Topic A7: Thermal comfort

Heat and moisture transfer through clothing for a person with contact surface

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SUMMARY

A detailed model of heat and moisture transfer through clothing is developed and has been implemented in the UC Berkeley Comfort Model (UCB Model), to simulate dry heat loss and moisture absorption/evaporation through clothing. Equations are presented to describe four paths of heat and moisture transfer between naked skin and environment, clothed skin and environment, and naked and clothed skin in direct contact with a solid surface. Case studies are presented for different typical clothing ensembles and different contact fractions of the contact area with a solid surface, a chair. The results show that the developed clothing model is a useful tool for the study of heat and moisture transfer through clothing and contact surfaces, and the assessment of thermal comfort in transient, non-uniform environments.

INTRODUCTION

The UC Berkeley Comfort Model (UCB Model, Huizenga et al., 2001) is a multiple-segmented physiology and comfort model. Each segment is modelled as four body layers (core, muscle, fat, and skin tissues) and a clothing layer. The model predicts physiology parameters (such as skin and core temperatures) and thermal sensation and comfort for 16 body parts as well as the whole body (e.g. hand sensation cold or hot, whole-body cold or hot, comfortable or uncomfortable etc., Zhang et al., 2003). Any body part is allowed to contact with a surface (such as a chair), and the contact surface can be heated or cooled (like a heated and cooled chair, or any contacting heating/cooling devices). The UCB Model was validated to predict the human physiological response in transient, non-uniform thermal environments. Two types of deficiencies were found in the UCB Model.

The moisture transport through clothing consists of evaporation, condensation and wicking (Havenith et al., 2008). In the UCB model, the moisture transfer through clothing used regain approach to calculate the amount of moisture within the clothing (Huizenga et al., 2001). The regain approach should be used in steady state but not suitable for transient and non-uniform thermal environments, because regain does not account for the moisture absorption and condensation. In this paper, we improved the modelling of moisture transfer through clothing by considering evaporation through clothing and moisture absorption/ wicking by clothing.

The contact solid surface is usually vapor and water impermeable (with a big evaporative resistance). The vapor from skin and moisture absorption within the clothing will be blocked when the skin or clothing contacts the surface. In the new modelling, we allow the moisture to be absorbed by clothing when contacting the surface.

The new improvements have been implemented into the Berkeley comfort model (Zhang et al., 2003). The simulation examples were studied with different typical clothing ensembles and different contact areas of a chair.

METHODOLOGIES

There are four paths through which heat is transferred from skin to environment (Figure 1): exposed skin and clothed skin to ambient air, exposed and clothed skin in direct contact with a solid surface. The surface areas for the four transfer paths are divided by fractions, and the sum of the naked and clothed fractions of each segment is 1.

$$f_{nude} * (f_{nude-env} + f_{nude-cont}) + f_{cloth} * (f_{cloth-env} + f_{cloth-cont}) = f_{nude} + f_{cloth} = 1 \quad (1)$$

Where f_{nude} and f_{cloth} are the fractions of the naked and the clothed areas of the segment, respectively. When this segment is nude, f_{nude} is 1 and f_{cloth} is zero. $f_{nude-env}$ and $f_{nude-cont}$ are the fractions of the naked area connected with ambient air and a solid surface, respectively. When the nude skin does not contact with a surface, then $f_{nude-env}$ is 1, and $f_{nude-cont}$ is zero. $f_{cloth-env}$ and $f_{cloth-cont}$ are the fractions of the clothed area connected with ambient air and a solid surface, respectively.

