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ABSTRACT

The UC Berkeley Comfort Model is a helpful simulation tool for the assessment of thermal comfort in non-uniform environments. A major element of the model is the implementation of a clothing node, which considers both heat and moisture capacitance of clothing. Heat capacity of the clothing has been demonstrated to be important when considering transient effects. Moisture capacitance is important to correctly model evaporative heat loss from the body through clothing. The moisture model uses the regain approach to calculate the amount of moisture that a specific fabric will absorb at a given humidity.

NOMENCLATURE

A	area (m^2)
c	specific heat capacity (J/kgK)
C	heat capacity (J/K)
f_{cl}	clothing surface area factor
F	view factor
h	heat transfer coefficient (W/m^2K)
h_{fg}	heat of vaporization of water (kJ/kg)
i	clothing vapour permeation efficiency
I	clothing insulation (clo)
Lr	Lewis ratio (K/kPa)
m	mass (g)
p	vapor pressure (kPa)
Q	heat (W)
R	regain content (%)
t	time (s)
T	temperature (K)
v	velocity (m/s)
w	skin wettedness
α	absorption coefficient
ε	emission coefficient
φ	relative humidity
σ	Stefan-Boltzmann constant (W/m^2K^4)
θ	temperature (°C)
Suffix	
a	air
cl	clothing
c	convective
e	evaporation
m	mean
n	nude
r	radiative
s	solar

INTRODUCTION

The task of clothing is, besides fashionable embodiment and expression, the protection against harmful environmental stresses including the climatic conditions. On this account, well being, health and productivity of humans largely depends on clothing. Humans usually wear clothing all day long - even in bed we are surrounded by textiles - therefore it is often characterized as a “second skin”. Except in tropical latitudes, a person needs constant protect to avoid simply freezing. But protection against cold is only one aspect of the physiological function of clothing. When the human body temperature rises above a certain level, an effective cooling is provided by the evaporation of sweat coming out of the glands. The type of clothing has a major impact on this process, since it is responsible for the diffusion of water vapor. Hence, clothing strongly influences the physiological operations including the temperature control of the human body. Detailed knowledge of the exact process, the importance of which should not be underestimated, is necessary to determine thermal comfort.

The human body converts the energy provided by food into work and heat, depending mainly on the level of activity. To guarantee a constant body temperature within a narrow range, the heat has to be released to the environment. This process is controlled by signals, which are sent by the thermoreceptors of the skin and the hypothalamus, managing heat production and heat exchange using four different mechanisms: vasodilation, vasoconstriction, perspiration and shivering. The main part of the heat release occurs through the skin, only a small percentage accounts for the heat transfer via respiration. Since the skin is usually largely covered with clothing, the heat release of the human body is strongly influenced by the heat and moisture transfer through clothing.

Heat release via skin can be divided into dry heat losses and losses through evaporation. The former can be split into convection, conduction, and, additionally, the radiative exchange with the surrounding surfaces. Dry losses depend largely on the insulation of the clothing, which includes the insulation of the clothing itself and the insulation of the air layer between skin and clothing and respectively the air between different clothing layers.

The second, the evaporative heat exchange with the environment, is the removal of heat from the human body by the evaporation of sweat from the skin. This process is mainly driven by the thermoregulatory system, the permeation efficiency of the clothing and the surrounding air's water vapour pressure. If the ratio of evaporated and produced perspiration is low, moisture accumulates in the clothing layer. This process influences the thermal characteristics of the garment due to swelling of the fibres causing changes in the size, shape and stiffness.

(Henry 1939) developed one of the first theories of coupled heat and moisture transfer through clothing considering accumulation effects. (Ogniewicz et al., 1981) proceeded with a steady-state model, which included both the convective and the diffusive transport mechanisms in the garment, along with phase change due to condensation and evaporation. Since time-dependent modelling is necessary due to water accumulation, (Farnworth 1986) developed a rather simple dynamic model that included heat transport by conduction and radiation as well as moisture transport by diffusion. Detailed dynamic modelling, including a comparison with experimental results, was later done by (Fan et al., 2005). (Wu et al., 2008; Wissler et al., 2009) presented mathematical models for heat and moisture transport through multi-layer clothing. Nowadays the heat and moisture transfer is a factor for the international standards (ISO 11092 1993; ASHRAE 2005; ISO 7730 2006; ISO 9920 2009).

