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ScienceDirect
Energy and Buildings 40 (2008) 1117–1123
ENERGY and BUILDINGS
www.elsevier.com/locate/enbuild

Short communication

A numerical simulation study for the human passive thermal system

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Received 20 September 2007; accepted 10 October 2007

Abstract

The objective of this study is to create a dynamic model representing a transient three-dimensional passive thermal model of the human body. The model is a multi-segmental, multi-layered representation of the human body with spatial subdivisions which simulates the heat transfer phenomena within the body and at its surface. In order to represent the mechanisms of heat transfer within the body, energy balance equations including conduction with adjacent tissue, heat storage, metabolic heat generation, and convective heat transfer due to the blood flow in the capillaries are taken into consideration for each tissue. The present model of the passive system accounts for the geometric and anatomic characteristics of the human body and considers the thermo-physical and the basal physiological properties of tissue materials. It is assumed that the body is exposed to combination of the convection, evaporation and radiation which are taken into account as boundary conditions when solving the passive thermal system equation. The model is capable of predicting human body temperature in any given environmental conditions. Finite difference solution scheme is used to find out the temperature distribution of human body. The results are compared with the experimental data of previous studies present in the literature. Consequently, the numerical results of present model show good agreement with the experimental data.

Keywords: Human body; Passive thermal model; Transient heat transfer

1. Introduction

It is important to know how the human body behaves under different environmental conditions. Especially in the area of heating, ventilating and air-conditioning, prediction of human thermal response is in great demand. Thermal regulation in human body depends on many interrelated factors. The human body can be separated into two interacting systems of thermoregulation: active and passive systems [1–4]. The active system is the temperature control system, which is responsible for the maintenance of the human body's temperature at a certain level. The active system predicts regulatory responses such as shivering, vasomotion, and sweating. The passive system simulates heat transfer in human body and its surroundings. By applying the theories of heat transfer and thermodynamics, namely by using the passive modeling of human thermal system, the thermal behavior of entire human body or a part of it can be predicted.

Pennes, who is one of the earliest scientists studied the human thermal system, had developed a passive model and the Bioheat equation in order to calculate the steady state one-dimensional temperature distribution in human forearm which was resembled as a single cylinder [5]. First core and shell model was introduced by Machle and Hatch [6]. Wdyndham and Atkins' single cylinder model was the first in predicting transient response of the human body [7]. Stolwijk and Hardy had considered local blood flow rate, metabolic rate, evaporation rate in their 25-node model of thermoregulation [8]. Many other multi-node models were based on the Stolwijk model with significant improvements such as body segments and layers [9,10].

In the present study, a transient three-dimensional thermal distribution of the human body is analyzed by using a numerical technique. Energy balance equations are written for each tissue including heat storage, metabolic heat generation, and convective heat transfer due to the blood flow in the capillaries. As boundary conditions, total effect of convection, radiation and evaporation are taken into consideration. The developed software is used to input the variables and to calculate the temperature throughout the entire body. It is possible to change the size of the any limb, environmental condition and sensivity

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0378-7788/$ – see front matter
doi:10.1016/j.enbuild.2007.10.015

Nomenclature

C_p	specific heat (J/kg K)
D	external diameter of the limb (m)
g	acceleration of gravity (=9.8 m/s^2)
Gr	Grashof number
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
K	coefficient for forced convection evaporation heat loss
Nu	Nusselt number
Pr	Prandtl number
P_v	vapor pressure of water at air temperature
q	heat flux (W/m^2)
r	radius of the limb (m)
Re	Reynolds number
RH	relative humidity of air
t	time (s)
T	temperature (°C)
v	velocity of air (m/s)
V	control volume

Greek letters

α	thermal diffusivity ($\alpha = k/\rho C_p$)
β	thermal expansion coefficient
ε	emissivity of the human body
σ	Stefan–Boltzmann constant (=5.67051 × 10^{-8} W/m^{2}K^4)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
ϕ	relative humidity

Subscripts

a	ambient air
art	artery
bl	blood
c	convection
d	diffusional
e	evaporation
E	grid point
f	film
free	free convection
forced	forced convection
h	harmonic mean
i	designation of the r location of discrete nodal points.
j	designation of the ϕ location of discrete nodal points
k	designation of the z location of discrete nodal points.
met	metabolic
P	grid point
r	radiation
s	surface
sw	sweat
v	vapor

of calculations. By this way, the model can be used in medical and thermal comfort applications.

