INTEGRAL SIMULATION OF THE HUMAN THERMAL SYSTEM

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ABSTRACT

In this work a numerical model that permits to simulate the human body thermal system is presented.

This computational model is based on the integral energy balance equation for the human body tissue, arterial and venous blood and mass balance equation for the blood. In the simulation of the human body, which is divided in 105 nodes, the following phenomena are considered: heat conduction through the tissue, heat exchange by radiation between the external tissue and the surrounding surface, internal metabolism, heat loss by evaporation and respiration, blood circulatory convection and heat exchange by convection between the external tissue and the environment. It was used a thermoregulation model to control the body temperature.

The model reproduced well the experimental data and can be used to predict thermal comfort conditions and local discomfort in subjects inside an acclimated environment.

KEYWORDS

Thermal comfort, numerical methods, human thermophysiology, comfort.

INTRODUCTION

A person expresses satisfaction with the environment when is thermally comfortable and doesn't feel local discomfort. The thermal comfort, that depends of air temperature, relative humidity, air velocity, mean radiant temperature, activity level and clothing thermal resistance, is associated with body skin temperature and is evaluated by the Predicted Mean Vote (PMV) index (Fanger 1970). The local discomfort, due to the excessive heating or cooling at a part of the human body, is evaluated by the warm or cold thermoreceptors from the human body.

The heat generates inside the human body, by metabolic reactions, is transported by conduction, through the tissue, and by blood circulatory convection, to the skin. The heat exchange between the body and the environment are done by convection, evaporation, respiration and radiation. When changes of the comfort conditions exists, the body temperature regulation is done by the thermoregulatory system.

The numerical modulation of human body thermal system, done in this paper, using thermophysiology mechanisms, can be used to determine the temperature field of tissue and blood, evaluate the thermal comfort level and local discomfort felt by a person inside an acclimated environment. Gagge in 1971 and some other authors, namely Ralph e Mohamed (1970), Eugene (1970), Dorothy (1970) and more recently Thellier et al. (1994), analyzed also this problem.

MATHEMATICAL MODEL

In this model are used integral energy balance equations for the human body tissue, arterial and venous blood. The heat balance equations are always written with the sensible heat storing term in the left member and the heat flux terms in the right one (Conceição 1996). The blood mass flow, in each one node, is determined through a mass balance equation system.

The hypothesis used to write the balance equations are the following: the human anatomy geometry is approximated by cylindrical and spherical elements, each one node consisting of a uniform porous material (tissue, bone, fat and capillary system), the properties and temperature in a node are uniform, the heat flux is treated as unidimensional, the radiative exchanges between elements are neglected and the person, considered as a gray body, is inside a compartment with black surfaces.

Simplified model of human body

In this work the human body is divided in 35 cylindrical and spherical elements (see Figure 1), being each on divided in 3 slices (internal, central and external), that is 105 nodes. Figure 1a represents also the principal arteries and veins of the circulatory system.

The internal slice of an element has a vein and an artery (see Figures 1b and 2). Figure 2 show also the capillary system scheme. When the element is localized in an extremity (head, fingers and foot) the artery is not considered (see Figure 3).

