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ANALYZING EFFECT OF TEMPERATURE VARIATION ON SKIN SUB-LAYERS USING FINITE ELEMENT APPROACH

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ABSTRACT

The temperature distribution in human body regulates variety of biological mechanism. Human Skin is a very complex structure and abnormality in temperature of various layer of skin play important role for curing and treatment diseases like tumor, cancer etc. The eight layers of human skin namely stratum corneum, stratum lucidum, stratum granulosum, stratum spinosum, stratum germinativum, papillary, reticular and subcutaneous tissue are considered for the study. A one dimensional Finite element model is developed to study the temperature distribution involving blood circulation rate, metabolic heat generation and thermal conductivity in human skin. A MATLAB program has been developed to obtain the numerical results.

KEYWORDS: ***Temperature Distribution, Blood mass flow rate, Dermal layers, Finite Element Method, Thermal Conductivity***

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INTRODUCTION

The human thermoregulatory is very complex system and it includes more control processes than any technical control system.[1] Human skin is a very complex tissue consisting of several distinct layers and components. Human body maintains its body core temperature constant within small range between (37±0.6)°C. Skin temperature distribution of the human body is a complex interaction of physical heat exchange processes and the potential for physiological adjustment. Temperature influences the functioning of biological systems.[2] The SST region consist mainly three layers namely epidermis, dermis and subcutaneous tissue. Epidermis is the most outer layer. The outer most layer divided in to five layers namely stratum corneum, stratum lucidum, stratum granulosum, stratum spinosum and stratum (basale) germinativum. The temperature regulation in a human body is accomplished through several major mechanisms. These are blood flow, temperature of incoming arterial blood, and heat exchange with the environment.[3] The skin surface is assumed to expose to the environment and the outer skin surface temperature is considered to be equal to the atmospheric temperature. The change in the temperature of the surroundings also affects the temperature of the human skin. The skin temperature is the crucial temperature when we refer to the skin's ability to lose heat to the surrounding ambience.[4] Human body perpetuates its body core temperature at a uniform temperature under the normal atmospheric conditions. In order to maintain this core temperature, parameters like rate of blood mass flow, rate of metabolic heat generation and thermal conductivity differ in response to changes in surrounding conditions.[5] However, in extreme parts of a human body the core temperature is not uniform at low atmospheric temperature. This may be because the arterial blood has cooled down while travelling towards the extremities. The heat flow in in-vivo tissues given by temperature distribution in tissue medium.[6] Patterson[7] made an attempt for experimental determination of temperature problems in Skin and Subcutaneous Tissues (SST) region. Saxena and Arya[8] developed a three layered finite element model to find the temperature problems in SST region for a one dimensional steady state case. Cooper and Trezek[9] found an analytic solution of heat diffusion equation for brain tissue with negligible effect of blood flow and metabolic heat generation. Trezek and cooper[10] computed the thermal conductivity of the brain tissue by considering all the parameters as constants. Several computer-simulated models of temperature distribution in a human dermal system have been developed. The aim of our study is to develop a model describing temperature distribution in human dermal parts and to calculate the temperature distribution at multi-layered skin and sub-dermal tissues by using variational finite element method. The present work is an attempt to study the distribution of temperature at deep dermal layers for heterogeneous thermal conductivity as a function of temperature.