2. Human thermal system

2.1. Bioheat equation of human passive thermal system

Passive system equation describes the passive system of human body with the mathematical point of view. In order to understand the heat transfer phenomena in the vivo tissues, the bioheat equation should be derived for an arbitrary small volume element by applying the principle of conservation of energy for living tissue [11]:

$$-\int_V \nabla \cdot q(r,\phi,z,t)\,\mathrm{d}V + \int_V q'''_{\mathrm{met}}\,\mathrm{d}V + \int_V q'''_{\mathrm{bl}}\,\mathrm{d}V = q'''_{\mathrm{s}} \qquad (1)$$

According to above equation, first term on the left-hand side is the conductive heat flux entering through the bounding surface of V, second term is the rate of energy generated by the metabolism in V, third term is the rate of energy transported by blood stream in V and the term on the right hand side refers to rate of energy storage in V.

Conduction in cylindrical coordinate system can be written as

$$\nabla q(r,\phi,z,t) = -k(r)\left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2}\right] \qquad (2)$$

The rate of energy generation within an organism is defined as the rate of transformation of chemical energy into heat and mechanical work by aerobic and anaerobic metabolic activities. These activities are the sum of the biochemical processes by which food is broken down into simpler compounds with the exchange of energy [11]. Total metabolic heat generation in the medium by

$$q_{\mathrm{met}} = \int_V q'''_{\mathrm{met}}\,\mathrm{d}V \qquad (3)$$

In present study, metabolic heat is assumed to be generated uniformly in each section of the cylinder. As an example, some layers produce much more metabolic heat, such as brain, which has the highest metabolic heat generation among the other tissue types. In contrast, bone tissues have no ability to produce heat. At rest, approximately 56% of total heat production produces by the internal organs, about 18% in the muscle and skin, 10% in the brain and 16% with the other organs [12].

Heat produced in the body should be absorbed by the bloodstream and conveyed to the body surface because of poor heat conductivity of the all body tissues. Therefore, the convective flow of blood throughout the body is very important in internal heat transfer [13].

The capillary bed forms the major site for the live exchange of mass and energy between the blood stream and surrounding tissue. This exchange is a function of several parameters including the rate of perfusion and the vascular anatomy, which vary widely among the different tissues, organs of the body.

The term which represents the rate of energy transported by blood stream is based on Fick's principle. According to Fick's principle, blood enters capillaries at the temperature of arterial blood, T_{art}, where heat exchanges occurs to bring the temperature to the surrounding tissue, T. Hence, total energy exchange between blood and tissue is given:

$$q_{bl} = \int_V \rho_{bl}\dot{w}_{bl}c_{Pbl}(T_{art} - T) \tag{4}$$

Present model accounts only heat exchange between the blood capillaries and the tissues. Further exchange of heat between the major venous vessels and the tissue surrounding them is also possible. However, this exchange is not significant compared to the exchange in the capillary bed. Therefore, heat exchanges between large blood vessels themselves and large blood vessels to tissue are not included in the thermal energy balance for the tissue. Another assumption is that there is no heat storage occurs in the bloodstream when the heat exchange occurs between the capillary bed and the tissue.

Over short periods and severe environments, heat storage in the tissue, which can be an important component of the heat balance, determines the tolerance time for work. Therefore, heat storage is likely to be important in human for periods of up to few hours [14].