In combination with the thermal interaction of the human body, (Shitzer et al., 1985) observed the heat exchange with clothing, even considering fluid-cooled garments. Both (Jones et al., 1992) and (Li et al., 1998) later introduced dynamic models of heat and moisture characteristics in interaction with two-node human thermoregulation model of (Gagge et al., 1971). (de Dear et al., 1993) created a very detailed skin and clothing model by dividing skin and clothing into 40 layers. (Fiala et al., 1999) and (Xu et al., 1997) developed their own human thermo-regulation models including heat and moisture transfer through clothing including accumulation effects. With a sweating thermal manikin, (Celcar et al., 2008) investigated the characteristics of clothing.

In order to determine thermal comfort it is necessary to understand the thermal behavior of the clothing (Voelker et al., 2009a). This present paper focuses on the thermal characteristics of clothing, dealing with heat and mass transfer from the skin through the clothing to the environment. The introduced clothing model is part of the UC Berkeley comfort model, with a supplementary node in every segment of the existing 65 node model (Huizenga et al., 2001; Hoffmann et al., 2008; Voelker et al., 2009b). The UC Berkeley comfort model considers different ways of heat loss. First, the nude skin is exposed to the surrounding air. Second, the skin is covered with clothing influencing the thermophysiological behavior of the human being. And third, the human is in direct contact to other materials such as a chair. However, this paper only deals with heat loss through clothing.

It is assumed that there is no latent heat transfer occurring directly between the skin and the environment. The latent heat exchange always occurs first between skin and clothing, and then, as the clothing's partial vapor pressure changes, there is a latent heat exchange between the clothing and the environment. Furthermore, we assume that the garment features isotropic properties, which includes an equilibrium between the moisture content at the surface of the fibres and the surrounding air.

Additionally, we have left out the change of the properties due to swelling of the fibres resulting from the absorption process, meaning that no change of volume occurs. Since the temperature does not strongly influence the characteristics of clothing, it is not observed.

HEAT AND MOISTURE TRANSFER THROUGH CLOTHING

The human body converts the energy provided by food into work and heat, depending mainly on the level of activity. For example, when doing office work, the human body has a metabolic rate of approximately 70 W/m² (1,2 met), which is equivalent to about 130 W for an average male person. To keep the body temperature at a constant level, heat is released via evaporation, radiation, convection, conduction and finally respiration. Since the latter affects only the core layer of the chest it is not taken into further consideration in this paper which only deals with heat transfer through the outer layer, from the skin through clothing to the environment. In the UCB thermal comfort model each segment of the human body can be completely nude, partly nude and partly clothed or fully clothed. The algorithms describing the sensible and latent heat transfer through the clothing apply only to the clothed fraction. The heat balance of the clothing node can be described as follows:

$$C_{cl}\frac{d\theta_{cl}}{dt} = \dot{Q}_{c,skin-cl} + \dot{Q}_{e,skin-cl} - \dot{Q}_{c,cl-env} - \dot{Q}_{e,cl-env} - \dot{Q}_{r,cl-env} + \dot{Q}_{s,cl-env} \qquad (1)$$

This heat balance contains the heat transfer from the skin to the clothing through convection ($Q_{c,skin\text{-}cl}$) and through evaporation ($Q_{e,skin\text{-}cl}$). The heat exchange with the environment is described by the heat losses through convection ($Q_{c,cl\text{-}env}$), evaporation ($Q_{e,cl\text{-}env}$), radiation ($Q_{r,cl\text{-}env}$) and possible gains due to solar radiation ($Q_{s,cl\text{-}env}$). C_{cl} indicates the heat capacity of the clothing and is calculated by

$$C_{cl} = m_{cl} \cdot c_{cl} \tag{2}$$

with m_{cl} as the clothing mass (for exemplary values see also table 1). However, depending on the level of insulation, the mass of clothing is roughly estimable according to (McCullough et al., 1985) with 0.74 clo/kg. Finally, c_{cl} expresses the specific heat capacity of the garment.

Sensible heat transfer from skin to clothing node

The sensible heat transfer from the skin node to the clothing node can be calculated using the equation

$$\dot{Q}_{c,skin-cl} = \frac{1}{I_a + I_{cl}} \cdot A_{cl} \cdot \left(\theta_{skin} - \theta_{cl}\right) , \tag{3}$$

with θ_{skin} describing the skin temperature calculated by the 65 node model and the clothing temperature θ_{clo}. I_a describes the insulation of the air layer, while I_{cl} is the summation of the effective insulation of the worn garments of every single segment of the human body. It can be roughly calculated by accumulating the number of overlaying clothing layers covering one body segment (Olesen 1985).

$$I_{cl} = \sum_i I_{clu,i} \tag{4}$$

Generally, the unit of the insulation is typically specified using the unit clo (1 clo = 0.155 m²K/W). Average values of the effective insulation of several garments can be seen in table 1.

