equation.

When evaluating significance of the effects of different internal and external boundary conditions on thermal sensation by HTM methodology, it could be noticed that:

- operative temperature is clearly dominant compared to air humidity values (see Fig. 5, 6, and 7)
- combinations of metabolic rate and operative temperature seems to dictate level of thermal sensation – which is scaled by insulation level of clothing (see Fig. 8, 9, and 10)
- operative temperature puts clear boundaries for combinations of clothing and metabolic rate when aiming to thermal neutrality of a human (see Fig. 11, 12, and 13)
- increase of metabolic rate by 1 Met increases thermal sensation index by approximately 0.8 – 1.5 units. This effect is stronger with increased clothing insulation level.
- increase of operative temperature by 1 °C increases thermal sensation index by approximately 0.1 – 0.2 units. The effect is stronger with increased clothing insulation level.
- increase of relative humidity by 10 % increases thermal sensation index by approximately 0.015 units. With heavier clothing and relative humidities above 40 % the effect increases to 0.04-0.05 units.
- increase of air velocity by 0.05 m/s decreases thermal sensation index by approximately 0.04 units.

CONCLUSION

According to the test cases presented, the new Human Thermal Model (HTM) seems promising for evaluating thermal sensation of occupants. In this study operative temperature, metabolic rate and

clothing were found to be the most dominant boundary conditions. Integrating building simulation model and advanced human thermal model clearly allows more accurate estimations of the effects, which different internal and external boundary conditions have on occupants. Therefore, HTM can be utilised, for example, for evaluating new technical concepts for future energy-efficient buildings.

NOMENCLATURE

h_c	convective heat transfer factor (W/m ² K)
v	air velocity (m/s)
$T_{skin,local}$	local skin temperature (°C)
$T_{skin,local,set}$	skin set point temperature (°C)
\ddot{T}_{skin}	mean whole-body skin temperature (°C)
\ddot{T}_{set}	mean whole-body skin set point temperature (°C)
$K1, C1, C2, C3$	body-part specific regression coefficients (-)

REFERENCES

- ASHRAE 1993. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Physiological principles and thermal comfort, ASHRAE Handbook Fundamentals, ASHRAE, Atlanta, USA, pp 8.1–8.32.
- ASHRAE 2003. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Standard 55P Thermal Environmental Conditions for Human Occupancy, ASHRAE, Atlanta, USA.
- deDear, R.J., Arens, E., Hui, Z., and Oguro, M. 1997. Convective and radiative heat transfer coefficients for individual human body segments, *Int. J. Biometeorol.* Vol. 40, pp. 141-156.
- Fanger, P. O. 1970. *Thermal Comfort*. McGraw-Hill, New York, USA.
- Fu, G. 1995. *A Transient, 3-D Mathematical Thermal Model for the Clothed Human*. Doctoral Dissertation, Kansas State University, USA.
- Gagge, A.P., Stolwijk, J.A.J. and Hardy, J.D. 1967. Comfort and thermal sensation and associated physiological responses at various ambient temperatures. *Environmental Research*, Vol. 1, pp. 1-20.
- Holopainen R. & Tuomaala P. 2010. New human thermal model integrated in a building simulation environment for a more accurate estimation of thermal comfort in transient conditions. SB10 Finland Sustainable Community – buildingSMART Conference, September 22 – 24, Espoo, Finland. http://www.vtt.fi/inf/julkaisut/muut/2010/New_human_thermal_model.pdf
- Humphreys, M.A. and Nicol, J.F. 2002. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Energy and Buildings* Vol. 34, pp. 667-684.
- ISO 1984. “Moderate thermal environments - determination of the PMV and PPD indices and specification of the conditions for thermal comfort,” International Standard ISO 7730, International Organisation for Standardization.
- Nevens, R.G. et al. 1966. Temperature-humidity chart for thermal comfort of seated persons. *ASHRAE Transactions*, Vol. 72, pp. 283-291.
- Nicol, J.F. and Humphreys, M.A. 2002. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, Vol. 34, pp. 563-572.
- Tuomaala P. 2002. Implementation and evaluation of air flow and heat transfer routines for building simulation tools, Doctoral Dissertation, VTT Publications 471, Espoo, Finland.
- Zhang, H. 2003. *Human Thermal Sensation and Comfort in Transient and Non-Uniform Thermal Environments* Hensen 1991, University of California, Berkeley, USA.