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A model of heat and moisture transfer through clothing integrated with the UC Berkeley comfort model

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ABSTRACT

A detailed model of heat and moisture transfer through clothing has been developed and implemented in the multi-segment UC Berkeley Thermophysiological Comfort model (BTCM). Equations are presented for two paths of heat and moisture transfer, between naked skin and environment, and clothed skin and environment. Transient behavior due to absorption and desorption by clothing is included. Segment-specific values for clothing insulation, vapor resistance, and the effects of air movement and walking are estimated from various sources. The new model is shown to simulate results from empirical studies with good accuracy. Parametric simulations are done to evaluate the physiological and comfort influences of the airspeed correction equations, and the heat transfer effects of different clothing levels at different temperatures. The results quantify the substantial air velocity and air temperature impacts on thermal physiology and thermal comfort. It can be seen that the new model is useful for studying heat and moisture transfer through clothing, and evaluating thermal comfort in transient environments.

1. Introduction

Thermal psychological models of the human body have great importance with the concept of local sensation and thermal comfort [1–2]. The thermal sensation and comfort are mainly based on the local skin and core temperatures [3–5]. Those models of human thermoregulation can predict the local skin and core temperatures, along with heat and moisture transfer between the human body and environment, hence evaluating the local and overall thermal sensation and comfort [2].

The UC Berkeley Thermophysiological Comfort model (BTCM) developed by Huizenga et al. [1] includes several improvements over the Stolwijk physiological model [6] from which it was derived. The BTCM model has 16 body segments whose areas correspond to a widely used electrical manikin [7]. Each of these segments is simulated as four body layers (core, muscle, fat, and skin tissues) and a clothing layer. A separate series of nodes represents the transport of heat by blood flow between segments, including the effect of countercurrent heat exchange between paired arteries and veins in the limbs. Each of the body segments is radiatively, convectively, and (where applicable) conductively coupled to a model of the surroundings.

The BTCM model's simulated segment skin and core temperatures are used to also predict perceived thermal sensation and comfort, for each segment and for the whole body (e.g. hand sensation cold or hot, whole-body cold or hot, etc.), using an embedded set of sensation and comfort models developed by Zhang [3–5]. The BTCM model has been validated against empirical physiological responses in transient, non-uniform thermal environments [1].

However, the treatment of clothing insulation in the BTCM model has been insufficient for the purposes of the model, which include predicting dynamic sensible and evaporative heat transfer for each body segment under a range of wind and walking conditions. This paper describes the new clothing model, compares its predictions to manikin studies of clothing insulation under wind, and to human subject tests of human thermal physiology.

The original clothing model calculated moisture absorption/desorption in the clothing using the regain approach [8–9]. This assumed the moisture content of the clothing to be at equilibrium with the relative humidity in the air. However, equilibrium with the environment is often not reached in transient thermal environments [10]. The clothing absorption/desorption needs to be considered as part of the model.

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Nomenclature

A	area (m^2)
C	specific heat (J/(kg °C))
F_{nude}	fraction of segment area naked (dimensionless)
$F_{clothed}$	fraction of segment area clothed (dimensionless)
f_{clo}	clothing area factor (dimensionless)
h	heat transfer coefficient (W/(m^2 °C))
I	thermal resistance (m^2 °C/W, clo)
k	correction factor (dimensionless)
Le	Lewis constant (16.5 °C/kPa)
M	metabolic heat production (W)
m	mass rate (kg/(m^2 s))
P	water vapor pressure (kPa)
q	heat storage or heat loss (W,W/m^2)
R_e	vapor resistance (kPa m^2 W^{-1})
T	temperature (°C)
t	time (s)
v	relative air velocity (m/s)
w	wettedness (dimensionless, a fraction from 0 to1)

Greek symbols

λ	enthalpy of water vaporization (2256 kJ/kg)

Subscripts

air	air
c	convection
clo	clothing
corr	corrected
env	environment
evap	evaporation
fat	fat
H_2O	H_2O (water)
nude	naked skin
sat	saturated
skin	skin
storage	storage
sw	sweating
tot	total
vf	view factor

In addition, the heat and moisture transfer through the air layer surrounding the clothing varied with airspeed using coefficients from manikin experiments in a wind tunnel [11], therefore, the thermal insulation and vapor resistance within the clothing layer are in fact affected by the relative air movement as well as by the air motion caused by walking [12].