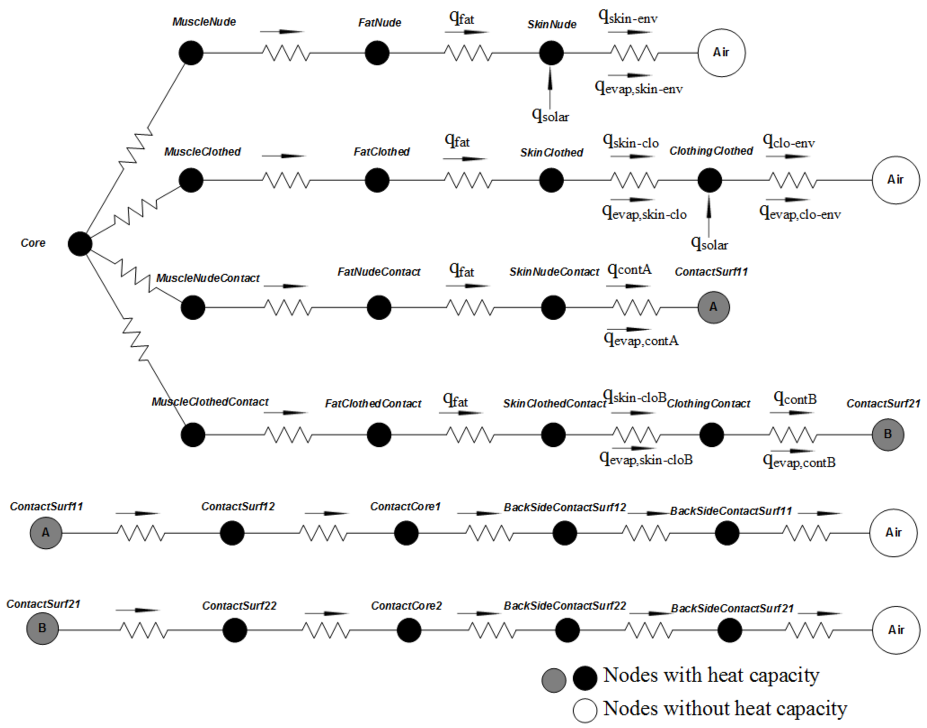


Figure 1. Node network.

Skin node

For the skin node of each individual segment, the stored heat within the skin is its metabolic heat production, the heat gain from the inner body layer (fat layer), and solar radiation, subtracting the heat loss from conduction, convection and radiation with the clothing or the ambient air, and the heat loss from sweating evaporation and absorption within clothing. The stored heat within the skin is calculated in below (unit in Watt).

$$q_{skin,storage} = q_{fat} + q_{skin,met} - q_{skin-env} - q_{skin-clo} - q_{skin-clo-cont} - q_{skin-cont} \\ - q_{evap,\ skin-env} - q_{evap,\ skin-clo} - q_{evap,\ skin-clo-cont} - q_{evap,\ \text{skin-}cont} + q_{solar,skin} \tag{2}$$

Where $q_{skin,storage}$ is the heat storage in skin node. q_{fat} is the heat gain from fat. $q_{skin,met}$ is the skin metabolic heat production. $q_{skin-env}$ and $q_{skin-clo}$ are the sensible heat losses from nude and clothed skin to the ambient environment, respectively. $q_{skin-cont}$ and $q_{skin-clo-cont}$ are the conductive heat losses through the naked and the clothed skin to the contact surface, respectively. $q_{evap,\ skin-env}$ and $q_{evap,\ skin-clo}$ are the latent heat exchanges between naked and clothed skin with ambient environment. $q_{evap,\ \text{skin-}cont}$ and $q_{evap,\ skin-clo-cont}$ are the latent heat exchanges through the naked and the clothed skin to the contact surface. $q_{solar,skin}$ is the heat exchange through the short-wave radiation from the sunlight (solar load).

$q_{skin-env}$ includes convective and radiative heat losses, and can be calculated using the below equation.

$$q_{skin-env} = Surf * f_{nude} * f_{nude-env} * \frac{(T_{skin} - T_{air})}{I_{air}} \tag{3}$$

Where $Surf$ is the skin surface area of the segment. T_{skin} and T_{air} are the skin and the ambient air temperatures, respectively (°C). I_{air} is the thermal resistance of the external air, *clo* (1 clo = 0.155 m^2KW^{-1}). I_{air} can be determined by the coefficients of the radiative and convective heat exchange, h_r and h_c . These two values are given in de Dear et al. (1997).

