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Local thermal sensation modelling – a review on the necessity and availability of local clothing properties and local metabolic heat production

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Abstract

Local thermal sensation modelling gained importance due to developments in personalized and locally applied heating and cooling systems in office environments. The accuracy of these models depends on skin temperature prediction by thermophysiological models, which in turn rely on accurate environmental and personal input data. Environmental parameters are measured or prescribed, but personal factors such as clothing properties and metabolic rates have to be estimated. Data for estimating the overall values of clothing properties and metabolic rates are available in several papers and standards. However, local values are more difficult to retrieve. For local clothing, this paper revealed that full and consistent data sets are not available in the published literature for typical office clothing sets. Furthermore, the values for local heat production were not verified for characteristic office activities, but were adapted empirically. Further analyses showed that variations in input parameters can lead to local skin temperature differences ($\Delta T_{\text{skin,loc}} = 0.4 - 4.4^\circ C$). These differences can affect the local sensation output, where $\Delta T_{\text{skin,loc}} = 1^\circ C$ is approximately one step on a 9-point thermal sensation scale. In conclusion, future research should include a systematic study of local clothing properties and the development of feasible methods for measuring and validating local heat production.

Keywords

thermal modelling, local thermal sensation, local clothing properties, local metabolic rates, thermophysiological models, input parameters

Practical implications

A human thermal model that predicts local skin temperatures and local thermal sensation accurately can help researchers as well as engineers to test and improve energy efficient local heating and cooling strategies in early design stages. Hence, costs and time spent on human subject experiments in this area can be reduced.
1 Introduction

The built environment currently accounts for 30-40% of the total energy consumption worldwide (IEA, 2013). Therefore, energy efficient buildings can contribute to the fulfillment of the European Union’s 2020 targets for energy and CO₂ reductions (European Commission, 2011). Improvements were made in the building sector due to better insulation and energy-efficient equipment (IEA, 2013). Yet, studies (e.g. van Dam (2013)) show that there are still discrepancies between the design and operating phase of residential and commercial buildings, which are, among others, caused by individual preferences for thermal comfort. Present thermal comfort standards and design guidelines are based on an average person exposed to quasi-steady state, uniform heating or cooling (ASHRAE, 2004; ISO, 2005) and hence, do not account for individual differences (Kingma and van Marken Lichtenbelt, 2015).

Individual thermal comfort might be assessed using modern human thermophysiological and coupled thermal sensation models. Thermal models have been developed since the 1960s and continuously improved. Detailed summaries of these models and their development are given, for example, by Cheng et al. (2012), Miiimu et al. (2013), de Dear et al. (2013), Fabbri (2015) and Katic & Zeiler (2014). Accordingly, human thermal models can be clustered into two main categories: 1) thermophysiological (TP) models and 2) thermal sensation (TS) models, which are also referred to as psychological models, e.g. (Cheng et al., 2012). These two categories are connected in a general concept of human thermal modelling (Figure 1). This concept also includes that TP models require input of environmental variables (e.g. operative temperature, humidity, wind speed), two personal factors namely clothing and metabolic rate and, optionally, individual characteristics (e.g. weight, height, age). Using this information, TP models calculate core, mean and local skin temperatures \( T_{\text{core}}, T_{\text{skin}} \) and \( T_{\text{sk,loc}} \) as well as their time derivatives \( dT/dt \) with the use of heat transfer and bioheat equations. Core and
skin temperatures as well as the change in skin temperature are consecutively used to predict thermal sensation and comfort via a TS model.

![Figure 1 General concept of human thermal modelling.](image)

TP models can also be divided into single-segment and multi-segment TP models. Segments are representations of the body or body parts, consisting of one or multiple layers around a cylindrical or spherical core. In single-segment models the exact geometry of body representation is less important and is usually used to define balances and characteristics. Multi-segment models divide the human body into several body parts, and the geometry (radius, length, layer thickness, etc.) becomes more important than for single-segment models. Every segment is usually assigned its own heat and mass balance, which is then combined in a whole-body balance. Table S1 summarizes the most important attributes of selected thermal models in each of the defined categories. This paper addresses specifically multi-segment TP and coupled TS models.

Multi-segment TP and coupled TS models are mainly applied to predict human whole-body thermal comfort in a built environment. Recently, heating and cooling systems influencing also the climate of specific body parts (here referred to as local) were developed to improve the thermal comfort and energy balance in office buildings e.g. (Arens et al., 1991; Foda and Sirén, 2012; Melikov et al., 1994; Parkinson et al., 2015; Veselý and Zeiler, 2014). Currently, these systems have to be tested with extensive human subject experiments. An accurate prediction of local and overall thermal comfort for these systems could help to preselect promising designs and improve the efficiency of human subject experiments. Therefore, the ability of thermal models to also predict local thermal comfort and sensation has to be re-evaluated.
In general, it is assumed that accurate prediction of local thermal sensation (LTS) depends on accurate local skin temperatures from TP models, which in turn need accurate local input values. The difficulty of obtaining precise input is different for environmental and personal parameters. Environmental conditions can mostly be easily obtained, since they are set or measured. However, personal factors such as local clothing values (insulation and evaporative resistance), metabolic heat production and its local distribution over the body, as well as local tissue insulation have to be estimated. The latter factor is, for example, discussed by Wijers et al. (2010) and Veicsteinas et al. (1982), but is not part of this paper. The whole-body clothing and metabolic data as described in the standards were reviewed in a paper by Havenith et al. (2002), and suggestions were made for improvements. For instance, Havenith et al. (2002) proposed to include clothing vapor resistance into thermal comfort calculations and to account for the effect of air and body movement on all clothing properties. Moreover, they question the precision of the measurements for metabolic rates and suggest enlarging the database for low level activities. However, for local personal input data (clothing and metabolic heat production) the availability, the accuracy and the limits have not been reviewed and discussed so far. To fill in this gap, this paper gives an overview of present models and addresses the following three main topics:

1) the necessity and availability of input data for local clothing properties and the options to account for changes in them due to air speed and body movement,

2) the necessity and availability of metabolic heat production and its local distribution,

3) the effects of uncertainties of local personal factors on LTS modelling.

2 Representation of clothing in thermophysiological models

TP models account for sensible and evaporative heat loss from the clothed body to the environment. Sensible heat exchange consists of a conductive, radiative and convective part. Con-
duction from the clothing surface to the environment is usually neglected, due to its small contribution to the overall heat losses. The radiative and convection heat are defined by:

\[ R = h_r f_{cl} (T_{cl} - T_r) \]  
\[ C = h_c f_{cl} (T_{cl} - T_a) \]  

where \( R \) and \( C \) are the radiative and convective heat loss (W m\(^{-2}\)), \( h_r \) and \( h_c \) are the radiant and convective heat transfer coefficients (W m\(^{-2}\) °C\(^{-1}\)), \( f_{cl} \) is the clothing area factor (ratio of the skin surface area of a nude person \( A_{Du} \) (Du Bois and Du Bois, 1916) and the surface area of the clothed body \( A_{cl} \) (ISO, 2009)), \( T_{cl} \) is the clothing surface temperature, \( T_r \) is the mean radiant temperature, and \( T_a \) is the ambient temperature (all temperatures in °C). The radiant heat transfer coefficient is hereby dependent on the temperature in the following way:

\[ h_r = 4\sigma \varepsilon \left( \frac{T_{cl} - T_r}{2} + 273 \right)^3 \frac{A_r}{A_{Du}} \]  

where \( \sigma \) is the Stefan-Boltzmann constant (5.67 \( \cdot \) 10\(^{-8}\) W m\(^{-2}\) K\(^{-4}\)), \( \varepsilon \) is the emissivity of the clothed body surface and \( A_r \) is the body surface area participating in radiative heat exchange.