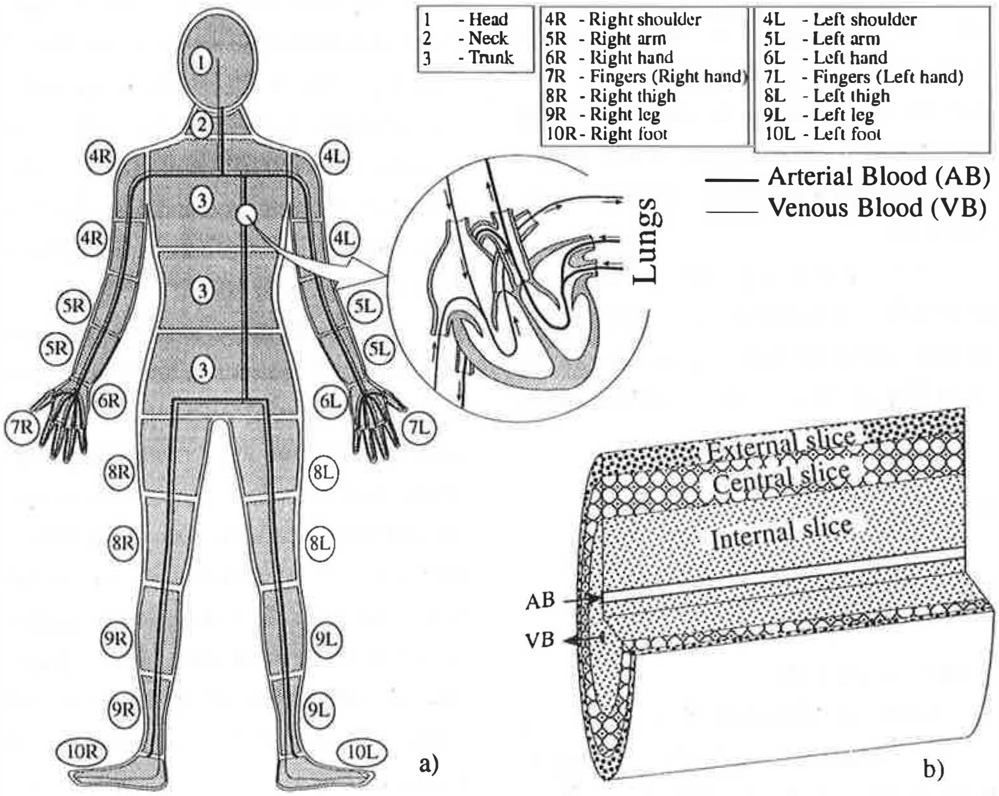

Figure 1 Human body scheme divided in 35 elements a) and each one divided in 3 slices b).

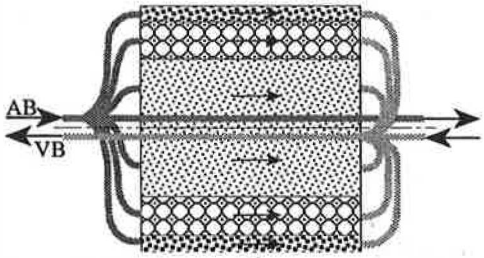

Figure 2 Scheme of the venous, arterial and capillary blood flow of an element.

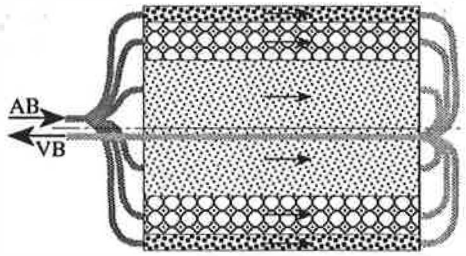

Figure 3 Scheme of blood flow distribution in an extremity element.

Heat balance equations

The integral heat balance equation for an internal slice is the following:

$$
\begin{aligned}
m_{t_i}^{(1)} Cp_t \frac{dT_{t_i}^{(1)}}{dt} = {} & \underbrace{\sum_{j=1}^{2\,or\,3} \left(\frac{T_{t_j} - T_{t_i}^{(1)}}{R_{ji}} \right)}_{(1t)} + \\
& + \underbrace{\dot{Q}_{g_i}^{(1)}}_{(2t)} + \underbrace{Cp_b \left(\dot{m}_{at_i}^{(1)} T_{a_{i-1}} - \dot{m}_{tv_i}^{(1)} T_{t_i}^{(1)} \right)}_{(3t)} - \\
& - \underbrace{\dot{m}_{Transf_i}^{(1\to2)} Cp_b T_{t_i}^{(1)}}_{(4t)} + \underbrace{\dot{Q}_{c_{at}}^{(1)}}_{(5t)} + \underbrace{\dot{Q}_{c_{vt}}^{(1)}}_{(6t)} + \\
& + \underbrace{\phi \dot{m}_p Cp_b \left(T_{v_i} - T_{t_i}^{(1)} \right)}_{(7t)}.
\end{aligned}
\qquad (1)
$$

Where the terms, in the right member, represent the heat flux due to the: conduction through the tissue between the node and the neighbors (1t), generation by metabolic reactions that are not constant in the body (2t), circulation by capillary blood (3t), thermoregulation from the internal to external slices (4t), convection from arterial (5t) and venous (6t) blood to the tissue and pulmonary respiration (7t).