The heat loss of the naked skin contacting with a solid surface, $q_{\text{skin-}cont}$ can be obtained by:

$$q_{\text{skin-}cont} = Surf * f_{nude} * f_{nude-cont} * \frac{(T_{skin} - T_{cont})}{I_{cont}} \tag{4}$$

T_{cont} is the temperature of the contact surface, °C. I_{cont} is the contact resistance, m^2KW^{-1}.
Similarly, $q_{skin-clo}$ is obtained by the temperature difference between the skin and clothing, and the intrinsic thermal resistance of the clothing, I_{clo} (*clo*). $q_{skin-clo-cont}$ can be obtained by temperature difference between the skin and contact surface, and the thermal resistance provided by the contact resistance and clothing.

To simplify the problem, water wicking and absorption/desorption through clothing are lumped as water absorption within clothing, adding the weight to the garment. The latent heat exchange from the naked skin to environment, $q_{evap,\ skin-env}$ can be calculated in below.

$$q_{evap,skin-env} = Surf * f_{nude} * f_{nude-env} * \frac{(P_{skin} - P_{air})}{R_{e,air}} \tag{5}$$

Where P_{skin} and P_{air} are the partial vapor pressures at skin and air temperatures, Pa. $R_{e,air}$ is the evaporative resistance of ambient air, $Pa \cdot m^2 \cdot W^{-1}$, and is related with the convective heat transfer coefficient and the air Lewis constant (Le , 0.0165 °C/Pa, Fiala et al., 1999). In the superficial cutaneous layer, the vapor pressure at the location where sweat glands are located is the saturated value at the skin temperature (Fiala et al., 1999). Therefore, the vapor pressure at the skin surface, P_{skin} can be calculated by the equation in below.

$$P_{skin} = \frac{\frac{P_{skin,sat}}{R_{e,skin}} + \frac{\lambda_{\mathrm{H_2O}}}{Surf * f_{nude}} m_{sw} + \frac{P_{air}}{R_{e,air}}}{\frac{1}{R_{e,air}} + \frac{1}{R_{e,skin}}} \quad \text{for the naked skin} \tag{6a}$$

$$P_{skin} = \frac{\frac{P_{skin,sat}}{R_{e,skin}} + \frac{\lambda_{\mathrm{H_2O}}}{Surf * f_{nude}} m_{sw} + \frac{P_{air}}{R_{e,tot}}}{\frac{1}{R_{e,tot}} + \frac{1}{R_{e,skin}}} \quad \text{for the clothed skin} \tag{6b}$$

Where $\lambda_{\mathrm{H_2O}}$ is the enthalpy of water vaporization, 2256 kJ/kg. m_{sw} is the rate of sweat production and elicited from the UCB model (Huizenga et al., 2001). $P_{skin,sat}$ is the saturated vapor pressure at the skin temperature. $R_{e,skin}$ is the evaporative resistance of the skin, and it is 330 m^2PaW^{-1} for a well hydrated person (Salloum et al., 2007). For clothed skin, $R_{e,tot}$ is the total evaporative resistance of clothing (m^2PaW^{-1}), including $R_{e,air}$ and the intrinsic evaporative resistance of clothing, $R_{e,clo}$.

For the clothed area, the moisture production from skin sweating equals to the sum of moisture storage by the clothing $m_{clo,cloth}$ and moisture evaporation through the clothing.

$$m_{sw} = m_{clo,cloth} + \frac{\left(P_{skin,sat} - P_{air}\right)}{\lambda_{\mathrm{H_2O}} * R_{e,tot}} \tag{7}$$

The latent heat exchange from the clothed skin to the clothing, $q_{evap,\,skin-clo}$ can be calculated by:

$$q_{evap,skin-clo} = Surf * f_{cloth} * f_{cloth-env} * \left[\frac{\left(P_{skin} - P_{air}\right)}{R_{e,tot}} + C_{\mathrm{H_2O}} * m_{clo,cloth}\left(T_{skin} - T_{clo}\right)\right] \tag{8}$$

Where $C_{\mathrm{H_2O}}$ is the specific heat of water, 4.2×10^3J kg^{-1}°C^{-1}.