Mostly, convective and radiative heat losses (\( C + R \)) from the skin to the environment are considered together in:

\[ C + R = \frac{T_{sk} - T_{cl}}{R_{cl}} = \frac{T_{sk} - T_{a,o}}{R_{cl} + 1/(f_{cl}(h_r + h_c))} \]  

where \( T_{sk} \) is the skin temperature (°C), \( R_{cl} \) is the thermal resistance of clothing (m\(^2\) K W\(^{-1}\)), and \( T_{a,o} \) is the ambient operative temperature (°C).

The evaporative heat loss \( E_{sk} \) can be written as:

\[ E_{sk} = \frac{w(P_{sk} - P_a)}{R_{e,cl} + 1/(f_{cl}h_e)} \]  

where \( w \) is the total skin wettedness, \( P_{sk} \) is the saturated water vapor pressure at the skin surface (kPa), \( P_a \) is the water vapor pressures of the ambient air (kPa) and \( h_e \) is the evaporative heat transfer coefficient (W m\(^{-2}\) °C\(^{-1}\)).
The clothing properties thermal resistance $R_{cl}$, the evaporative resistance $R_{e,cl}$ and the area factor $f_{cl}$ have to be known to account for heat losses through clothing. The thermal resistance $R_{cl}$ is also often called clothing insulation $I_{cl}$, which is then given in the clo unit (1 clo = 0.155 m²·K/W). The clothing insulation is part of the total insulation $I_T$ provided by the clothing and the adjacent air layer. The total insulation can be calculated from the clothing insulation, the insulation of the air layer $I_a$ and the clothing area factor:

$$I_T = I_{cl} + \frac{I_a}{f_{cl}}$$  \hspace{1cm} (6)

Evaporative heat losses are often calculated using the clothing permeability index $i_{cl}$, which is calculated from the thermal and evaporative resistance, $R_{cl}$ and $R_{e,cl}$, respectively, as well as the Lewis relation $LR$ (0.0165 K/Pa):

$$i_{cl}LR = \frac{R_{cl}}{R_{e,cl}}$$  \hspace{1cm} (7)

All clothing properties are generally given as whole-body coefficients and values are provided in current standard, e.g. EN-ISO 9920 (ISO, 2009) or ASHRAE/55 (ASHRAE, 2004).

### 2.1 Clothing in thermophysiological models

Multi-segment TP models assign clothing separately to every simulated body part. The modeling of the local clothing is approached differently in the models. Table S2 summarizes the main attributes of the local clothing models used. Additionally, the required input data for the clothing model is mentioned.

The modeling of local clothing can be divided into three approaches:

1) detailed differential equations for heat and mass transfer,
2) integration of thermal and evaporative resistances for heat losses from the skin to the environment and
3) calculation of convective and radiative heat losses using the clothing temperature.
The first concept is used in the TP models by Stolwijk (1971), Wissler (1985) as well as Fu and Jones (1996). The main disadvantage of these models is the difficulty to measure or estimate the required input data, e.g. air gap width. The second method for local clothing modeling is established in the more recent TP models. Even though their concepts are similar, they are implemented differently. Lotens (1993), for instance, uses a detailed resistance scheme for a skin-clothing-air-clothing-air system, where concepts of radiation, diffusion and ventilation are integrated (Figure S1). In contrast, the models by and based on Fiala (1998) and Tanabe (2002) define a local effective heat transfer coefficient $U'_{ct}$ and a local effective evaporative coefficient $U'_{e,ct}$ to account for heat and moisture exchange between the skin and the environment:

$$U'_{ct} = \frac{1}{\sum_{j=1}^{n}(l'_{ct})_j} + \frac{1}{f'_{ct}(h_c + h_R)} \tag{8}$$

$$U'_{e,ct} = \frac{LR}{\sum_{j=1}^{n}(l'_{e,ct})_j} + \frac{1}{f'_{ct} \cdot h_c} \tag{9}$$

where $l'_{ct}$ is the local heat resistance of the j-th clothing layer (W/m²K), $f'_{ct}$ is the local clothing area factor and $l'_{e,ct}$ is the local moisture permeability index. Lastly, for the improved UCB clothing model, a distinction is made between clothed and not-clothed pathway from core to environment (Figure S2). The third approach to local clothing modeling is only found in the Multi-segmental Pierce model. To calculate the convective and radiative heat losses with (1) and (2), an iterative procedure is performed to choose the correct clothing temperature.

### 2.2 Local clothing insulation and evaporative resistance values

In current data bases, e.g. EN ISO 9920 (ISO, 2009) and McCullough (1985, 1989), clothing insulation and evaporative resistance is given for whole-body approaches. Therefore, these values cannot be directly applied at local segments. Most TP models described in section 2.1 use their own local data, which is either measured for specific cases or taken from an in-house
database, which is not publically accessible. Only a few papers were published on local clothing properties, which will be presented here.

In the available literature, four studies were found which published sufficient data on local clothing insulation values: Curlee (2004) and Nelsen et al. (2005), Havenith et al. (2012), Lee et al. (2013) and Lu et al. (2015). In Table 1, local clothing insulation values for different body parts are given for the four published studies using an example of a clothing ensemble consisting of underwear, t-shirt, trousers, socks and shoes. The table shows that local clothing insulation values vary across these studies. For instance, the local clothing insulation on the chest ranges from 0.116 to 1.14 m²K/W and on the feet even from 0.079 to 0.287 m²K/W. Thus, it is difficult to choose an adequate value to be used in a TP model.

<table>
<thead>
<tr>
<th>Body part</th>
<th>Clothing items</th>
<th>Local clothing area factor**</th>
<th>Lee (No. 8)</th>
<th>Lu (EN 9)</th>
<th>Nelson &amp; Curlee</th>
<th>Havenith (22°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole-body</td>
<td>--</td>
<td>--</td>
<td>0.081</td>
<td>/</td>
<td>0.088*</td>
<td>0.081</td>
</tr>
<tr>
<td>Head/ Hand</td>
<td>None</td>
<td>--</td>
<td>0.00</td>
<td>/</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Chest</td>
<td>Bra, t-shirt</td>
<td>1.22</td>
<td>0.177</td>
<td>0.169</td>
<td>0.174</td>
<td>0.116</td>
</tr>
<tr>
<td>Back</td>
<td></td>
<td>1.22</td>
<td>0.130</td>
<td>0.122</td>
<td>0.174</td>
<td>0.116</td>
</tr>
<tr>
<td>Abdomen</td>
<td>T-shirt</td>
<td>1.23</td>
<td>/</td>
<td>0.169</td>
<td>0.116</td>
<td>0.116</td>
</tr>
<tr>
<td>Pelvis</td>
<td>Panty + t-shirt + trousers</td>
<td>1.17</td>
<td>0.161</td>
<td>0.223</td>
<td>0.321</td>
<td>0.116</td>
</tr>
<tr>
<td>Upper arm</td>
<td>T-shirt</td>
<td>1.23</td>
<td>0.065</td>
<td>0.068</td>
<td>0.116</td>
<td>0.116</td>
</tr>
<tr>
<td>Forearm</td>
<td>None</td>
<td>(1.23)</td>
<td>0.00</td>
<td>0.023</td>
<td>0.000</td>
<td>0.104</td>
</tr>
<tr>
<td>Thigh</td>
<td>Trousers (fitted)</td>
<td>1.20</td>
<td>0.090</td>
<td>0.085</td>
<td>0.144</td>
<td>0.126</td>
</tr>
<tr>
<td>Lower leg</td>
<td>Trousers (loose)</td>
<td>1.44</td>
<td>0.096</td>
<td>0.076</td>
<td>0.197</td>
<td>0.126</td>
</tr>
<tr>
<td>Foot</td>
<td>Socks + shoes</td>
<td>1.25</td>
<td>0.127</td>
<td>/***</td>
<td>0.287</td>
<td>0.079</td>
</tr>
</tbody>
</table>