Under transient conditions part of the thermal energy generated or transferred to the control volume may go to alter the amount stored inside it. Thus, the rate of change in storage of thermal energy is given by

$$q_s''' = \frac{\partial}{\partial t}\int_V \rho c_p T \, dV \tag{5}$$

Below equation can be obtained by substituting Eqs. (2)–(5) into Eq. (1):

$$\int_V \left[-\nabla \cdot q(r,\phi,z,t) + q_{met}'''(r) + \rho_{bl}\dot{w}_{bl}(r)c_{pbl} \times (T_{art} - T) - \rho(r)c_p(r)\frac{\partial T(r,\phi,z,t)}{\partial t}\right] dV = 0 \tag{6}$$

If the volume V may be chosen so small as to remove the integral, passive thermal system bioheat equation can be obtained:

$$\rho(r)c_p(r)\frac{\partial T(r,\phi,z,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \phi}\left(k\frac{\partial T}{\partial \phi}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + q_{met}'''(r) + [\rho_{bl}\dot{w}_{bl}(r)c_{pbl}(T_{art} - T)] \tag{7}$$

2.2. Heat exchange with environment

At the outer surface of the human body, heat transfer consists of a liner combination of convection, radiation, and sweat evaporation. Physical features of the limbs, air velocity around the body, the ambient temperature and the relative humidity of the air should be taken into account in order to calculate the heat transfer between the human body and the environment.

Radiation is the loss of heat in the form of infrared waves. All objects continually radiate energy in accordance with the Stefan–Boltzmann law. When the surrounding is cooler than the body, net radiative heat loss occurs. Under normal conditions, close to half of body heat loss occurs by radiation. In contrast, a net heat gain via radiation occurs when the surrounding is hotter than the body [13].

The amount of incident radiation that is captured by a body depends on its area, the incident flux, and the body's absorptivity. It is common to estimate the absorptivity of a body as equal to its emissivity at the temperature of the surroundings, although this is strictly true only when the body is in radiative equilibrium with the surroundings.

The net rate of heat exchange by radiation between an organism and its environment, usually expressed in terms of unit area of the total body surface:

$$q_r = \varepsilon\sigma(T_s^4 - T_a^4) \tag{8}$$

Convective heat losses from the body strongly depending on air velocity characterized by

$$q_c = h_c(T_s - T_a) \tag{9}$$

The convective heat transfer coefficient, h_c, is calculated from the equation given below:

$$Nu = \frac{h_c D_{\lim b}}{k_a} \tag{10}$$

The movements of fluid which carry heat away from the body surface may be driven by two mechanisms: free convection due to density differences in the fluid associated with temperature gradients, or forced convection due to external forces such as wind [15].

In free convection case, the Nusselt number is given by

$$Nu = 0.63\, Gr^{0.25}\, Pr^{0.25} \tag{11}$$

where Pr is the Prandtl number of the air at given temperature and Gr is the Grashof number which is expressed by

$$Gr = \frac{g\beta(T_s - T_a)L^3}{\nu_a^3} \tag{12}$$

In forced convection case, the Nusselt number is given by [15]:

$$Nu = 0.26\, Re^{0.60}\, Pr^{0.33}, \quad \text{for } 10^3 \le Re \le 5\times10^4 \tag{13}$$

$$Nu = 0.026\, Re^{0.81}\, Pr^{0.33}, \quad \text{for } 4\times10^4 \le Re \le 4\times10^5 \tag{14}$$

Reynolds number, Re, is calculated from the equation below:

$$Re = \frac{D_{\lim b}v}{\nu_a} \tag{15}$$

Water diffusion through the human skin is part of the insensible perspiration. This diffusion totals about 350 ml/day in an average person and is assumed to be proportional to the difference between the vapor pressure of water at the skin temperature and the partial pressure of water vapor in the ambient air [13].

$$q_d = \frac{4184}{3600}(0.35)(P_s - P_a) \tag{16}$$

$$P_s = 1.92T_s - 25.3 \tag{17}$$

$$P_a = P_v(\%\text{RH}) \tag{18}$$

When the heat loss amount is not enough to maintain the core temperature in a suitable range, mechanism for increasing the heat loss is the sweating response. Then, evaporation from the wetted surface occurs [13]. Heat loss by sweat secretion per unit area is given by

$$q_{sw} = \frac{4184}{3600}K_e(P_s - P_a) \tag{19}$$

3. Numerical method

3.1. Modeling

Modeling of passive human thermal system deals with the heat transfer phenomena in human body and at its surface. Application of heat balance to a tissue control volume results in equations which simulate the passive system in the mathematical point of view. Solving these equations by chosen method leads to predict the thermal behavior of entire human body or a part of it for different environmental conditions.