The new clothing model considers, for each body segment, the effect of clothing moisture absorption/desorption rate on heat transfer, as well as the effect of airspeed on the thermal and vapor resistance of clothing. It is based on a whole-body unsteady-state thermal model for clothing from Jones and Ogawa [13], combined with airspeed corrections derived from ISO 9920 [14]. In simulating a particular garment or an ensemble of garments, the BTCM requires local clothing properties specific to each of the body segments. These segment-level properties must be simulated based on several sources, given that empirical data are not yet complete.

The clothing model is described below, compared with recent empirical clothing data, and used to compare comfort effects for different ambient velocity levels, air temperatures and clothing ensembles.

2. Mathematical formulation

The existing physiology, thermal regulation, blood flow, and radiant exchange models of the BTCM model remain unchanged. The following describes only the modeling of heat and moisture from skin and through clothing to the air.

As shown in Fig. 1, two paths are considered through which heat is transferred from exposed skin or clothed skin to ambient air. The sum fraction of naked and clothed area of each segment is 1.

$$F_{nude} + F_{clothed} = 1 \quad (1)$$

where F_{nude} and $F_{clothed}$ are the fractions of the segment area that are naked and clothed, respectively. When this segment is totally nude, the clothed fraction is zero.

2.1. Skin node

For the skin node, the stored heat within the skin is the heat gain from the inner body layers and metabolic heat production, subtracting the heat loss from conduction, convection and radiation with the clothing or the environment, and the heat loss from sweating evaporation and absorption within clothing. The heat transfer by conduction is described in Ref. [15], and is not considered in this paper. The stored heat within the skin,$q_{skin,storage}$, is:

$$q_{skin,storage} = q_{fat} + M_{skin} - q_{skin-env} - q_{skin-clo} - q_{evap,\ skin-env} - q_{evap,\ skin-clo} \quad (2)$$

where q_{fat} and M_{skin} are the heat gain from fat and skin metabolic heat production, respectively, as calculated by the BTCM model [1]. $q_{skin-env}$ is the sensible heat loss from nude skin to the environment, and $q_{skin-clo}$ is the sensible heat loss from clothed skin to the clothing. $q_{evap,\ skin-env}$ and $q_{evap,\ skin-clo}$ are the latent heat exchange between skin and environment from the naked skin, and between skin and clothing from the clothed skin, respectively.$q_{skin-env}$ and $q_{evap,\ skin-env}$ are zero when the segment is covered entirely by clothing, and $q_{skin-clo}$ and $q_{evap,\ skin-clo}$ are zero when the segment is entirely nude.

2.1.1. Sensible heat transfer

The BTCM model separates $q_{skin-env}$ into convection and radiative heat transfer. Convective heat transfer is influenced by the air velocity and air temperature near each segment. View factors between each body segment and surrounding surfaces are used to calculate the radiative heat transfer in non-uniform environments [1]. $q_{skin-env}$ is calculated as:

$$q_{skin-env} = A * F_{nude} * \left(h_c (T_{skin} - T_{air}) + q_{vf-skin} \right) \quad (3)$$

where A is the total skin surface area of the segment. T_{skin} and T_{air} are the skin and ambient air temperatures, respectively (°C). $q_{vf-skin}$ is the radiative heat transfer calculated by view factors, W/m^2, which is described in Ref. [1]. h_c is the coefficient of the convective heat exchange, (W m^{-2} °C^{-1}), determined for each segment by de Dear et al. [16].

$q_{skin-clo}$ is obtained by the temperature difference between skin and the clothing (T_{clo}). I_{clo} is the number of clo unit for the intrinsic thermal resistance of the clothing (1 clo = 0.155 m^2 K W^{-1}):

$$q_{skin-clo} = A * F_{clothed} * \frac{(T_{skin} - T_{clo})}{I_{clo}} \quad (4)$$