Table 1
Garment insulation and mass (McCullough et al., 1985; ASHRAE 2005)

GARMENT	**m [kg]**	**I_{clu} [clo]**
Briefs	0.065	0.04
Shirt	0.196	0.28
Trousers	0.459	0.24
Socks	0.049	0.03
Suit jacket	0.652	0.48
Shoes	0.186	0.04

However, the insulation of the clothing and the additional layer of air are influenced by air velocity as well as by human movement. This may result in a decrease of the clothing's insulation value, which may be corrected. The corrected factor for the decreased clothing insulation can be determined according to (ISO 7730 2006). The outer surface of a clothed part is calculated using the factor f_{cl}, which augments the skin surface according to the type of clothing by

$$A_{cl} = A_{skin} \cdot f_{cl} , \tag{5}$$

whereas the parameter f_{cl} represents the clothing area factor, which is the ratio of the projected surface area of the clothed body to the projected surface area of the nude. It is possible to determine the clothing area factor exactly by using photographic methods, but a rough estimate is feasible according to (McCullough et al., 1985) using the following equation:

$$f_{cl} = \frac{A_{cl}}{A_n} \approx 1.0 + 0.31 \cdot I_{cl} . \tag{6}$$

Latent heat transfer from skin to clothing node

The amount of latent heat being released from the skin is influenced by two issues. Firstly, it depends on the body's heat balance. Only under warm ambient conditions or high exercise levels will significant sweating occur. The human body's heat balance determines whether or not to release heat via evaporation. The principle of the control system which is applied to the thermal comfort model is described, amongst others, in (Hoffmann et al., 2008). Two control signals, called SWEAT and WARM, based on (Stolwijk 1971), are determined based on the temperature differences between the calculated skin and core temperatures and their set points. By using the coefficient sweatfac, the following equation also takes into account the fact that different body parts are unequally able to sweat. In the model, the evaporative heat transfer is firstly calculated as

$$\dot{Q}^{*}_{e,skin-cl} = \text{sweatfac} \cdot \text{SWEAT} \cdot 2^{\frac{\text{WARM}}{10}} . \tag{7}$$

Second, the environment's vapour pressure limits the ability of evaporation. The maximum evaporation of the human body is limited to the surrounding vapour pressure. Once the partial vapour pressure of the clothing node is known, the difference between the saturated vapour pressure on the skin's surface (assuming the skin being completely sweat covered) and the partial vapour pressure of the air / clothing determines the maximum evaporative heat loss.

$$\dot{Q}_{e,max} = h_e \cdot A_{cl} \cdot \left(p_{sat,skin} - p_{cl}\right) \tag{8}$$

In case the skin is not completely covered by sweat, (Eq. 10) using the skin wettedness w modifies the evaporation rate between skin and clothing. As it is difficult to determine the evaporative heat transfer coefficient h_e [W/Pa·m²], a simplified equation is used for the calculation:

$$h_e = \frac{LR \cdot i_m}{I_{cl} \cdot 0.155} \tag{9}$$

The Lewis relation (LR) simply describes the relationship between convective heat transfer and mass transfer coefficients and equals, at typical indoor conditions, 16.5 K/kPa (ASHRAE 2005). The parameter i_m describes the total vapour permeation efficiency, which shows the evaporative performance of the clothing system (Woodcock 1962). It is the ratio of the actual evaporative heat flow capability between the skin and the environment to sensible heat flow capability to Lewis ratio (ASHRAE 2005). It is a dimensionless quantity, which does not include insulation or thickness value. A value of zero means completely impermeable, the maximum is equal to 1 and stands for ideally permeable clothing. In opposition to the parameter i_{cl}, it includes the resistance of the air layer surrounding the human body. According to (McCullough et al., 1989; ASHRAE 2005), an average value of i_m = 0.4 can be used. Additional values are provided in table 2.