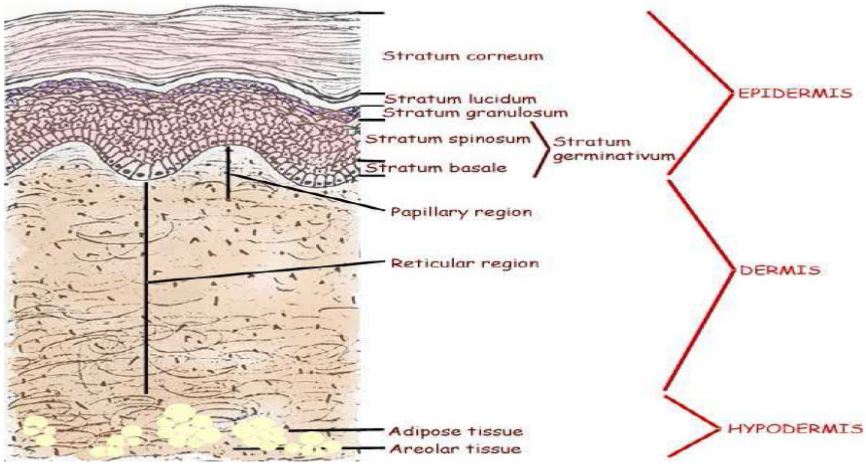


Figure 1
Human Skin layer [11]

The Penne's model is used to address the heat exchange in living tissues. This model is based on the assumption of the energy exchange between the blood vessels and the surrounding tissues. Penne's model may give suitable temperature distributions in whole body, organs and tumor analysis.[12] This formulation will now be extended to incorporate heat sources and boundary conditions that can vary with time. Many interesting bio-heat applications involve heating and cooling by time-varying environmental or therapeutic influences.[13] Heat transfer problems in human are related to medical sciences and have a role in treatment and in the diagnosis of deceases like tumor, skin burn, skin itching etc. They can estimate the time and the course of treatment with information on the temperature where thermometry is lacking. Heat transfer in biological system involves metabolic heat generation, conduction, convection, radiation, evaporation and blood perfusion in human tissue but all physiological function generates heat by means of metabolic reaction in biological systems.[14] The balance between the heat generation and loss from the body to the environment is very important to maintain body core temperature. Any physiological abnormality will disturb the homeostatic conditions for the temperature.[15] Therefore the study of heat transfer under normal and abnormal conditions will be useful for various clinical conditions. The goal of our study is to develop a model describing temperature in human dermal parts.

MATHEMATICAL MODEL

The Mathematical model used for bio-heat transfer is based on the penne equation[11] which incorporate the effect of metabolism and blood perfusion in to the standard thermal diffusion equation:

$$\rho c\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\mathrm{K}\frac{\partial}{\partial x}T\right)+c_b m_b w_b(T_a-T)+S \qquad (1)$$

Here ρ, x, c, K and S are respectively the density, specific heat, thermal conductivity and rate of metabolic heat generation in tissues. Also the other quantity w_b, m_b, c_b and T_a are the blood perfusion rate, the blood mass flow rate, specific heat of the blood, and arterial blood temperature respectively.

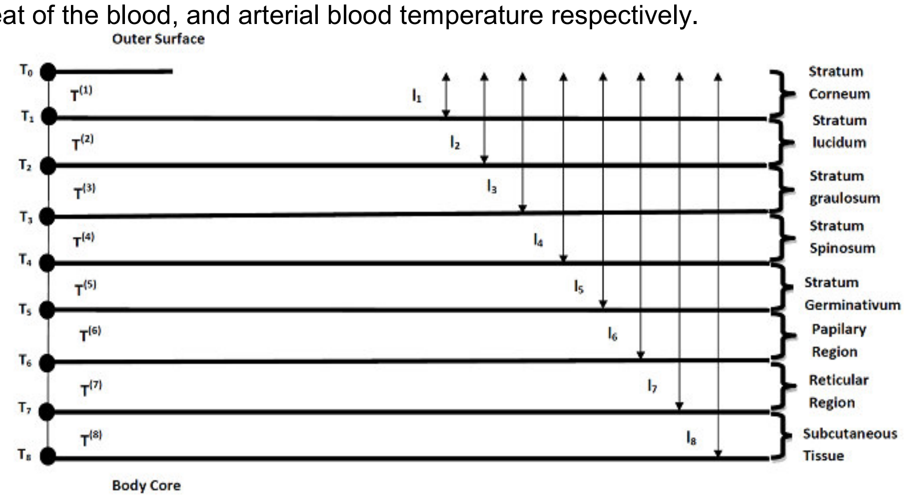


Figure 2
Finite Element Discretization of Eight layers of Skin with Nine Nodal Points