* Men’s Summer Casual from (McCullough et al., 1989)

** taken from (Nelson et al., 2005)

*** for the simulations in chapter 4, a value of 0.127 m²K/W is assumed

The reasons for the differences in the clothing thermal resistances can be found in the different approaches taken and different clothing specifications used in the four papers. The data of Curlee (2004) is based on a computational method, where the whole-body thermal clothing insulation values, evaporative resistances and area factors by McCullough (1989) were recalculated into local values. In contrast, Lee et al. (2013) and Lu et al. (2015) report measured values, which were obtained in experimental conditions following the standards ISO 9920 (ISO, 2009), but with different thermal manikins and postures. A third approach was taken by
Havenith et al. (2012), who collected local thermal insulation values depending on the ambient temperature and then transferred the findings into empirical equations for 7 body parts. Apart from the different methods, the actual material, drape of the clothing or air gaps between clothing and manikin might be different as well. Limited material information can only be found for Curlee (2004) and Lu et al. (2015). For example, the t-shirt is described in Curlee (2004) as “broadcloth” and in Lu et al. (2015) as “cotton”. In Lee et al. (2013) and Havenith et al. (2012), no specifications of the materials are given. In all cases, the drape of the clothing or occurring air gaps are hardly described. All in all, these variations in methods and clothing specifications lead to a high uncertainty for the usage of these values in TP modelling.

Further values for clothing insulation and evaporative resistances can be found in studies investigating the effect of air speed and body movement on these values (see section 2.3). However, these studies mostly feature only one or two clothing ensembles.

2.3 Effect of air penetration on clothing properties

Air penetration in clothing due to air or body movement reduces the clothing thermal insulation and evaporative resistance. This was shown in several studies for overall thermal insulation (Havenith and Nilsson, 2004; Havenith et al., 1990b; Holmér et al., 1999; Nielsen et al., 1985; Parsons et al., 1999) and total evaporative resistance (Havenith et al., 1990a). The standard ISO 9920 (ISO, 2009) provides equations to correct the whole-body values for air velocity and walking speed. The same correction factor is applied for thermal insulation and evaporative resistance.

In the revised UC Berkeley clothing model by Fu et al. (2014), different approaches to clothing insulation correction factors were compared to the values given in ISO 9920. The authors concluded that the equations in ISO 9920 might be used as a first approach. However, for wind speed it was said that the correction for the trunk might be overestimated and for the
extremities it might be underestimated. Furthermore, it was assumed that the equation for the evaporative resistance is also valid on segment level, but no investigation was done yet.

Wang et al. (2012) investigated the effect of air and body movement on the local clothing evaporative resistance for three light clothing ensembles (0.132, 0.225 and 0.237 clo) at 14 body elements. The experiments were conducted at three research facilities all using a Newton sweating manikin and in standard conditions (ISO, 2009). Local clothing evaporative resistances were measured at three air speeds (0.13, 0.48 and 0.70 m/s) and three walking speeds (0, 0.96 and 1.17 m/s). The results show that air speed reduced the local evaporative resistance at all body parts and the reduction ranges from about 50% up to 86% depending on the site. Walking speed reduced the local evaporative resistance, especially at distal body parts such as hands and calves. Additionally, the article provides correction equations for combined air and body movement. It was concluded that the measurements need to be conducted for more clothing ensembles and a larger variety of wind and walking speeds to facilitate proper use for human thermal modelling. Moreover, the results are compared to the equations provided by ISO 9920. In contrast to Fu et al. (2014), the authors concluded that the equations in the standard are not accurate enough for calculating the correction of local evaporative resistance.

As mentioned in section 2.2, Lu et al. (2015) conducted measurements on local thermal insulation and the effect of body movement and air speed. Moreover, the interaction effect of body movement and air speed was analyzed using multiple nonlinear regression. The authors came up with correction equations for 11 body parts and the whole body as functions of air and walking speed. The results are based on three clothing combinations representing light, medium and protective clothing insulation. Hence, the results are very specific to the clothing ensembles and cannot be used directly for other outfits. However, the results give a good estimation of the reduction to be expected on local thermal insulation by air speed and body
movement. Similar studies were done by Anttonen & Hiltunen (2009) for a military clothing ensemble and by Oguro et al. (Oguro et al., 2001, 2002) for a clothing combination of panties, bra, long sleeved shirt, trousers, socks and shoes.

Based on Tanabe’s model (Tanabe et al., 2002), Wan and Fan (2008) described a transient model including heat loss from the microclimate between skin and clothing due to clothing ventilation and air penetration. Clothing ventilation and air penetration are included in energy and mass balances at every segment with the terms $Q_{vent}$ and $\dot{m}_{vent}$, respectively. Both terms can be expressed using the formulas by Qian (2005):

$$Q_{vent,i} = KVI (V_{wind} + 2V_{walk} - v_0)(T_{mc,i} + T_a)$$

$$\dot{m}_{vent,i} = \frac{KVR}{\lambda} (V_{wind} + 2V_{walk} - v_0)(P_{mc,i} - P_a)$$

where $KVI$ and $KVR$ are empirical parameters for calculating the heat and moisture transfer caused by ventilation, $V_{wind}$ is the wind speed of the environment, $V_{walk}$ is the walking speed, $v_0$ is a reference air velocity, $T_{mc,i}$ is the temperature of the microclimate, $T_a$ is the temperature of the environment, $\lambda$ is the latent heat of evaporation of water, $P_{mc,i}$ is the water vapor pressure of the microclimate, and $P_a$ is the water vapor pressure of the environment. Moreover, the authors apply an electric circuit analogy including clothing ventilation and air penetration in a skin-clothing-environment system to calculate convective coefficients for heat and moisture transfer (Figure S3). In Qian (2005), the constants $KVI$ and $KVR$ were derived based on measurements and regression analysis of whole-body thermal properties. Hence, the application at segment level might be questionable. Wan & Fan compared simulation and experimental results for mean skin temperature, but due to the whole-body nature of $KVI$ and $KVR$, outcomes for local skin temperature might differ.

2.4 Summary and discussion of necessity and availability of local clothing values

There is a variety of clothing models used for thermal modelling which can consider clothing on a body segment level (see Table S2). The main input parameters for the models are the
local clothing insulation $I_{cl^*}$ or resistance $R_{elcl^*}$, the local clothing evaporative resistance $R_{e,elcl^*}$ or moisture permeability index $i_{elcl^*}$, and the local clothing area factor $f_{elcl^*}$. Values of these input parameters were measured or computed by the authors of the TP models for validation or research purposes. However, the used values were generally not published. Consequently, this fact limits the usability of TP models by other researchers, who have to rely on other published data, general data bases, e.g. standards, or require the appropriate measurement equipment, e.g. a sweating thermal manikin.