The heat balance equation for a central slice is:

$$
\begin{aligned}
m_{t_i}^{(2)} Cp_t \frac{dT_{t_i}^{(2)}}{dt} = {} & \underbrace{\sum_{j=1}^{3\,or\,4} \left(\frac{T_{t_j} - T_{t_i}^{(2)}}{R_{ji}} \right)}_{(1t)} + \\
& + \underbrace{\dot{Q}_{g_i}^{(2)}}_{(2t)} + \underbrace{Cp_b \left(\dot{m}_{at_i}^{(2)} T_{a_{i-1}} - \dot{m}_{tv_i}^{(2)} T_{t_i}^{(2)} \right)}_{(3t)} + \\
& + \underbrace{Cp_b \left(\dot{m}_{transf_i}^{(1\to2)} T_{t_i}^{(1)} - \dot{m}_{transf_i}^{(2\to3)} T_{t_i}^{(2)} \right)}_{(4t)}
\end{aligned}
\qquad (2)
$$

Finally, the heat balance equation for an external slice is the following:

$$
\begin{aligned}
m_{t_i}^{(3)} Cp_t \frac{dT_{t_i}^{(3)}}{dt} = {} & \underbrace{\sum_{j=1}^{2\,or\,3} \left(\frac{T_{t_j} - T_{t_i}^{(3)}}{R_{ji}} \right)}_{(1t)} + \\
& + \underbrace{\dot{Q}_{g_i}^{(3)}}_{(2t)} + \underbrace{Cp_b \left(\dot{m}_{at_i}^{(3)} T_{a_{i-1}} - \dot{m}_{tv_i}^{(3)} T_{t_i}^{(3)} \right)}_{(3t)} + \\
& + \underbrace{\dot{m}_{transf_i}^{(2\to3)} Cp_b T_{t_i}^{(2)}}_{(4t)} + \underbrace{\dot{Q}_{c_i}^{(3)}}_{(8t)} - \underbrace{\dot{Q}_{e_i}^{(3)}}_{(9t)} + \underbrace{\dot{Q}_{r_i}^{(3)}}_{(10t)}
\end{aligned}
\qquad (3)
$$

The terms (8t) and (9t) are associated to the heat exchange by convection and evaporation between the skin and the environment. The heat exchange by radiation between the skin and the surrounding surface is represented in the term (10t).

The corresponding equation for the arterial blood is the following:

$$
\begin{aligned}
m_{a_i} Cp_b \frac{dT_{a_i}}{dt} = {} & \underbrace{\dot{m}_{a_i} Cp_b \left(T_{a_{i-1}} - T_{a_i} \right)}_{(1b)} + \\
& + \underbrace{\dot{Q}_{c_{ta}}^{(1)}}_{(2b)} + \underbrace{\dot{Q}_{c_{va}}^{(1)}}_{(3b)} + \underbrace{\phi \dot{m}_p Cp_b \left(T_{t_i}^{(1)} - T_{a_i} \right)}_{(4b)}
\end{aligned}
\qquad (4)
$$

Where the terms, in the right member, represent the heat flux due to the: arterial blood circulation (1b), convection between the arterial blood and the tissue (2b), convection between the arterial and venous blood (3b) and arterial blood from the pulmonary capillaries (4b).

The heat balance equation for a venous blood is:

$$m_{v_i} Cp_b \frac{dT_{v_i}}{dt} = \underbrace{\dot{Q}^{(1)}_{c_{tv}}}_{(2b)} + \underbrace{\dot{Q}^{(1)}_{c_{va}}}_{(3b)} + \underbrace{+Cp_b\left(\dot{m}_{v_{i+1}} T_{v_{i+1}} - \dot{m}_{v_i} T_{v_i}\right)}_{(1b)} + \underbrace{+\sum_{j=1}^{3} \dot{m}^{(j)}_{tv_i} Cp_b T^{(j)}_{t_i}}_{(5b)} - \underbrace{\phi \dot{Q}_p}_{(6b)}. \quad (5)$$

The heat flux due the blood from the capillaries to the venous blood is represented in the term (5b). The term (6b) is associated to the heat loss through the pulmunary respiration system.