The loss of heat from the skin surface due to convection, radiation and evaporation is considered. So the mixed boundary condition is taken as:

$$-K\frac{\partial T}{\partial t}\bigg|_{\text{At skin outer surface}}=h\left(T-T_\infty\right)+LE \qquad (2)$$

Where, h=Combined heat transfer coefficient due to convection and radiation T_∞=Surrounding temperature, L=Latent heat of evaporation, E=Rate of sweat evaporation, the inner body core temperature T_b is assumed to be 37°C. The thickness of stratum corneum, stratum lucidum, stratum granulosum, stratum spinosum, stratum germinativum (basale), papillary region, reticular region and subcutaneous tissue have been considered as l_1, l_2-l_1, l_3-l_2, $l_4-l_3, l_5-l_4, l_6-l_5, l_7-l_6, l_8-l_7$ respectively and T_0, T_1, T_2, T_3, T_4, T_5, T_6, T_7 and T_8 = T_b are the nodal temperatures at a distances $x=l_0$, $x=l_1$, $x=l_2$, $x=l_3$, $x=l_4$, $x=l_5$, $x=l_6$, $x=l_7$ and $x=l_8$. $T^{(i)}$ (i = 1, 2, 3, 4, 5, 6, 7, 8) be the temperature functions in the layers stratum corneum, stratum lucidum, stratum granulosum, stratum spinosum, stratum germinativum (basale), papillary region, reticular region and subcutaneous tissue respectively.

Table 1
Shape function at different layers of skin

Name of the layers	Shape function $T^{(i)}(x)$
Stratum Corneum $(0\le x\le l_1)$	$T^{(1)}=T_0+\frac{T_1-T_0}{l_1}x$
Stratum lucidum $(l_1\le x\le l_2)$	$T^{(2)}=\frac{l_2T_1-l_1T_2}{l_2-l_1}+\frac{T_2-T_1}{l_2-l_1}x$
Stratum graulosum $(l_2\le x\le l_3)$	$T^{(3)}=\frac{l_3T_2-l_2T_3}{l_3-l_2}+\frac{T_3-T_2}{l_3-l_2}x$
Stratum Spinosum $(l_3\le x\le l_4)$	$T^{(4)}=\frac{l_4T_3-l_3T_4}{l_4-l_3}+\frac{T_4-T_3}{l_4-l_3}x$
Stratum Germinativum $(l_4\le x\le l_5)$	$T^{(5)}=\frac{l_5T_4-l_4T_5}{l_5-l_4}+\frac{T_5-T_4}{l_5-l_4}x$
Papilary Region $(l_5\le x\le l_6)$	$T^{(6)}=\frac{l_6T_5-l_5T_6}{l_6-l_5}+\frac{T_6-T_5}{l_6-l_5}x$
Reticular Region $(l_6\le x\le l_7)$	$T^{(7)}=\frac{l_7T_6-l_6T_7}{l_7-l_6}+\frac{T_7-T_6}{l_7-l_6}x$
Subcutaneous Tissue $(l_7\le x\le l_8)$	$T^{(8)}=\frac{l_8T_7-l_7T_8}{l_8-l_7}+\frac{T_8-T_7}{l_8-l_7}x$

Table 2
Values of $T_a^{(i)}$, $K^{(i)\,(i)}$, $M^{(i)} = w^{(i)}b * m^{(i)}b * c^{(i)}b$ and $S^{(i)}$ at i^{th} element of skin layers