For local thermal insulation, there are limited publications on measured data. Additionally, standards, e.g. ISO 9920 (ISO, 2009), only provide global values. In one study, the effort was made to recalculate global clothing insulation into local values for a large number of clothing items which then can be combined to clothing ensembles. However, the comparison of clothing insulation values of the found studies shows discrepancies. In case of evaporative resistances even fewer values are available. Both outcomes emphasize the uncertainty attached to these values as input in TP models.

Local clothing properties are also influenced by air speed and body movement. Studies have investigated the reduction rates for clothing insulation and evaporative resistance for a small number of clothing ensembles. However, the results cannot be generalized, because of the limited number of tested clothing outfits.

All in all, research for local clothing properties seems to lack dependable and consistent data to be used in TP modelling.

3 Metabolic rate and its distribution over the body

The human body needs energy for maintaining the core temperature at approximately 37°C and for executing mechanical work. The energy is provided in a biochemical process at cell level, where food and oxygen is transformed to heat $H$ and also external work $W$ as well as
carbon dioxide and water as released byproducts. The detailed process can be found in standard literature for human biology or physiology, e.g. (Guyton and Hall, 2006). The total amount of energy converted ($H + W$) is referred to as (total) metabolic rate $M$. The metabolic rate is often provided in the *met* unit, which is based on the amount of energy used by a resting, seated person: $1 \text{ met} = 50 \text{ kcal m}^{-2} \text{h}^{-1} = 58.15 \text{ W m}^{-2}$ (ASHRAE, 2001; Parsons, 2014). The metabolic rate for maintaining basic body functions and temperature in supine position is defined as *basal* metabolic rate and is usually set to 0.8 met.

Individual total metabolic rates can be measured by direct or indirect calorimetry. For direct calorimetry, the subject is placed in a whole-body calorimeter and the energy balance of this person is carefully considered. Indirect calorimetry measures the oxygen consumption and carbon dioxide production of a subject. Further details of the measurement methods can be found in (Parsons, 2014), (Havenith et al., 2002) or in the standard EN-ISO 8996 (ISO, 2004). Based on these measurements, empirical equations and generalized tables for a variety of activities are available. Empirical models calculate metabolic rates using for example the human’s weight, height or heart rate as input parameters. One example is the revised Harris and Benedict equations (Roza and Shizgal, 1984) which calculated the basic metabolic rate (BMR) in kcal/day for males and females:

$$BMR_{\text{male}} = 88.362 + (13.397 \cdot w) + (4.799 \cdot h) - (5.677 \cdot a) \quad (12)$$

$$BMR_{\text{female}} = 447.593 + (9.247 \cdot w) + (3.098 \cdot h) - (4.330 \cdot a) \quad (13)$$

where $w$ is the weight (kg), $h$ is the height (cm), and $a$ is the age (years). Further equations are also summarized in Parsons (2014). Additionally, tables for metabolic rates of basic activities are provided in standard EN-ISO 8996 (ISO, 2004) or ASHRAE/55 (ASHRAE, 2004). Tabularized values give an approximation for metabolic rates, but their error can be significant (up to ±50%) especially for activity levels over 3 met (ASHRAE, 2001). This uncertainty
is mainly due to the differences in body composition of a specific subject and the average person in the model.

For temperature calculation in TP models, the metabolic heat production ($H$) has to be distinguished from the total metabolic rate ($M$) and the mechanical work ($W$). Thus, a mechanical efficiency factor $\eta$ is introduced (14), which then is used to calculate the metabolic heat production (15):

$$\eta = \frac{W}{M} \quad (14)$$

$$H = M(1 - \eta) \quad (15)$$

According to Parsons (2014) and Wyistdham et al. (1966), $\eta$ ranges from zero for activities below 1.6 met and linearly increases up to 0.2 for activities from 1.6 to 5 met, i.e. at least 80% of the metabolic rate is used for heat production.

### 3.1 Local metabolic heat production in multi-segment thermophysiological models

In multi-segment TP models, the total metabolic heat production is the sum of the heat production in all tissue layers at all segments. In Stolwijk’s model (Stolwijk, 1971), the heat production is split up into three parts: 1) local basal heat production in all tissue layers (total of 0.8 met), 2) extra metabolic heat production in the muscle layers due to activity >0.8 met (muscular heat production) and 3) heat production due to shivering (not discussed here). The principle was adopted by the consecutive models of Fiala et al. (1999), Huizenga et al. (2001) and Tanabe et al. (2002). A different approach is taken by Wissler (1985), who calculated metabolic heat production based on chemical reactions using $O_2$ and glucose intake in the body. For the multi-segmental TP models by Smith (1991), Fu (1995) and Foda et al. (2011), the approach to local metabolic heat production is not clear from the published papers.
Basal local metabolic heat production in Stolwijk’s TP model (Stolwijk, 1971) is based on the paper by Aschoff & Wever (1958). The local values of the six body parts add up to 74.4 kcal/h or 86.5 W, which is the total basal metabolic heat production for an average man.

In the model by Fiala (1998) the values for the basal metabolic heat production of each body part are taken from Werner & Buse (1988), who also refer to Stolwijk (1971). These values are obtained in thermo-neutral conditions, i.e. the human body does not need any regulation mechanism to maintain its core temperature. If the tissue temperature $T$ differs from the temperature of thermal neutrality $T_0$, local basal metabolic heat production changes. This change is described with the Q10 effect with a rate change of 2 (Werner and Buse, 1988):

$$\Delta q_{m,\text{bas}} = q_{m,0,\text{bas}} \cdot [2^{(T-T_0)/10} - 1]$$

(16)

where $\Delta q_{m,\text{bas}}$ is the change in metabolic heat production, $q_{m,0,\text{bas}}$ is the basal metabolic heat production, and $T$ and $T_0$ are the actual and thermo-neutral temperature of a tissue layer, respectively.

The metabolic heat production in the UC Berkley model by Huizenga et al. (2001) is calculated using the formulas by Harris & Benedict (1918):

$$BMR_{\text{male}} = 66.5 + (13.75 \cdot w) + (5.003 \cdot h) - (6.755 \cdot a)$$

(17)

$$BMR_{\text{female}} = 655.1 + (9.563 \cdot w) + (1.850 \cdot h) - (4.676 \cdot a)$$

(18)

where $BMR$ is the basal metabolic rate (kcal/day), $w$ is the weight (kg), $h$ is the height (cm), and $a$ is the age (years). In contrast to the other models based on Stolwijk, it is not mentioned how the heat is distributed over the body parts and their layers. However, since the model “is based on the Stolwijk model as well as on work by Tanabe in Japan” (Huizenga et al., 2001), the assumption can be made that the values for local basal metabolic heat production are similar to either of these models. In Tanabe et al. (2002), values for local basal metabolic rates are published, but no primary source is given.
Additional total muscular heat production $H$ (see also (1)) is added to the local basal metabolic heat of the muscle layers $q_{m, bas, muscle}$ with the means of distribution coefficients $a_{m,w}$:

$$q_{m,muscle} = q_{m, bas, muscle} + q_{m,muscle,Stolwijk} = q_{m, bas, muscle} + a_{m,w,Stolwijk} \cdot H$$  \hspace{1cm} (19)