In order to simulate all these heat-transport phenomena, the model should account for the geometric and anatomic characteristics of the human body such as geometry of organism, metabolic heat production, role of blood in heat transfer, conduction of heat due to the thermal gradients, the interaction with the environment.

Present model is a multi-segmental, multi-layered representation of the human body. The human body parts resemble cylinders in appearance; therefore it is convenient to use cylinders to model the human body. The body is divided into 16 concentric cylinders, which depict the head, neck, abdomen, thorax, upper arms, lower arms, hands, thighs, calves, and feet. Spatial division of any body part is consisted of bone, muscle, fat and skin.

Each limb is subdivided in the radial direction, describing the distributions of the various tissue types throughout the body. According to this division, assuming that the tissue thermal conductivity, specific heat of the tissue, tissue density and the blood perfusion rate of the tissue are segmentally uniform in each layer.

In this model, thermoregulatory mechanism in the organism and their functions are not considered. Therefore, vasomotor activity, sweating, shivering, increased metabolism due to glandular activity, and panting are neglected. These parameters are taken into account in active modeling of the human thermal system, which deals with maintaining the human body's temperature at a constant level.

3.2. Numerical method

The bioheat equation given in Eq. (7), solved in the radial, tangential and axial directions by using the finite difference technique in order to find out the temperature distribution of the overall unclothed human body. In the present model, each sector of each tissue shell is divided into nodes. User defines the mesh size of the each limb and the space of the two nodes in r, ϕ and z directions by choosing the sensitivity of the calculations in the software.

When the node is at the interface of the two different homogeneous tissue types, the thermal properties such as thermal conductivity, density, specific heat, of this interface node are obtained by considering the neighboring tissue layers. If it is assumed that the control volume surrounding the grid point P is filled with a material of uniform conductivity k_P, and the one around E with a material of uniform conductivity k_E, thus the thermal conductivity of interface e in the cylindrical coordinate system can be written by using the harmonic mean of k_P and k_E.

The most straight forward procedure for obtaining the interface thermal properties is to use the harmonic mean of points P and E:

$$\text{k}_h = \frac{\ln(r_P/r_E)}{\ln(r_P/r_E)/k_P + \ln(r_e/r_E)/k_E} = \frac{k_P k_E \ln(r_P/r_E)}{k_E \ln(r_P/r_e) + k_P \ln(r_e/r_E)} \tag{20}$$

Other thermal properties and the physiological properties, such as blood perfusion rate, can be also obtained by using the harmonic mean of the two neighboring tissue layers properties.

3.3. Initial and boundary conditions

An initial boundary condition should be given in order to solve the transient passive human thermal system equation. Initial condition is given as an input in the software and represents as

$$T(0, r, \Phi, z) = T_{in}, \quad \text{at } t = 0 \tag{21}$$

Another boundary condition used for solving Eq. (7) is the symmetrical boundary condition. Due to the symmetrical condition of representative geometry, temperature difference along the tangential axis at $\Phi = 0$ and $\Phi = \pi$ is taken 0, namely

$$\frac{\partial T}{\partial \phi} = 0, \quad \text{at } \Phi = 0 \text{ and } \Phi = \pi \tag{22}$$

According to given informations above, at the outer surface of the human body the heat exchange between the body and the environment can be written in mathematical point of view by

$$-k\frac{\partial T}{\partial r} = h_c(T_s - T_a) + \varepsilon\sigma(T_s^4 - T_a^4) + \frac{4184}{3600}(0.35)(P_s - P_a) + \frac{4184}{3600}K_e(P_s - P_a) \tag{23}$$

3.4. Biothermal software

Software called Biothermal is created in Visual Basic language [16]. The software consists of two parts called: visual and module. In visual part of the software, first page is input page in which user assigns the radius and length of each limb, environmental conditions, initial temperature of the human body and sensitivity of the calculation.

