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Short communication

A numerical simulation study for the human passive thermal system

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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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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]:

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

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

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

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

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

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.