Table 2
Moisture permeability index for clothing (McCullough et al., 1989)

ENSEMBLE	$\mathbf{i_m}$
Men's business suit	0.37
Men's summer casual	0.43
Jeans & shirt	0.40
Insulated coverall	0.39

Even under low activity conditions or a cold climate without obvious sweating, the skin is still covered by a 6 % sweating rate of the maximum sweating possible (Arens et al., 2006). Therefore the actual evaporative heat loss from skin to clothing can be expressed as following:

$$w = 0.06 + 0.94 \frac{\dot{Q}^*_{e,skin-cl}}{\dot{Q}_{e,max}} \tag{10}$$

$$\dot{Q}^*_{e,skin-cl} = w \cdot \dot{Q}_{e,max} \tag{11}$$

Water absorption in the clothing node

When moisture is transferred from skin to clothing the humidity in the tissue will increase. The water being absorbed in the clothing node can be expressed as following

$$\dot{m}_{H_2O_{abs}} = \frac{\dot{Q}_{e,skin-cl}}{h_{fg}} \tag{12}$$

The parameter h_{fg} is the heat of vaporization of water and is equal to $2.43 \cdot 10^3$ J/g at 30°C according to (ASHRAE 2005). The absorption of water has a major impact on the heat and mass transfer through the clothing layer. First of all, absorbed water in the clothing layer increases both heat capacity and thermal conductivity. Therefore, the sensible heat transfer through the clothing layer changes. With an increased water content more heat can be stored in the tissue, while at the same time the heat conduction to the outer surface increases as well. Due to the absorption process, the heat capacity of the clothing is modified by

$$C_{cl} = m_{cl} \cdot c_{cl} + m_{H_2O_{abs}} \cdot c_{H_2O} \tag{13}$$

Secondly, the vapour pressure of the clothing node increases with increasing water content and might even reach the level of saturation. An increasing vapour pressure limits at the same time the ability to sweat. In order to determine the new vapour in the clothing node the so called regain approach is used. The first scientific approach to investigate regain was done by (Schloesing 1893), who investigated the hygroscopicity of several fabrics. Further comprehensive research on water absorption and desorption in clothing was carried out by (Urquhart et al., 1924; Speakman et al., 1936). According to (Morton et al., 1997), the regain is calculated by

$$R = \frac{\dot{m}_{H_2O_{abs}}}{m_{cl}} \cdot \Delta t \quad . \tag{14}$$

However, a garment's moisture regain is not only controlled by the human being's perspiration or the air humidity, but also depends on the garment's past. Illustrated in figure 1, the plot of regain against relative air humidity shows two main curves describing a path-dependent hysterese loop. The lower curve of the plot is called the absorption isotherm and shows the equilibrium regain of a garment which was at the beginning absolutely dry and was exposed to gradually higher humidities.

The upper curve is generated when the garment was initially soaked and is then exposed to gradually lower humidities. This curve is called the desorption isotherm. One can observe, that both curves show a sigmoidal characteristic. At low relative air humidity, the curves are quite steep, followed by a linear course at medium humidities. At high humidities, finally, the course is extremely steep again, which has an imprecise effect during measurements.

Between the two curves, additional intermediate curves exist. For example, if the absorption process begins at approximately 10 % on the desorption curve, it will not join the absorption curve before a relative air humidity of 60 % is reached. The same phenomenon applies for the opposite direction: If desorption starts at 90 % humidity on the absorption curve, it will not meet the desorption curve before 30 %. To get on either the absorption curve or the desorption curve it is therefore essential to start at either absolutely dry or absolutely wet conditions.

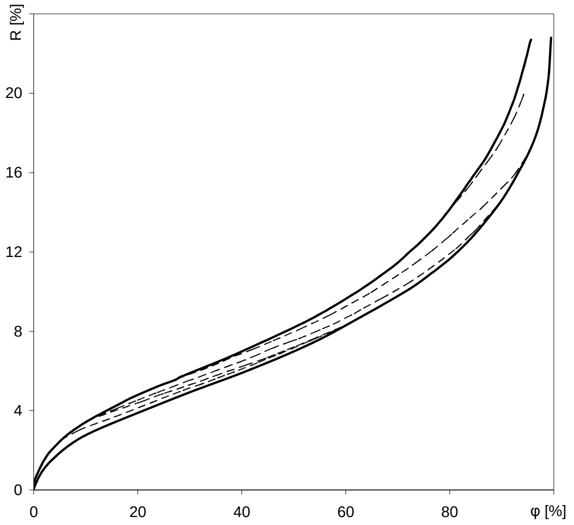

Figure 1 Adsorption/desorption of water by cotton (Urquhart et al., 1930)

However, such conditions rarely occur in reality, beyond the lab. Therefore, this model ignores the difference regain between the two processes, using for the sake of simplicity only the absorption curve by regression. At beginning of a simulation, the model assumes that the clothing reaches its equilibrium with the environment. Knowing the relative humidity of the air, it is possible to determine the regain of the fabric by the first regression. After calculating the mass transfer between the skin and the clothing, the new regain can be calculated. From this new calculated regain, the relative humidity of the garment will be assessed by the second regression. Once the clothing temperature and its relative humidity is known, the calculation of the partial vapour pressure of the clothing p_{cl} is realized.