The default values seen in body dimension part are taken from the literature. Changing capability of each element's radius and length value leads the model to be flexible in terms of body dimensions. For environmental conditions, temperature and relative humidity of the air and velocity of air can be assigned. User defines the mesh size of the element by selecting the high, medium or low sensitivity button.

After assigning the body dimensions and environmental conditions with defining the calculation sensitivity, the values are transformed to the module part of the software. During the calculation, user can see the maximum and minimum temperature values in the whole human body along with the temperature distribution.

4. Results and discussion

4.1. Model verification

The present model should be verified in order to determine accuracy of the model. The verification process is done by comparison of the experimental data and the analytical solutions given in the literature (Fig. 1).

The temperature distributions of human body are obtained at given cases in Table 1.

4.1.1. Case 1

Pennes found out the steady state temperature distribution in human arm in natural convection condition of 26 °C temperature and 50% relative humidity, experimentally [17]. The initial temperature of the arm was 36 °C. The very same condition is used in order to compare the data. As it is seen in Fig. 2, present study results follow the same trend and show a good agreement with Pennes' experimental data.

4.1.2. Case 2

The experimental data for Case 2 is taken from Takata et al. [18]. During the experiment, unclothed skin temperatures at the arm were measured in a room at 35 °C and relative humidity 90% for half an hour. Initially, the subject temperature was measured 32 °C. In addition to this, the experimental results were analyzed by using the Gagge model, which is two-node model of human thermophysical responses. The conditions given in Case 2 is used by our Biothermal software and our model showed better agreement with the experimental data than calculated data by Takada et al. The reason for this that, in order to simulate the skin temperature of arm, Takada et al. was used Gagge model which depicts the human body as a cylinder which consists of only core and skin (Fig. 3).

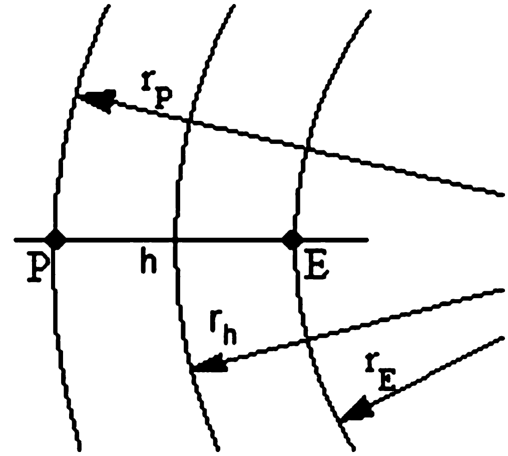

Fig. 1. Intersection face between two layers.

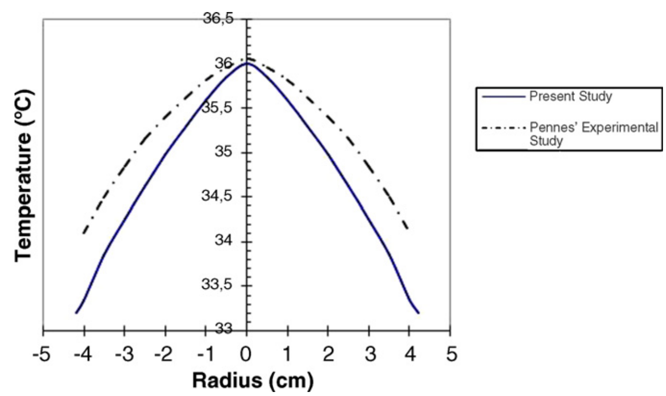

Fig. 2. Comparison of the human forearm temperature with Pennes' data.