Thermal exchange with the blood

The heat flux by forced convection between the blood (arterial or venous) and the tissue is:

$$\dot{Q}^{(1)}_{c_{bt}} = h_{bt} A_{bt}\left(T_b - T^{(1)}_{t_i}\right), \quad (6)$$

where h_{bt} is determined by convection empirical expressions of flow inside tubes and A_{bt} depends of the dimension of the veins or artery.

The blood pumped by the heart is a function of the activity level. The distribution of blood in the human body, which is not uniform, is determined, in each node, by mass balance equation:

$$\sum \dot{m}_{b_{in}} = \sum \dot{m}_{b_{out}}. \quad (7)$$

Thermal exchange with environment

The thermal exchange, by sensible and latent heat, between the human body and the environment is done by: convection (sensible heat), evaporation (latent heat), radiation (sensible heat) and pulmonary respiration (sensible and latent heat) (ASHRAE Handbook 1989 and Fanger 1970):

$$\dot{Q}^{(3)}_{c_i} = h^{(3)}_{t_i} A^{(3)}_{t_i}\left(T_{air} - T^{(3)}_{t_i}\right) \quad (8)$$

$$\dot{Q}^{(3)}_{e_i} = \dot{Q}^{(3)}_{e_{sw_i}} + \dot{Q}^{(3)}_{e_{d_i}} = 2.43\times10^6 \dot{m}_{e_{sw_i}} + 0.0305\left(256\, T^{(3)}_{t_i} - 3373 - P_{air}\right)A^{(3)}_{t_i} \quad (9)$$

$$Q^{(3)}_{r_i} = \varepsilon\sigma A^{(3)}_{t_i}\left[\left(T_r\right)^4 - \left(T^{(3)}_{t_i}\right)^4\right] \quad (10)$$

$$\dot{Q}_p = \left[1.4\times10^{-3}(T_{exp} - T_{air}) + 1.72\times10^{-5}(5867 - P_{air}\right]\dot{Q}_g \quad (11)$$

Thermoregulatory system

The thermoregulatory system of the human body, that regulates the body temperature, is controlled by warm and cold signals from the skin and core thermoreceptors,

$$\begin{cases} WS_j = \begin{cases} 0 & T_j \le T_{j,n_i} \\ T_j - T_{j,n} & T_j > T_{j,n_i} \end{cases} \\ \text{with } j \equiv cr_i, sk_i, body_i \\ CS_j = \begin{cases} T_{j,n} - T_j & T_j < T_{j,n_i} \\ 0 & T_j \ge T_{j,n_i} \end{cases} \end{cases} \quad (12)$$

and is constituted by three control processes (ASHRAE Handbook, 1989):

- heat transport from internal to external slices, controlled by WS_{cr} and CS_{sk}, this being determined by $\dot{m}_{Transf_i}$, (see Figure 4);
- heat loss through evaporation, controlled by WS_{body} and WS_{sk}, that is, determining by $\dot{m}_{e_{sw_i}}$;
- additional metabolism heat through shivering, $\dot{Q}^{(j)}_{shiv_i}$, determined by CS_{sk} and CS_{cr} ($\dot{Q}^{(j)}_{g_i} = Q^{(j)}_{act} + \dot{Q}^{(j)}_{shiv_i}$)

The value of the skin neutral temperature, T_{sk_i,n_i}, which depends of the activity level, is presented in Fanger (1970) and the core neutral temperature, T_{cr_i,n_i}, is 36.8 °C. The body neutral temperature, T_{body_i,n_i}, can be determined by the weighted average of the skin and core temperatures.