The first set of coefficients was published by Stolwijk and were based on bicycle exercises (see Table 2). However, these coefficients were kept constant for all activities including sitting and standing. Fiala’s model (Fiala, 1998) adopted this basic principle, but the additional metabolic heat production in a muscle layer $q_{m,w,muscle,Fiala}$ depends also on the volume of the muscle $V_{mus}$:

$$q_{m,w,muscle,Fiala} = \frac{\delta(a_{m,w,i} H)}{\delta V_{mus,i}}$$  \hspace{1cm} (20)

The distribution coefficients $a_{m,w,i}$ for standing activities are the same as in Stolwijk (1971), but for the upper body the value is divided between neck, shoulders, thorax and abdomen. In the case of sedentary work, Fiala (1999) adjusted $a_{m,w,i}$ to higher values in the upper body (Table 2). Lastly, Tanabe et al. (2002) calculated the heat production in the muscle layers using equation (21):

$$q_{m,muscle,Tanabe} = 58.2(M - q_{m, bas, muscle})A_{Du}Metf_{muscle}$$  \hspace{1cm} (21)

where $M$ is total metabolic rate and $Metf_{muscle}$ is the muscular metabolic heat distribution coefficient in Tanabe’s model (Table 2). Similar to Stolwijk, the coefficients are not changed for different activities.

### Table 2 Comparison of distribution coefficients for heat production in muscles due to exercise for different body-parts in different thermophysiological models namely Stolwijk, Fiala and Tanabe

<table>
<thead>
<tr>
<th>Body part</th>
<th>Stolwijk</th>
<th>Fiala (standing)</th>
<th>Fiala (seated)</th>
<th>Tanabe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Shoulders &amp; Neck</td>
<td>0.30</td>
<td>0.03</td>
<td>0.08</td>
<td>0.052</td>
</tr>
<tr>
<td>Chest/ Thorax</td>
<td>0.07</td>
<td>0.12</td>
<td>--</td>
<td>0.091</td>
</tr>
<tr>
<td>Back</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.080</td>
</tr>
<tr>
<td>Abdomen/ Pelvis</td>
<td>0.20</td>
<td>0.46</td>
<td>0.08</td>
<td>0.129</td>
</tr>
<tr>
<td>Upper arm + Forearm</td>
<td>0.08</td>
<td>0.08</td>
<td>0.19</td>
<td>0.028</td>
</tr>
<tr>
<td>Hand</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Thigh</td>
<td>0.60</td>
<td>0.60</td>
<td>0.11</td>
<td>0.402</td>
</tr>
<tr>
<td>Lower leg</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.198</td>
</tr>
<tr>
<td>Foot</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>
3.2 Discussion on local metabolic heat distribution coefficients

The heat production in muscle layers is determined by local metabolic heat distribution coefficients (LDCs). The amount of heat produced in a specific muscle layer depends on the intensity of the activity, but also on the type of and posture during the activity. For example, walking at moderate speed and sorting books into a shelf can have similar activity levels. However, the muscles performing the work and therefore, producing heat might be different. Hence, the LDCs should be adjusted to different types of activity. In contrast to this reasoning, most current TP models adopted the LDCs based on bicycle exercise by Stolwijk (1971) for all activities, even though, the activity level for riding a bicycle is higher than for other activities like sitting or standing and the muscular activity is also different. Some adjustments to these LDCs were made empirically by Fiala (2001) for seated conditions and by Tanabe (2002) for the distribution of muscle activity at the upper body (Table 2). The papers by Munir et al. (2009) and Psikuta et al. (2012) show that the change by Fiala (2001) improved the prediction of the local skin temperatures. However, adjusting the LDCs empirically carries the risk that the values are only valid for the specific case. For a sufficient empirical determination of the LDCs, the environmental conditions, the clothing and the individual characteristics have to be varied while performing the same activity. Moreover, other sources for error have to be excluded. In the case of the adjusted values by Fiala (2001), the reasoning behind the modification is not published and therefore, the certainty of these values is unknown. One reason for the empirical approach to LDCs is that a practical measurement method for the values does not exist. All in all, the reliability of the currently used LDCs might be questioned. To fill this gap, methods are needed to determine reliable LDCs for different activities.

4 Effect of local personal factors on local skin temperature and its implication on local thermal sensation

The previous sections showed that the literature provides different sets of clothing insulation values for a similar clothing ensemble, and also, varying LDCs. To assess the significance of
the discrepancies in these input data, their effect on local skin temperature and ultimately, on local thermal sensation (LTS) needs to be discussed. For this purpose, we computed the local skin temperatures in two cases: 1) for the four clothing sets listed in Table 1 and 2) for three sets of LDCs in Table 2, two by Fiala (2001) and one by Tanabe (2002). The basic values by Stolwijk (1971) were excluded, because no details were given on how the coefficient for the upper body is distributed over the single body parts. All scenarios in each case were named according to the main authors: “Nelson & Curlee”, “Havenith”, “Lee” and “Lu” for the comparison of clothing (case 1), and “Fiala seated”, “Fiala standing” and “Tanabe” for the comparison of muscular metabolic heat distribution coefficients (case 2). For all simulations, the TP model ThermoSEM was used as defined by Kingma (2012), which is a multi-segmental model consisting of 19 body parts. Per default, this model simulates an average adult man (73.5 kg, body surface area of 1.86m², body fat percentage of 14%, 87.1 W total basal metabolic heat). These values are not changed for the simulations in this study. Additionally, ThermoSEM requires input data for the activity level, the environmental conditions, and worn clothing ensemble. These values are set differently for the comparison of local skin temperatures based on different clothing insulation values or various LDCs.

In case 1, the activity level was set to a value of 1 met to reduce the influence of heat production due to activity on the local skin temperatures. Furthermore, ThermoSEM uses the muscular heat distribution coefficients by Fiala (1999) for a seated position as default values (Table 2). The environmental conditions were assumed to be uniform and steady state. The effect of different environmental temperatures on the results was investigated by choosing an operative temperature of 22°C and 26°C. Other environmental parameters were not changed (air speed of 0.05 m/s, 40% relative humidity).

In case 2, we investigated two activities namely standing and walking at 4.3 km/h resulting in activity levels of 1.2 met and 2.6 met, respectively (ASHRAE, 2001). No clothing insulation
was applied to eliminate its influence. To reduce the influence of vasomotion in the body, the operative temperature was calculated to represent thermal balance of the body with the environment (Kingma et al., 2014). This calculation resulted in an operative temperature of 26 °C for standing, and 20 °C for walking at 4.3 km/h.

For all computations, the simulation time was set to 60 minutes and all skin temperatures were averaged over the last 45 minutes in each scenario. Since the main interest was in the maximal possible deviation in skin temperature, this maximum difference for any body part \( x \) in case 1 and case 2 were calculated as follows:

\[
\Delta T_{sk,max,case1,x} = \max(|(\bar{T}_{sk,Curlee,x} - \bar{T}_{sk,Havenith,x})|, |(\bar{T}_{sk,Curlee,x} - \bar{T}_{sk,lee,x})|, (\bar{T}_{sk,Havenith,x} - \bar{T}_{sk,lee,x})|)
\]

\[
\Delta T_{sk,max,case2,x} = \max(|(\bar{T}_{sk,FialaSeated,x} - \bar{T}_{sk,FialaStand,x})|, |(\bar{T}_{sk,FialaSeated,x} - \bar{T}_{sk,Tanabe,x})|, |(\bar{T}_{sk,FialaStand,x} - \bar{T}_{sk,Tanabe,x})|)
\]

where \( \Delta T_{sk,max,case1/2,x} \) is the maximum difference in skin temperature for any body part \( x \) in case 1 or 2 and \( \bar{T}_{sk,Scenario,x} \) is the 45-minute average of the skin temperature of any body part \( x \) in any scenario. For comparison, also the averages are calculated analog to (22) and (23) by dividing the sum of all the differences by the number of scenarios in each case.