i^{th} Element	Name of the layer	$T_a^{(i)}$	$K^{(i)}$	$M^{(i)}$	$S^{(i)}$
1	Stratum Corneum	$T_a^{(1)} = 0$	$K^{(1)}$ =0.20934	$M^{(1)}$ = 0.0000001	$S^{(1)}$ =0.0000001
2	Stratum lucidum	$T_a^{(2)} = 0$	$K^{(2)}$ =0.3134	$M^{(2)}$ =0.0000003	$S^{(2)}$ =0.0000003
3	Stratum graulosum	$T_a^{(3)} = 0$	$K^{(3)}$ =0.3134	$M^{(3)}$ =0.0000004	$S^{(3)}$ =0.0000004
4	Stratum Spinosum	$T_a^{(4)} = 0$	$K^{(4)}$ =0.06934	$M^{(4)}$ =174	$S^{(4)}$ =114.1855
5	Stratum Germinativum	$T_a^{(5)} = 0$	$K^{(5)}$ =0.06934	$M^{(5)}$ =612	$S^{(5)}$ =304.495
6	Papilary Region	$T_a^{(6)} = T_b$	$K^{(6)}$ =0.1768	$M^{(6)}$ =1486.5	$S^{(6)}$ =685.112
7	Reticular Region	$T_a^{(7)} = T_b$	$K^{(7)}$ =0.31868	$M^{(7)}$ =2198.1	$S^{(7)}$ =1256
8	Subcutaneous Tissue	$T_a^{(8)} = T_b$	$K^{(8)}$ =0.41868	$M^{(8)}$ =2198.1	$S^{(8)}$ =1256

SOLUTION OF PROBLEM

The variation integral form of (1) in one dimensional unsteady state case together with outer skin boundary condition (2) is given by

$$I = \frac{1}{2}\int_0^1 \left[K\left(\frac{\partial T}{\partial x}\right)^2 + M\left(T_a - T\right)^2 - 2ST + \rho c\left(\frac{\partial T^2}{\partial t}\right)\right] dx + \frac{1}{2}h\left(T - T_\infty\right)^2 + 2LET \tag{3}$$

where, $M=w_b*m_b*c_b$

We calculate I separately for the eight elements of skin layers: I_1 for stratum corneum, I_2 for Stratum lucidum, I_3 for Stratum graulosum, I_4 for Stratum spinosum, I_5 for Stratum Germinativum, I_6 for papillary region, I_7 for reticular region and I_8 for subcutaneous tissue.

$$I_1 = \frac{1}{2}\int_0^{l_1} \left[K^{(1)}\left(\frac{dT^{(1)}}{dx}\right)^2 + M^{(1)}\left(T_a^{(1)} - T^{(1)}\right)^2 - 2S^{(1)}T^{(1)} + \rho c\left(\frac{\partial T^{(1)^2}}{\partial t}\right)\right] dx + \frac{1}{2}h\left(T_0 - T_\infty\right)^2 + 2LET_0 \tag{4}$$

$$I_2 = \frac{1}{2}\int_{l_1}^{l_2} \left[K^{(2)}\left(\frac{dT^{(2)}}{dx}\right)^2 + M^{(2)}\left(T_a^{(2)} - T^{(2)}\right)^2 - 2S^{(2)}T^{(2)} + \rho c\left(\frac{\partial T^{(2)^2}}{\partial t}\right)\right] dx \tag{5}$$

$$I_3 = \frac{1}{2}\int_{l_2}^{l_3} \left[K^{(3)}\left(\frac{dT^{(3)}}{dx}\right)^2 + M^{(3)}\left(T_a^{(3)} - T^{(3)}\right)^2 - 2S^{(3)}T^{(3)} + \rho c\left(\frac{\partial T^{(3)^2}}{\partial t}\right)\right] dx \tag{6}$$

$$I_4 = \frac{1}{2}\int_{l_3}^{l_4} \left[K^{(4)}\left(\frac{dT^{(4)}}{dx}\right)^2 + M^{(4)}\left(T_a^{(4)} - T^{(4)}\right)^2 - 2S^{(4)}T^{(4)} + \rho c\left(\frac{\partial T^{(4)^2}}{\partial t}\right)\right] dx \tag{7}$$

$$I_5 = \frac{1}{2}\int_{l_4}^{l_5} \left[K^{(5)}\left(\frac{dT^{(5)}}{dx}\right)^2 + M^{(5)}\left(T_a^{(5)} - T^{(5)}\right)^2 - 2S^{(5)}T^{(5)} + \rho c\left(\frac{\partial T^{(5)^2}}{\partial t}\right)\right] dx \tag{8}$$