4.1.3. Case 3

The temperature distribution of muscle tissue within a homogenous cylinder was solved, analytically, by Eberhart [3]. The cylinder was initially in thermal equilibrium with the environment at 0 °C. At $t = 0$ the cylinder was suddenly supplied with a constant rate of blood flow. In this study, the calculated temperature of the muscle tissue in leg is compared

Table 1
Conditions of experimental and analytical studies

Case	Air temperature (°C)	Relative humidity (%)	Air velocity (m/s)	Initial temperature (°C)
1	26	50	0.05	36
2	35	90	0.05	32
3	0	45	0.05	0
4	24.6	50	0.1	34

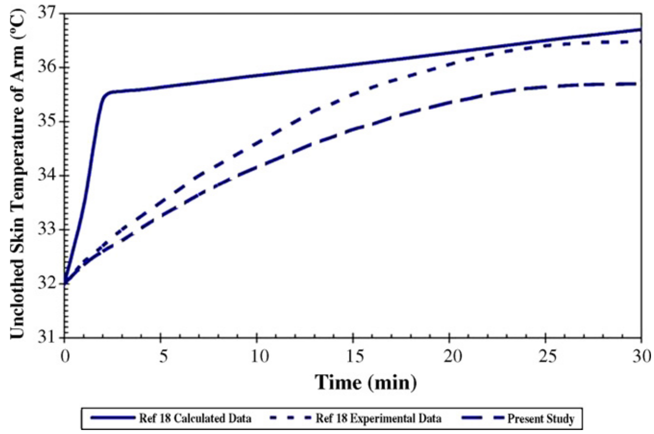

Fig. 3. Comparison of the unclothed skin temperature of arm with Takata et al. data.

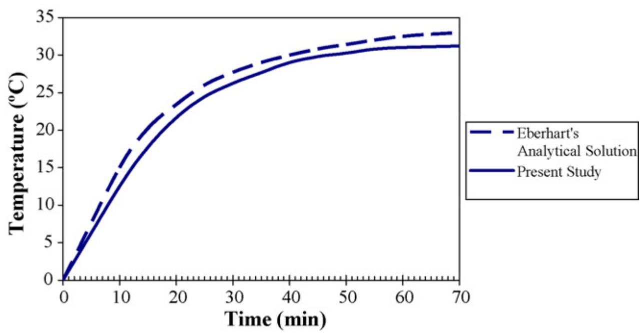

Fig. 4. Comparison of the muscle tissue temperature of leg with Eberhart's analytical solution.

with an analytical solution of Eberhart. As it is seen in Fig. 4, calculated muscle tissue temperature in leg by present model shows good agreement with the analytical solution.

Some sectional views of the leg are taken at different time durations are shown in Fig. 5.

4.1.4. Case 4

Case 4 is the comparison of present model with a model used by Arkin and Shitzer [2]. Their model was combined model of the human thermal system, namely it included both active and passive system simulations. Although the present model includes only the passive system of the human thermal system,

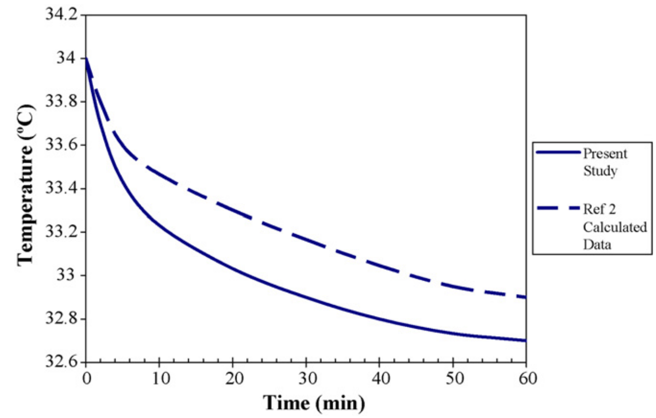

Fig. 6. Comparison of the mean skin temperature of human body with Arkin's and Shitzer's data.

good agreement is seen with the calculated data by Arkin and Shitzer [2]. The deviation between two graphs is caused by the human thermal responses such as vasoconstriction, vasodilation, sweating or shivering (Fig. 6).

4.1.5. Case 5

Apart from comparison with other studies, a scenario is written in order to show the temperature changes in mean body and skin with respect to time. In this scenario, at $t = 0$ a man enters the Room 1 with condition of 28.1 °C and 43% relative humidity. This room condition is in the range of thermal comfort zone defined by ASHRAE [19]. After staying 10 min there, he enters another room which is hotter than previous room with 47.8 °C room temperature and 27% relative humidity. After 10 min of stay, he enters a different room with same temperature value with the previous room but higher relative humidity which is 99%. After 20 min stay, he enters a room which is at 47.8 °C and 0% relative humidity. After staying 10 min there, he enters back to the first room (Table 2).