Finally, in section 4.3, the impact of the temperature differences on LTS is discussed using the LTS model by Zhang (2003).

### 4.1 Differences in local skin temperature for different sets of local clothing values

Figure 2 shows the maximum and average skin temperature differences of all four clothing data sets for the mean and six local body sites in two operative temperatures \( T_o \). It can be seen that the maximum and average difference in skin temperature depends on the body site and also on the operative temperature. For most body parts, the variation in skin temperatures ranges from about 0.4 to 1.4 °C with lower values for the higher operative temperature. In contrast to the other body parts, the foot skin temperature shows the highest maximum and
average temperature discrepancy of up to 4.4 °C and 2.4 °C for \(T_o = 22°C\) and \(T_o = 26°C\), respectively. Furthermore, the difference in skin temperature does not necessarily relate to the difference in clothing insulation (see Table 3). For example, the difference in clothing insulation for the abdomen and foot are the same, but the skin temperature difference of the foot is much higher than the one of the abdomen. Additionally, also temperature deviations can be found at body parts without clothing for instance the forehead and hand.

![Figure 2](image.png)

**Figure 2** Maximum and average local skin temperature differences for all four clothing data sets

<table>
<thead>
<tr>
<th></th>
<th>Forehead</th>
<th>Upper arm</th>
<th>Hand</th>
<th>Thigh</th>
<th>Foot</th>
<th>Abdomen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. difference in skin temp. [°C]</td>
<td>0.8</td>
<td>1.2</td>
<td>1.1</td>
<td>1.3</td>
<td>4.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Max. difference in clothing insulation [m²K/W*10⁻²]</td>
<td>0</td>
<td>4.65</td>
<td>0.16</td>
<td>6.2</td>
<td>20.8</td>
<td>20.8</td>
</tr>
</tbody>
</table>

The temperature deviations at non-clothed body parts and the lacking correlation between differences in clothing and skin temperatures may be explained by looking at the local heat balances in the TP models. At every body part, heat is gained through metabolic processes, lost to the environment due to the temperature difference between skin and environment, stored in the tissue layers, and exchanged internally via blood perfusion. When adding clothing insulation to the heat balances, this reduces the heat losses to the environment at the clothed body part. To restore a thermal balance (heat production equals heat losses), more heat should be removed via the uncovered body parts by increasing local skin temperatures. Since heat is also exchanged internally via the blood perfusion, the clothing also indirectly
influences other local heat balances. In detail, the heat fluxes of the blood flows from each body part are mixed in the central blood pool. From this step, the temperatures for the returning blood flows are calculated for the next simulation step. Some of these temperatures are corrected for counter current heat exchange that takes place due to closely located arteries and veins in some body parts. All in all, this physiological mechanism requires that the local clothing data is precise at all body parts.

The influence of operative temperature on the variation in the skin temperature differences is also due to its effect on the heat balances of the model. Firstly, higher operative temperatures lead initially to reduce heat losses to the environment, because of the decreased temperature difference between the skin and the environment. Because of the smaller effective temperature difference, the influence of clothing is reduced as well. Secondly, the operative temperature can also affect the thermoregulatory processes in the body and their implications for the local heat balances. On one hand, in cold environments vasoconstriction may occur in some body parts. This response decreases the blood flow and hence, the heat exchange with other body parts. In this case, the impact of clothing might be kept more locally. On the other hand, warm environments lead to vasodilation, i.e. the blood flow to the body parts is increased. This process may lead to a larger influence of the calculated returning heat flux from the blood pool which depends on all other body parts. However, in the moderate conditions presented here, both processes are absent.

In addition to the discussion on local clothing value in section 2.4, it needs to be mentioned that the presented results contradict the assumption by, e.g. Nelson & Curlee (2005) (section 2.2) that uncovered surfaces of a thermal manikin are not influenced by clothed surfaces. Even though, thermal manikins do not include any blood perfusion for practical reasons, the effect of this assumption on the clothing insulation values needs to be studied further.
4.2 Differences in local skin temperature for different distribution coefficients of local metabolic heat

The impact of different sets of LDCs was calculated for two activities for an average man without clothing. The maximum and average temperature difference in-between scenarios for these simulations are shown in Figure 3 for the body average and for 6 separate body parts. In all cases, the temperature differences are equal to or lower than 1.3 °C. When comparing the activity levels, the temperature difference is higher for upper arm, hand and thigh, and much lower for mean, forehead and abdomen. Additionally, the temperature differences do not entirely relate to the differences in the LDCs (Table 4), which is similar to the results for the local clothing. For example, the difference in LDCs for the hand is very low, but still a maximum skin temperature difference of 0.8°C can be seen. For the abdomen, the effect is reversed. Here, the variation in LDCs is larger, but the skin temperature difference is low. Also, differences in skin temperature for body parts without allocated muscular heat, e.g. the forehead, are found, but they are below 0.3°C.

![Figure 3](image)

**Figure 3** Maximum and average temperature differences for all three sets of muscular metabolic heat distribution coefficients

<table>
<thead>
<tr>
<th></th>
<th>Forehead</th>
<th>Upper arm</th>
<th>Hand</th>
<th>Thigh</th>
<th>Foot</th>
<th>Abdomen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. difference in skin temp. [°C]</td>
<td>0.03</td>
<td>1.3</td>
<td>0.8</td>
<td>0.8</td>
<td>1.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Max. difference in muscular metabolic heat distribution [-]</td>
<td>0</td>
<td>0.04</td>
<td>0.005</td>
<td>0.17</td>
<td>0.005</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 4 Comparison of maximum difference in local heat distribution coefficients and skin temperature at operative temperature $T_a = 20°C$ and an activity level of 2.6 met.
In the simulations of this section, the heat gain at the local balances is influenced by the sets of LDCs which determine how the overall metabolic heat production is redistributed to the local energy balances. Since these heat balances directly relate to the skin temperatures, uncertainties in the LDCs may increase the error in predicting local skin temperatures. As discussed in the previous subsection on the effect of local clothing properties, the skin temperature of one body site is also affected by all other body parts through the internal heat exchange of blood flows via the central blood pool. The heat exchange might furthermore be influenced by vasomotion. Again, this physiological effect is not present in the presented simulations.

As discussed in section 3.2, the actual heat production in specific muscles also depends on the type of activity. The simulations for Figure 3 are based on different LDCs which represent different types of activity. For example, the scenario “Fiala standing” was originally based on bicycle experiments by Stolwijk and the scenario “Fiala seated” was fitted for a sitting position. Therefore, the comparison of the simulation results for the different sets of LDCs may lead by itself to some deviation in local skin temperature. However, in most TP models one set of LDCs is set as default or the specific type of activity for which they were defined is not traceable, e.g. Tanabe (2002). Hence, the comparison in this paper shows the consequence when LDCs are not adjusted to the type of activity simulated.