The contact surface can be assumed vapor and water impermeable (with a big evaporative resistance). For the contact area with totally wetted skin, the extra water from sweating is totally dripped for the naked skin, or totally absorbed by the clothing for the clothed skin. Therefore, $q_{evap,\,\mathrm{skin}\text{-}cont}$ can be obtained by:

$$q_{evap,\,\mathrm{skin}\text{-}cont} = Surf * f_{nude} * f_{nude-cont} * \frac{\left(P_{skin} - P_{air}\right)}{R_{e,cont} + R_{e,air}} \tag{9}$$

For the contact area with clothing, the moisture transfer from skin can be calculated by:

$$m_{sw} = m_{clo,cont} + \frac{\left(P_{skin,sat} - P_{air}\right)}{\lambda_{\mathrm{H_2O}} * (R_{e,tot} + \frac{R_{e,cont}}{f_{clo}})} \tag{10}$$

f_{clo} is the clothing area factor (McCullough et al., 1985). $q_{evap,\,skin-clo-cont}$ can be obtained by

$$q_{evap,\,skin-clo-cont} = Surf * f_{cloth} * f_{cloth-cont} * \left[\frac{\left(P_{skin} - P_{air}\right)}{R_{e,tot} + \frac{R_{e,cont}}{f_{clo}}} + C_{\mathrm{H_2O}} * m_{clo-cont}\left(T_{skin} - T_{clo}\right)\right] \tag{11}$$

The skin can absorb radiation from the short wave solar (Huizenga et al., 2001). The short wave radiation is determined by skin absorptance α_{skin} and solar radiation intensity $I_{solar,skin}$.

$$q_{solar,skin} = \alpha_{skin} I_{solar,skin} \tag{12}$$

Clothing node

The clothing node of heat storage can be calculated from the equation below.

$$\begin{aligned} q_{clo,storage} &= q_{skin-clo} - q_{clo-env} + q_{skin-clo-cont} - q_{clo-cont} + q_{evap,\ skin-clo} - q_{evap,clo\text{-}env} \\ &+ q_{evap,\ skin-cont} - q_{evap,\ \mathrm{clo}\text{-}cont} + q_{solar,clo} \end{aligned} \tag{13}$$

Where $q_{clo-env}$ and $q_{evap,\ clo-env}$ are the sensible and latent heat loss between the clothing node and the environment, respectively.

$$q_{clo-env} = Surf * f_{clo} * f_{cloth} * f_{cloth-env} * \frac{(T_{clo} - T_{air})}{I_{air}} \tag{14}$$

$$q_{evap,clo-env} = Surf * f_{clo} * f_{cloth} * f_{cloth-env} * \frac{(P_{cloth} - P_{air})}{R_{e,air}} \tag{15}$$

The heat loss of the clothing contacting with a solid surface, $q_{clo-cont}$ can be obtained by:

$$q_{clo-cont} = Surf * f_{clo} * f_{cloth} * f_{cloth-cont} * \frac{(T_{clo} - T_{cont})}{I_{cont}} \tag{16}$$

$q_{evap,\ \mathrm{clo}\text{-}cont}$ is assumed as zero, for the sweating water is totally absorbed by the clothing. $q_{solar,clo}$ is the absorbed short wave solar radiation from clothing.

$$q_{solar,clo} = \alpha_{clo} I_{solar,clo} \tag{17}$$

Where α_{clo} is the absorbance to the short wave radiation of clothing. $I_{solar,clo}$ is the solar radiation intensity received by the clothing.

The water from sweating is absorbed by the clothing when the skin is saturated, i.e. P_{skin} exceeds the saturated vapor pressure $P_{skin,sat}$. C_{clo} is the specific heat of clothing, J kg^{-1}°C^{-1}. The temperature increase of the clothing with the absorbed water is obtained in below.

$$\Delta T_{clo} = \frac{q_{clo,storage}}{Surf\left(C_{clo} m_{clo} + C_{\mathrm{H_2O}} * f_{cloth} * m_{clo,cloth} + C_{\mathrm{H_2O}} * f_{cont} * f_B * m_{clo,cont}\right)} \tag{18}$$

Contact node

The UCB model included a contact surface for each segment (Huizenga et al., 2001), with the fractions of naked and clothed skin. Each contact surface is divided into five layers (two contact layer near the skin, a core layer and two back side layers near the air). Each layer has its thermal conductivity, specific heat and thickness.