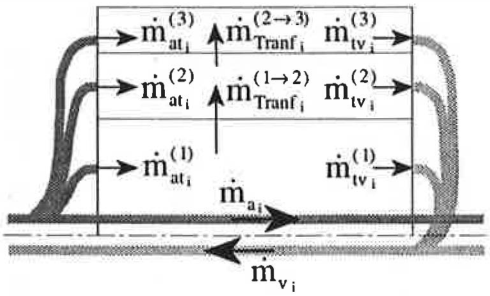

Figure 4 Blood flux in an element, considering the thermoregulatory system.

PMV index

The PMV value is determined by (Fanger 1970):

$$PMV = \left(0.303 e^{-0.036\left(\frac{\dot{Q}_g}{A_{body}}\right)} + 0.028 \right) \times \left\{ \frac{\dot{Q}_g}{A_{body}} - \sum_{i=1}^{35} \left[\frac{\dot{Q}^{(3)}_{e_i} + \dot{Q}^{(3)}_{r_i} + \dot{Q}^{(3)}_{c_i}}{A_{body}} \right] - \frac{\dot{Q}_p}{A_{body}} \right\} \quad (14)$$

Mathematical solution of the model

The integration of the first order differential equations system, for the heat balance equations, is performed with a Runge-Kutta-Fehlberg method with error control. The linear equations system, for the blood mass balance equations, is determined by a direct method.

NUMERICAL MODEL VALIDATION

It were used results of Thellier et al. (1994) to validate the present computational model. The experiment of these authors, using six nude men, was done in a controled climatic chamber, where the evolution of air and wall temperature are presented in Figure 5 and the air velocity was 0.25 m/s. Four locals skin temperatures were measured permiting to determine the body's skin mean temperature. In the simulation a typical person with 70 kg weight and 1.7 m height is used.

Figure 6 shows the comparison between the measured (interrupted line) and calculated (thin line) values of the body's skin mean temperature. Since the person's temperatures were different, in this figure we present the maximum and minimum temperature evolution obtained in the six men.

The forecasted body skin mean temperature evolution by the numerical model is in good agreement with the experimental data. It was also verified a good forecast for the trunk, shoulder and thigh skin mean temperature.

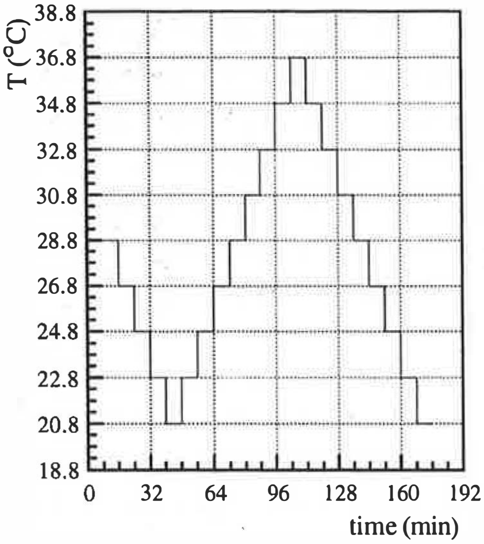

Figure 5 Evolution of air temperature.

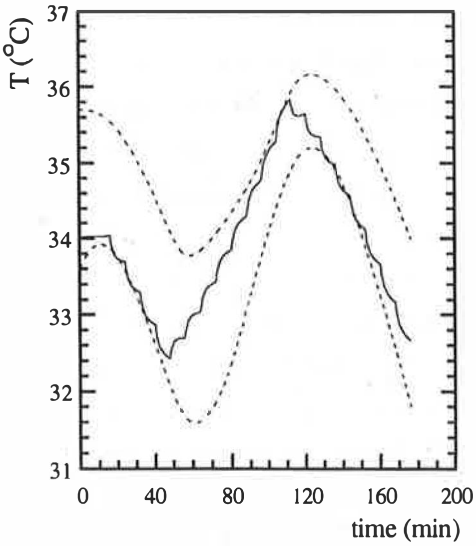

Figure 6 Evolution of body skin mean temperature.

The evolution of the mean PMV index determined numerically, evaluates the global thermal comfort and is presented in Figure 7.