The graphs in Figure 3 also emphasize that the results for mean and local skin temperatures can be very different. Most of the current TP and coupled TS models (Table S1) are validated for mean skin temperature and overall thermal sensation (OTS), respectively. For expanding these models to local skin temperature and LTS, the impacts on the local heat balances, as discussed above, have to be carefully considered.

4.3 Implication of differences in local skin temperature on local thermal sensation

The previous sections showed that uncertainties in local clothing properties and LDCs lead potentially to deviations in local skin temperature. To estimate the need for accurate input
data, the impact of these findings on LTS was investigated. This evaluation was done using the functions for LTS provided by Zhang (2003) for static conditions:

\[
LTS_{stat} = 4 \left( \frac{2}{1 + e^{-C1(T_{sk,loc} - T_{sk,loc,set})}} - K1 \right) \]

where \( T_{sk,loc} \) is the local skin temperature, \( T_{sk,loc,set} \) is the local skin temperature in neutral conditions (set point), \( T_{sk} \) in the mean skin temperature, \( T_{sk,set} \) is the mean skin temperature in neutral conditions (set point), and \( C1 \) as well as \( K1 \) are regression coefficients for a specific body part. As examples, the body sites upper arm and foot were chosen (Figure 4), since these locations showed the highest temperature differences in the simulations of the previous sections. Additionally, they have an important influence on the OTS and thermal comfort, as was discussed by Zhang et al. (2010).

![Figure 4](image)

**Figure 4 Functions of LTS for a) upper arm and b) foot. The deviation from mean skin temperature to its set point is varied from -2 to +2 °C as shown in the legend.**

Figure 4 displays the functions of LTS for the two body parts. LTS is displayed according to the 9-point ASHRAE scale from “very cold” to “neutral” to “hot”. The graphs depend on the deviation of the local and mean skin temperature from their set points. Assuming that the set points are fixed, an estimation of the influence of local skin temperature on LTS can be made.

For example, the maximum temperature difference for the upper arm was 1.3°C. This result translates into a change in thermal sensation from neutral \((T_{sk,loc} - T_{sk,loc,set} = 0°C)\) to slightly warm/warm or neutral to slightly cool/cool for \(T_{sk,loc} - T_{sk,loc,set}\) equals +1.3°C and -
1.3°C, respectively. More extreme changes are found for the foot, where the temperature deviation ranged from 2.2 up to 4°C. Starting from neutral, these discrepancies change the LTS starting from neutral to warm/very warm or cool/cold. However, in general the reported skin temperature differences are around 1°C or lower. Thus, for these body parts, the change in LTS is around one step on the sensation scale.

The impact of these findings on local heating and cooling research can be seen from two perspectives: 1) considering the normal fluctuations in LTS votes and 2) considering the statistical significance between two sensation votes. For the first point of view, studies show that LTS votes within a group of subjects vary between 2 steps on the sensation scale (Dalewski et al., 2014; Melikov and Knudsen, 2007). This finding would be in line with the presented variation of thermal sensation for most body parts, excluding upper arm and foot. For the second perspective, researchers found significant differences in thermal comfort in scenarios, where the LTS was changed with environmental measures one step on the sensation scale (Kaczmarczyk et al., 2010; Li et al., 2010). This implies that the input data of all body parts is critical for local thermal modelling.

All in all, this analysis shows that variations in local skin temperatures can result in large difference in LTS. Hence, the data for clothing properties and LDCs should be chosen carefully, to avoid false results.

4.4 Limitation of the analysis

The analysis in sections 4.1 to 4.3 gives an example of how the deviations in local clothing properties or in LDCs can affect LTS. The results are dependent on the reliability of the used TP and TS model. However, the impact of their inaccuracy on the conclusions is limited, because the same models were used in all cases. Furthermore, the simulations were simplified by implementing only uniform conditions, a single clothing outfit and an average man. In contrast, studies on local heating and cooling deal with non-uniform conditions, a variety of
clothing sets and divers human subjects. These variations may lead to even more uncertainties in the input parameters resulting in large variations in local skin temperatures. Therefore, additional data is required and it should be measured as accurate as possible.

5 Conclusion

To help develop efficient local heating and cooling concepts as well as to test the comfort boundaries for non-uniform environments in modern buildings, local thermal modeling is required. Thermal sensation can be modeled with multi-segment thermophysiological and coupled sensation models. These models calculate local skin temperatures and, furthermore, can account for local clothing properties as well as for changes in local metabolic heat. This study gives an overview of available local data, investigated their consistency throughout literature and examined their effect on local thermal sensation modelling.

The following conclusions can be drawn:

- Full and consistent data sets for local clothing properties including insulation, evaporative resistance and their change due to air penetration are not fully available in published literature for a typical variety of office clothing sets.
- Distribution coefficients for muscular heat production are not verified for office activities, namely sitting, standing and walking, but were adapted empirically.
- Variations in local clothing properties and in coefficients for muscular heat distribution affect the accuracy of the local sensation output (about one step on a 9-point thermal sensation scale per 1°C change in local skin temperature).

These conclusions lead to possible future research which could include:

- a systematic study on local clothing properties and their change due to air speed and body movement,
- development of feasible methods for measuring and validating local heat production.
Finally, since thermophysiological models aim to be applied in design phases of modern buildings and therefore, might be used by building and civil engineers, an effort might be needed to include local clothing and local metabolic heat data in available standards.

References


Fu, G. (1995) A transient 3D mathematical thermal model for the clothed human, Kansas State University, Manhattan, Kansas.