$$I_6 = \frac{1}{2}\int_{l_5}^{l6} \left[K^{(6)}\left(\frac{dT^{(6)}}{dx}\right)^2 + M^{(6)}\left(T_a^{(6)} - T^{(6)}\right)^2 - 2S^{(6)}T^{(6)} + \rho c\left(\frac{\partial T^{(6)^2}}{\partial t}\right)\right] dx \tag{9}$$

$$I_7 = \frac{1}{2}\int_{l_6}^{l_7} \left[K^{(7)}\left(\frac{dT^{(7)}}{dx}\right)^2 + M^{(7)}\left(T_a^{(7)} - T^{(7)}\right)^2 - 2S^{(7)}T^{(7)} + \rho c\left(\frac{\partial T^{(7)^2}}{\partial t}\right)\right] dx \tag{10}$$

$$I_8 = \frac{1}{2}\int_{l_7}^{l_8}\left[K^{(8)}\left(\frac{dT^{(8)}}{dx}\right)^2 + M^{(8)}\left(T_a^{(8)} - T^{(8)}\right)^2 - 2S^{(8)}T^{(8)} + \rho c\left(\frac{\partial T^{(8)^2}}{\partial t}\right)\right]dx \qquad (11)$$

Evaluating the integral I_i (i=1, 2, 3, ...8) with the help of layers wise assumptions.

Now the integrates I_i are evaluated from the equation (4) to (11) are assembled as:

$$I = \sum_{i=1}^{8} I_i \qquad (12)$$

we substitute $T_8 = T_b$ in above equation (12),where T_b is the body core temperature.

Now I is extremized with respect to nodal temperature $T_0, T_1, T_2, T_3, T_4, T_5, T_6, T_7$ as given below:

$$\frac{dI}{dT_j} = \sum_{i=1}^{8}\frac{dI_i}{dT_j} = 0, \qquad j = 0,1,2,..........7 \qquad (13)$$

We get a system of ordinary differential equation is matrix form as:

$$C\frac{\partial \overline{T}}{\partial t} + P\overline{T} = W \qquad (14)$$

Where,

$$\overline{T} = \begin{bmatrix} T_0 \\ T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \end{bmatrix} \quad \text{and} \quad \frac{\partial \overline{T}}{\partial t} = \begin{bmatrix} \frac{\partial T_0}{\partial t} \\ \frac{\partial T_1}{\partial t} \\ \frac{\partial T_2}{\partial t} \\ \frac{\partial T_3}{\partial t} \\ \frac{\partial T_4}{\partial t} \\ \frac{\partial T_5}{\partial t} \\ \frac{\partial T_6}{\partial t} \\ \frac{\partial T_7}{\partial t} \end{bmatrix} \qquad (15)$$

C and P are system matrices and W is system vector.

To solve the system of ordinary differentiation equation (14) we use Crank-Nicolson method. This method moves the solution of the system ahead in time according to the relation[16]

$$\left(C + \frac{\Delta t}{2}P\right)\overline{T}^{(i+1)} = \left(C - \frac{\Delta t}{2}P\right)\overline{T}^{(i)} + \Delta t W \qquad (16)$$

where Δt is step size of time, and $\overline{T}^{(0)}$ is 8×1 matrix for initial nodal temperatures at time t=0sec. Generally, under normal condition the temperature decreases from body core towards skin surface. Hence we considerT_0, T_1, T_2, T_3, T_4, T_5, T_6, T_7 and T_8 in linear order towards body core at t=0. Thus we assume the following initial condition for $\overline{T}^{(0)}$

$$T(x,0) = T(0,0) + rx \qquad (17)$$

Considering initial temperature 32°C at skin surface because at normal atmospheric temperatures skin surface temperature is around 32°C and r is a constant.

NUMERICAL RESULTS AND DISCUSSION

The following values of physical and physiological parameters have been used as prescribed [1, 4, 5, 9, 11] to compute the numerical results. They are tabulated in Tables 1, 2, 3 and 4.