As it is seen in Fig. 7, the temperature of skin is affected dramatically when the environmental condition changes. Skin temperature reached its highest value when the man is in Room 3. Because, the temperature and the relative humidity rise of the environment causes heat loss by diffusion and evaporation. This causes high temperature value in the body which is very harmful even fatal for human.

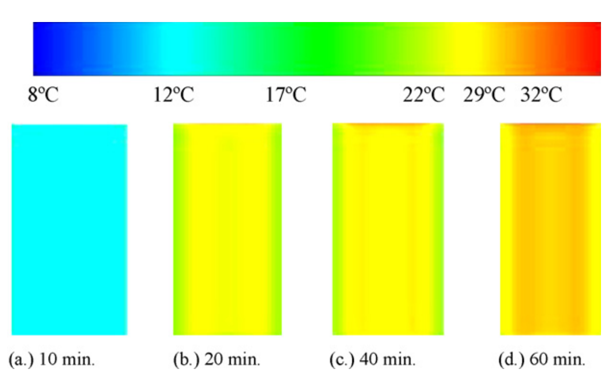

Fig. 5. Simulation of temperature changes in leg with time.

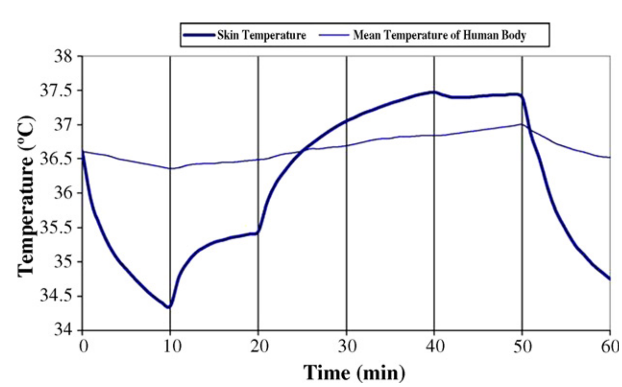

Fig. 7. Simulation of temperature changes in human body with time.

Table 2
Conditions of room in the scenario

Room	Air temperature (°C)	Relative humidity (%)	Time duration (min)
1	28.1	50	10
2	47.8	27	10
3	47.8	99	20
4	47.8	0	10

5. Conclusions

In the present model, a transient three-dimensional mathematical modeling of the human passive system has been developed using finite difference technique. In order to increase the accuracy of the model, the human body has been divided into 16 cylinders and each cylinder has been divided into four radial layers which represent the tissue types such as bone, fat, muscle, skin, viscera, lung, and brain. According to the assumptions, the Bioheat equation has been derived and written for each tissue element. In model, it has been assumed that the human body dissipates heat by the combination of convection, radiation and evaporation.

Software, which has been written in Visual Basic language, called Biothermal, has been used to determine temperature distribution at succeeding time step of the viscera, lung, and brain, all tissue types of the torso, neck, head, leg, foot, arm, and hand. Also, the software is capable of demonstrating the sectional view of the various body limbs and full human body.

In this model, unlike previous studies, the software user defines the dimensions of the body limbs and environmental conditions. Additionally, user may choose the sensitivity of the calculation according to desired sensitivity. All these properties of the software make the present model more flexible than the previous models used in the literature.

In order to verify the accuracy of the model, computer simulation results have been compared with available experimental data, analytical solution and calculated data of previous studies for different environmental conditions. Based on these comparisons, some conclusions have been drawn regarding the model accuracy and applicability.

In addition, a scenario has been written for simulating the environment temperatures at abnormal conditions. In this scenario, it could be seen that the mean temperature of the human body remains almost constant although, the skin temperature of the body fluctuates with varying environmental conditions.

The present model can be enlarged by taking into account the heat loss by respiration, clothing insulating factor and metabolic heat generation during physical activities. These could be the future work of succeeding studies.

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