HEAT TRANSFER ON THE OUTER SURFACE

Sensible heat loss

The sensible heat exchange between the surface of the clothing and the environment comprises the convective heat transfer with the ambient air, the long wave radiation exchange with the environment and the short wave absorption of solar radiation. The convective term can be expressed as

$$\dot{Q}_{c,cl-env} = h_c \cdot A_{cl} \cdot \left(\theta_{cl} - \theta_a\right), \qquad (15)$$

depending on the difference of the temperature of the clothing node and the temperature of the surrounding air. As in the case of the sensible heat transport from the skin to the clothing, the dry heat loss is calculated using a heat transfer coefficient. These were derived from experiments with thermal manikins in climate chambers and depend strongly on the air velocity and the observed segment (table 3).

Table 3
Convective heat transfer coefficients [W/m²K] (de Dear et al., 1997)

SEGMENT	h_c ($v \leq 0.1$ m/s)	$h_c = a \cdot v^n$ ($v > 0.1$ m/s)	
		a	n
Head	3.7	11.75	0.625
Chest	3.0	9.1	0.59
Back	2.6	8.9	0.63
Pelvis	2.8	8.2	0.65
Shoulder	3.4	11.4	0.64
Arm	3.8	11.75	0.625
Hand	4.5	14.45	0.6
Thigh	3.7	8.9	0.6
Leg	4.0	13.15	0.57
Foot	4.2	12.9	0.545

The radiation heat exchange with the environment is based on the Stefan-Boltzmann law. For each body segment and the surrounding environmental surfaces including other body parts, view factors are calculated. The radiation heat exchange depends on the surface area, the surface temperature, the emission ratio and, finally, the position.

$$\dot{Q}_{r,cl-env} = \sum_{m=1} F_{cl \to m} \cdot A_{cl} \cdot \sigma \cdot \left(\varepsilon_{cl} \cdot T_{cl}^4 - \varepsilon_m \cdot T_m^4\right) \qquad (16)$$

Additionally, the human body is not only exposed to the long-wave heat exchange with the environmental surfaces, but also to short-wave solar radiation. Taking solar altitude, azimuth and direct radiation into consideration, the incident radiation q_s on a specific oriented surface is calculated. The clothing node absorbs the short-wave radiation depending on the absorption coefficient of the clothing. In the model a value of $\alpha = 0.6$ is considered.

$$\dot{Q}_{s,cl-env} = q_s \cdot A_{cl} \cdot \alpha_{cl} \qquad (17)$$

Latent heat loss

Once the new vapour pressure is calculated using the regain approach, the latent heat transfer from the clothing node to the environment can be calculated as

$$\dot{Q}_{e,cl-env} = h_e \cdot A_{cl} \cdot (p_{cl} - p_a) \qquad (18)$$

With the clothing model being introduced in this paper, the existing 65 nodes of the UC Berkeley Comfort Model are extended by an additional 16 nodes being responsible for the simulation of the human clothing. Hence, the assessment of thermal comfort becomes more realistic under both steady and transient conditions. In the near future, the application of the extended model under various boudary conditions including a comprehensive validation is planned.

CONCLUSION

This paper deals with the heat and mass transfer from the human body through the clothing layer to the environment. The introduced model is part of the UC Berkeley Comfort Model, only with the addition of a clothing node to every segment of the existing 65 node model. The heat balance of this node contains the heat transfer from the skin to the clothing through convection and through evaporation. The heat exchange with the environment is described by the heat losses through convection, evaporation, radiation and possible gains due to solar radiation.

The sensible heat transfer from the skin node to the clothing node through convection depends on the temperature difference between the skin and the clothing node as well as on the insulation of the clothing including the surrounding air layer. The amount of evaporative heat exchange between the skin and the clothing node is influenced by the sweat production, the vapour pressure and the permeation and insulation of the clothing.

When moisture is transferred from skin to clothing, the humidity in the garment will change. The regain approach is applied to calculate the amount of moisture that a specific fabric will absorb at a given relative humidity.

The heat exchange between the surface of the clothing and the environment consists of the convective heat exchange with the ambient air, the long wave radiation exchange with the environment, the short wave absorption of solar radiation and finally, the evaporative heat loss.

With the detailed clothing model considering both sensible and latent heat transfer, the UC Berkeley Comfort Model is able to assess thermal comfort under realistic, transient conditions.

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