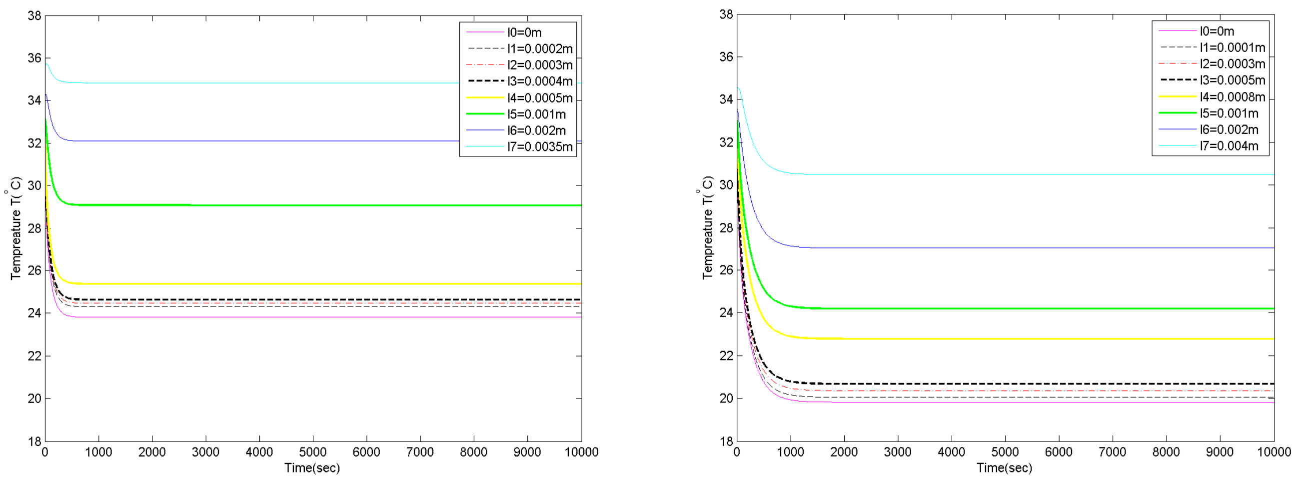
Table 3
Value of Biophysical Parameters

Parameter	Value	Unit
L	2.4×10^{6}	J/kg
h	6.2802	w/m^{2} °C
c	$3.475.044\times10^{3}$	J/kg °C
ρ	1.05×10^{3}	Kg/m^{2}
E	1.9×10^{-4}	w/m^{2}

Table 4
Two Sets of Dermal Layers

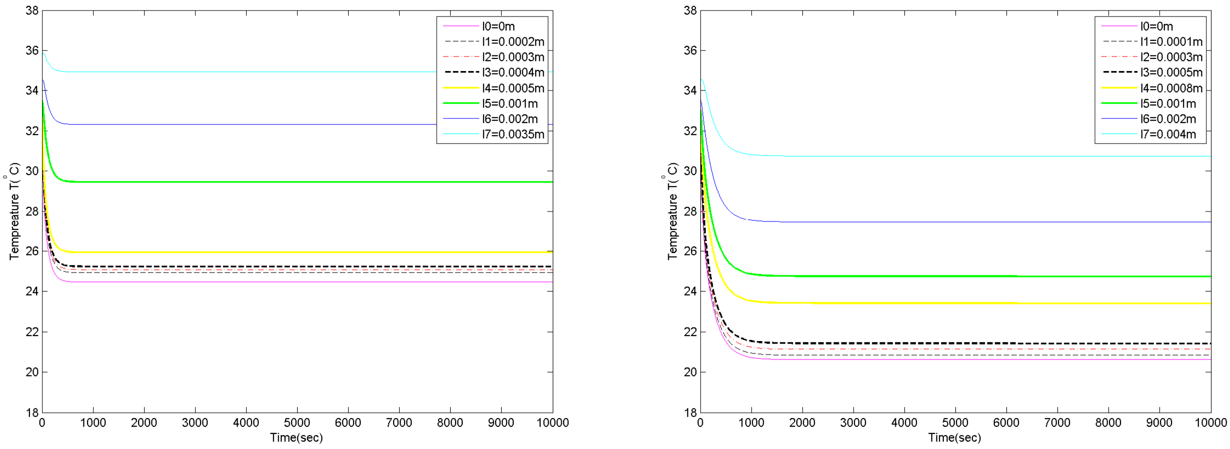
Sets	l_0 (m)	l_1 (m)	l_2 (m)	l_3 (m)	l_4 (m)	l_5 (m)	l_6 (m)	l_7 (m)	l_8 (m)
I	0	0.0002	0.003	0.004	0.005	0.001	0.002	0.035	0.005
II	0	0.0001	0.0003	0.0005	0.0008	0.001	0.002	0.004	0.009