### Table S1 Overview of thermophysiological and thermal sensation models

<table>
<thead>
<tr>
<th>year</th>
<th>model</th>
<th>description</th>
<th>restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>Fanger (Fanger, 1970)</td>
<td>• one node</td>
<td>• uniform temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• empirical</td>
<td>• only whole body</td>
</tr>
<tr>
<td>1971</td>
<td>Givoni (Givoni and Goldman, 1971)</td>
<td>• one node</td>
<td>• only hot environment</td>
</tr>
<tr>
<td>1971</td>
<td>Pierce two-node model</td>
<td>• two nodes: core and skin</td>
<td>• exposure time &lt; 1h</td>
</tr>
<tr>
<td></td>
<td>(Gagge et al., 1971)</td>
<td>• control and controlled system</td>
<td>• only uniform</td>
</tr>
<tr>
<td>1977</td>
<td>KSU-model</td>
<td>• like Gagge (1971), but other control equation</td>
<td></td>
</tr>
<tr>
<td>1991</td>
<td>Smith (Smith, 1991) as cited in (Miimu et al., 2013)</td>
<td>• three-dimensional finite element model</td>
<td>• no clothing model</td>
</tr>
<tr>
<td>1992</td>
<td>Lotens (Lotens and Havenith, 1992; Lotens, 1993)</td>
<td>• emphasis on clothing</td>
<td>• limited physiology and thermoregulation</td>
</tr>
<tr>
<td>1995</td>
<td>Fu (Fu and Jones, 1996; Fu, 1995)</td>
<td>• based on Smith (1991)</td>
<td>• high demand on computational resources</td>
</tr>
<tr>
<td>1999</td>
<td>UTCI-Fiala</td>
<td>• based on Stolwijk</td>
<td>• 5°C &lt; T_{mean} &lt; 50°C</td>
</tr>
<tr>
<td>2001</td>
<td>UCB model</td>
<td>• 19 segments, 4 - 5 layers, 3 sectors; 187 nodes</td>
<td>• 0.8 - 10 met</td>
</tr>
<tr>
<td></td>
<td>(Huizenga et al., 2001)</td>
<td>• detailed passive system</td>
<td>• regression based</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• steady-state and transient bioheat equation</td>
<td>• setpoint based</td>
</tr>
<tr>
<td>2002</td>
<td>Tanabe (Tanabe et al., 2002)</td>
<td>• based on Stolwijk</td>
<td>• setpoint based</td>
</tr>
<tr>
<td>2003</td>
<td>Nilsson (Nilsson and Holmér, 2003; Nilsson, 2007)</td>
<td>• 16 segments, 65 nodes</td>
<td>• validated for mild environments only</td>
</tr>
<tr>
<td>2003</td>
<td>Lomas/ Fiala (Lomas et al., 2003)</td>
<td>• passive &amp; active system; steady-state &amp; transient</td>
<td>• steady state</td>
</tr>
<tr>
<td>2003</td>
<td>Zhang/ UC Berkley (Zhang, 2003)</td>
<td>• 15 cylindrical body parts, 5 layers</td>
<td>• measured neutral condition</td>
</tr>
<tr>
<td>2011</td>
<td>Multi-segmental Pierce model (Foda and Siren, 2011)</td>
<td>• local skin setpoints based on neutral conditions</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>Fager PMV model</td>
<td>• empirical</td>
<td>• uniform temperature</td>
</tr>
<tr>
<td></td>
<td>(Fanger, 1970)</td>
<td>Dynamic Thermal Stimulus model: area averaged</td>
<td>• whole body only</td>
</tr>
<tr>
<td></td>
<td></td>
<td>thermal sensation</td>
<td>• only local skin temperatures; not enough for whole body thermal state</td>
</tr>
<tr>
<td>2003</td>
<td>Lomas/ Fiala (Lomas et al., 2003)</td>
<td>• dynamic thermal sensation model</td>
<td>• empirical model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• mean skin &amp; core temp. &amp; time derivatives</td>
<td>• steady state</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• transient conditions</td>
<td>• for automotive application</td>
</tr>
<tr>
<td>2003</td>
<td>Zhang/ UC Berkley (Zhang, 2003)</td>
<td>• uniform &amp; non-uniform environment</td>
<td>• for thermal neutral zone</td>
</tr>
<tr>
<td>2011</td>
<td>ThermoSEM (Kingma et al., 2012; Schellen et al., 2013)</td>
<td>• thermal sensation based on neurophysiology</td>
<td>• whole-body thermal sensation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• uniform &amp; non-uniform</td>
<td>• validated for mild thermal challenges only</td>
</tr>
<tr>
<td>Year</td>
<td>Model</td>
<td>Clothing model</td>
<td>Required data input</td>
</tr>
<tr>
<td>------</td>
<td>-------</td>
<td>----------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>1971</td>
<td>Stolwijk (Stolwijk and Hardy, 1966; Stolwijk, 1971)</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>heat &amp; mass transfer differential equations for fabric-airspace-skin-body system</td>
<td>diffusion &amp; heat transfer coefficients</td>
</tr>
<tr>
<td></td>
<td></td>
<td>set of equations and boundary conditions solved numerically</td>
<td>conductivity of fabric</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&amp; set of equations and boundary conditions solved numerically</td>
<td>local clothing insulation and evaporative resistance of fabric</td>
</tr>
<tr>
<td></td>
<td></td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>during validation subjects wore shorts, but clo value not considered</td>
<td>none</td>
</tr>
<tr>
<td>1991/1995</td>
<td>Smith/ Fu (Fu and Jones, 1996; Fu, 1995; Smith, 1991)</td>
<td>transient, quasi-two-dimensional model of clothing heat &amp; moisture transfer based on the clothing model by Jones &amp; Ogawa (1992, 1993)</td>
<td>local values for clothing insulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>heat transport through air layers by radiation, and conduction</td>
<td>local area factor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>moisture transport through air layers by diffusion</td>
<td>local permeability index or evaporative resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>o vapor pressure model instead of skin wetness model</td>
<td>local area factors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>o describes upper limit of the moisture accumulation: 35 g/m²</td>
<td>correction factors for air and body movement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>none</td>
<td>procedure repeated if temperatures θcl and θct deviate more than 0.001°C</td>
</tr>
<tr>
<td>1992</td>
<td>Lotens (Lotens and Havenith, 1992; Lotens, 1993)</td>
<td>four layer model: under clothing, trapped air layer, outer garment, adjacent air</td>
<td>heat transfer coefficients, moisture uptake, weight, radiation properties of clothing items</td>
</tr>
<tr>
<td></td>
<td></td>
<td>resistance network for dry heat and evaporative transfer systems</td>
<td>width of trapped air layer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&amp; ventilation and wind speed</td>
<td>clothing area factor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&amp; clothing area factor</td>
<td>&amp; &amp;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&amp; &amp;</td>
<td>&amp;</td>
</tr>
<tr>
<td>1999</td>
<td>UTCI-Fiala (Fiala et al., 1999, 2001, 2012)</td>
<td>clothing included for each sector of every segment.</td>
<td>local values for clothing insulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>local effective heat transfer coefficient ( U_{cl} ) and a local effective evaporative coefficient ( U_{cl,e} ) for multi-layered clothing ensemble.</td>
<td>local area factor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>evaporative heat losses through clothing with approach as in Jones &amp; Ogawa (1992)</td>
<td>local permeability index or evaporative resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&amp; &amp;</td>
<td>&amp;</td>
</tr>
<tr>
<td>2001</td>
<td>UCB model (Huizenga et al., 2001)</td>
<td>improved clothing model by (Fu et al., 2014)</td>
<td>local values for clothing insulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>distinction between clothed and not-clothed pathway from body core to environment</td>
<td>local evaporative resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>absorption and desorption by clothing included by balancing the specific heat flux around the clothing node</td>
<td>local area factors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&amp; &amp;</td>
<td>&amp;</td>
</tr>
<tr>
<td>2002</td>
<td>Tanabe (Tanabe et al., 2002)</td>
<td>same as UTCI-Fiala</td>
<td>local values for clothing insulation</td>
</tr>
<tr>
<td>2007</td>
<td>ThermoSEM (Kingma et al., 2010; Severens, 2008)</td>
<td>same as UTCI-Fiala</td>
<td>local area factor</td>
</tr>
<tr>
<td>2011</td>
<td>Multi-segmental Pierce model (Foda and Sirén, 2011)</td>
<td>radiative &amp; convective heat losses as functions of clothing temperature</td>
<td>local values for clothing insulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iterative procedure for estimating clothing temperature ( T_{cl} ) as function of radiative &amp; convective heat transfer coefficients (see (1) and (2))</td>
<td>local clothing area factor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>procedure repeated if temperatures ( T_{cl} ) and ( T_{ct} ) deviate more than 0.001°C</td>
<td>&amp;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&amp;</td>
<td>&amp;</td>
</tr>
</tbody>
</table>

**Table S2 Implementation of clothing in multi-segment thermophysiological models**
Figure S1 Heat and moisture transport resistance model according to Lotens and Havenith (1992)

Figure S2 Node network model according to Fu et al. (2014)

Figure S3 Electric circuit analogy for including clothing ventilation and air penetration into a body-clothing-environment system by Wan and Fan (2008)