For each layer, the heat loss through solid surfaces is via conduction and vapor transport. The heat storage of each layer can be calculated from heat transfer between the current layer with two neighboring layers. The last layer exposed to the environment includes heat losses to ambient air via convection and radiation.

RESULTS AND DISCUSSION

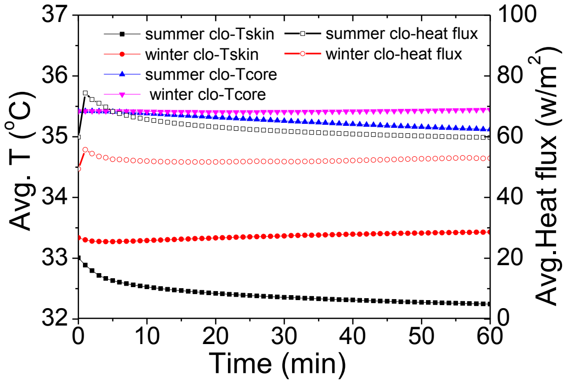
Effect of clothing type on thermal comfort

The effects of thermal properties of clothing, thermal insulation and evaporative resistance on human physiology and thermal comfort are studied. Two types of clothing (for summer and winter indoor) were used. Their thermal properties (the intrinsic thermal insulation and evaporative resistance) are shown in Table 1. In this case study, a sedentary person is sitting on a chair in a car. The contact fractions of the naked and clothed area are set as 0 for all body segments, eliminating the influence of contact. The air temperature and air velocity are set as 26 ^{o}C and 0.1m/s, respectively.

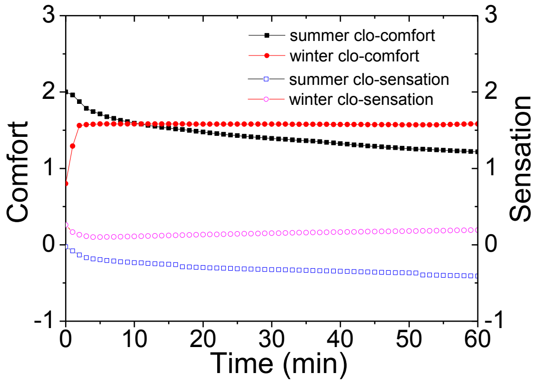
Table 1. Thermal properties of the two types of clothing for summer and winter indoor.

Segment	Summer		Winter indoor	
	Thermal resistance (*clo*)	Evaporative resistance (m^2Pa/W)	Thermal resistance (*clo*)	Evaporative resistance (m^2Pa/W)
Head	0	0	0	0
Chest	1.10	198	1.98	356.4
Back	0.90	162	1.27	228.6
Pelvis	0.93	167.4	0.93	167.4
Upper arm	0.74	133.2	1.42	255.6
Lower arm	0.41	73.8	0.99	178.2
Hand	0	0	0	0
Thigh	0.49	88.2	0.95	171
Leg	0.48	86.4	0.71	127.8
Foot	0.49	88.2	0.93	167.4

Figure 2 shows the averaged results of skin and core temperature, heat flux, and overall comfort and sensation for 60 min. From Figure 2(a), it can be seen that the skin and core temperatures of the body with the winter indoor clothing are more than those with the summer clothing. As expected, the heat flux for the winter indoor clothing is also lower than that for the summer clothing. The thermal insulation and evaporative resistance of each segment for the winter indoor are higher than those for the summer (seen in Table 1). From the equations developed above, Heat and moisture transfer through clothing can slow down with a bigger thermal resistance of clothing. Heat from human body without transferring into the environment will increase the temperature of the body tissue.