The signals for the shoulder and thigh skin thermoreceptors, used to evaluate the local thermal discomfort, are showed in the Figure 8.

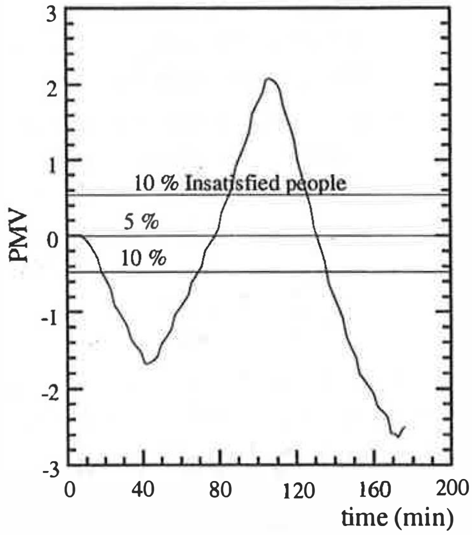

Figure 7 Determination of PMV index.

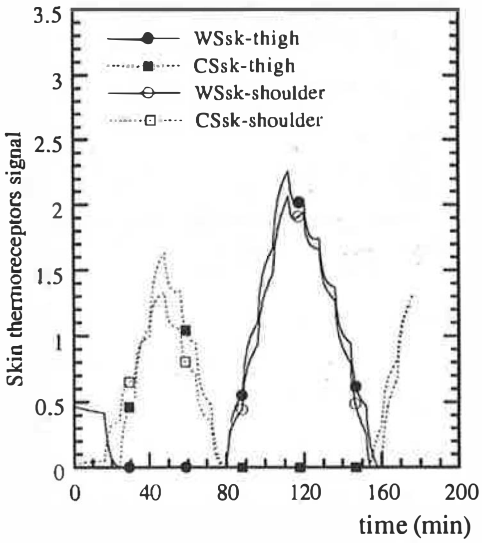

Figure 8 Signals of shoulder and thigh skin thermoreceptors.

The previous figures show that in begining, at 80 and 130 minutes the PMV index is in accord with the comfort conditions. The signals of shoulder and thigh skin thermoceptors show that only at 80 minutes the skin is comfortable.

CONCLUSIONS

A computational model, developed with the objective of simulating the human body thermal system, was presented. The validation, with some experimental data, shows that the program forecast the human body temperature in transient conditions.

This model, which evaluated the comfort level and local discomfort, can be used to develop and optimize air conditioning systems.

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NOMENCLATURE

Complete symbol

ε - Surface emissivity.
ϕ - Take the value 1 when the element contain the lungs and 0 in the otters.
P_{air} - Vapor parcial pression.
σ [Wm^{-2}¤C^{-4}] - Stefan-Boltzmann constant.
t [s] - Time.

Main symbol

A [m^2] - Surface area.
Cp [J °C^{-1}kg^{-1}] - Specific heat to the constant pression.
CS - Cold signal.
h [W m^{-2} °C^{-1}] - Mean convective heat transfer coefficient.
$\dot{m}$ [kg s^{-1}] - Mass flow rate.
m [kg] - Mass.
$\dot{Q}$ [W] - Heat flux.
R [°C W^{-1}] - Thermal resistance.
T [°C] - Temperature.
WS - Warm signal.

Sub-indexes (Relative to...)

a - Arterial blood.
act - Generated heat due to the activity.
air - Air around the person.

b - Blood.
body - Human body.
c - Heat convective.
cr - Core of human body.
e - Heat evaporation.
e_d - Evaporation due to the water vapor diffusion.
e_{sw} - Evaporation of sweat.
exp - Expired air.
g - Total metabolism heat generated.
i - Element i.
in - Inlet in the node.
n - Neutral temperature (comfortable).
out - Outlet in the node.
p - Pulmonary respiration.
r - Heat radiant.
shiv - Generated heat through shivering.
sk - Skin of the human body.
t - Tissue of the human body.
Transf - Heat transfer due thermoregulatory system.
v - Venous blood.

Super-indexes (Relative to...)
(1) - Internal slice.
(2) - Central slice.
(3) - External slice.