(a) Skin, core temperature and heat flux



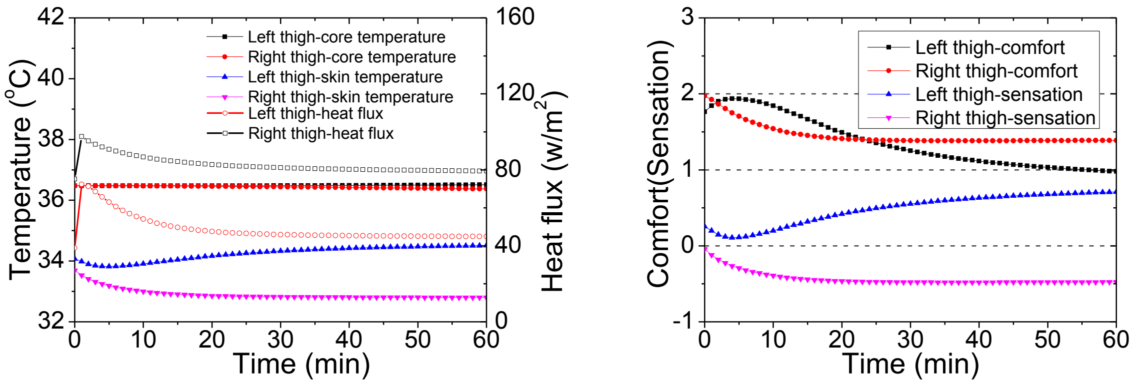
(b) Overall comfort and sensation

Figure 2. Skin, core temperature and heat flux (a), and overall comfort and sensation (b) for two types of clothing.

Figure 2(b) shows that the overall sensation for the winter indoor (0.19 at 60 min) is higher than that for the summer (-0.42 at 60 min). It is indicated that the summer clothing is a little not competent to keep the human body warm in this thermal environment (air temperature of 26 ^{o}C and air velocity of 0.1m/s). In comparison, the winter indoor clothing can slow down the heat loss from the body to the environment, thus the overall thermal comfort is is a little higher than that of the summer clothing when the sedentary person sitting for 60 min.

Effect of contact fraction on thermal comfort

The effects of the contact fractions of the naked and clothed areas were studied with the comparison of left and right thigh, for a sedentary person (dressed with the summer clothing) sitting on the chair in a car. This case study is the same as the case study described above, except that the contact fractions of the naked and clothed area are set as 0.5 for left thigh, and 0 for right thigh. Figure 3 shows the results of skin and core temperature, heat flux, and local comfort and sensation for 60 min. It can be seen that the skin temperature is higher and heat flux is lower for the left thigh which contacts the chair. This is because that the chair adds insulation to the left thigh. However, this didn't cause any difference on core temperatures between the two thighs.



(a) Skin, core temperature and heat flux

(b) Local comfort and sensation

Figure 3. Skin, core temperature and heat flux (a), and local comfort and sensation (b) for left and right thigh.

With a contact surface for the naked and clothed area of the left thigh, the heat loss via convection and vapour transfer to environment (heat flux in Figure 3(a)) is partly blocked by the contact chair. The heat flux for right thigh is almost twice as the amount for left thigh. As a consequence, the skin temperature of left thigh at 60 min (34.51 ^{o}C) is higher than the setpoint temperature (33.87 ^{o}C) for the local thermal sensation model from Zhang (2003). However, the skin temperature of right thigh at 60 min (32.79 ^{o}C) is less than that setpoint temperature. Therefore, local sensation is different between the two symmetrical segments (Figure 3(b)), one slightly warm and one slightly cool. The local sensation of left and right thigh is bigger and less than zero, respectively. The value of the local sensation (compared with zero) has great effects on local thermal comfort. The difference of the local thermal comfort of the two segments changes with the simulation time. It can be attributed that the contact didn't cause any difference on core temperatures between the two thighs (Figure 3(a)).

CONCLUSIONS

In this paper, we have improved the modelling of heat and moisture transfer through clothing with a contact surface, based on the UCB Model. Four paths of heat and moisture transfer are described in details between naked and clothed skin with environment or in direct contact with a solid, and heat and moisture transfer equations were provided. The human thermal response and thermal comfort are predicted and compared for different typical clothing ensembles and different contact fractions of the contact area with a solid surface. The results show that the contact with a solid surface has great effects on thermal sensation and comfort.

This advanced model is useful for a wide range of applications, such as thermal comfort evaluation in transient, non-uniform thermal environments, including office buildings, automobiles, and outdoors with different clothing ensembles for each body segment.

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