The Pennes' bioheat equation determining the temperature in the multi-layer human skin has been modeled by Finite element method. The physical region is being discretized into many small sub regions and the value of various physiological quantities at every grid point is supplied for each time step. The variational integrals corresponding to each of the sub regions were calculated to estimate the temperature at each layer. The numerical value of temperature at each nodal points obtained from equation (16) is shown in figures below by taking various atmospheric temperatures. The unsteady state temperature profiles are presented in figure 3 to figure 6 for the two set of skin thickness at different atmospheric temperatures. We observed from these figures that the curves for the nodal temperature rises more rapidly in set I and reach steady state case earlier as compare to set II data of thickness. This is happen due to lower thickness of skin in data set I than to data set II. We also observed that the temperature fall down as we move away from body core to the skin surface. The temperatures T_i are having higher values at high atmospheric temperatures as compared to low atmospheric temperatures. But the difference between initial temperature and the temperature at time t=10000sec is higher for the low atmospheric temperature as compared to high atmospheric temperatures. This is because more heat moves outsides by sweat evaporation at higher atmospheric temperatures. The thicknesses of the skin and various atmospheric conditions have the significant effects on the temperature of skin layers.



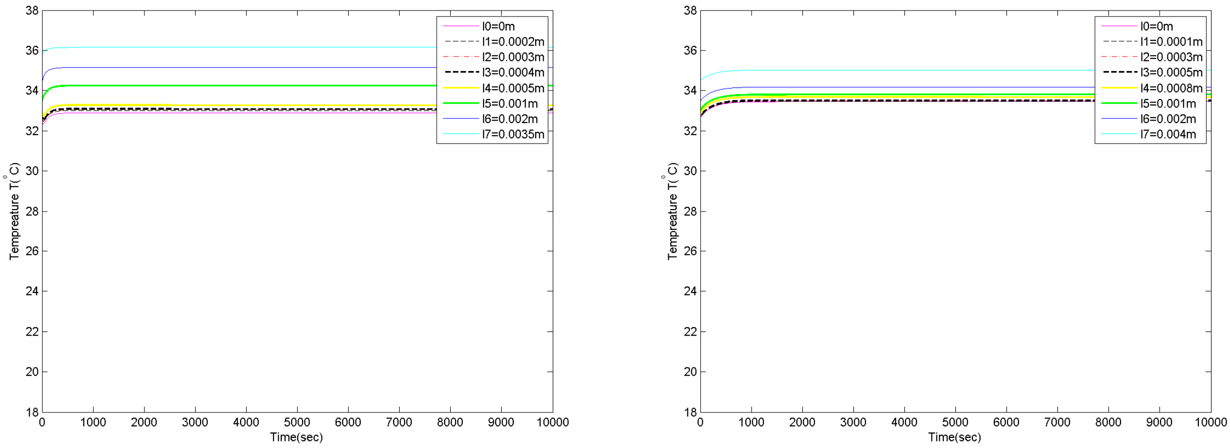
(a) (b)

Figure 3
Temporal temperature variation at atmospheric temperature 15°C on different nodal points for (a) SET I (b) SET II



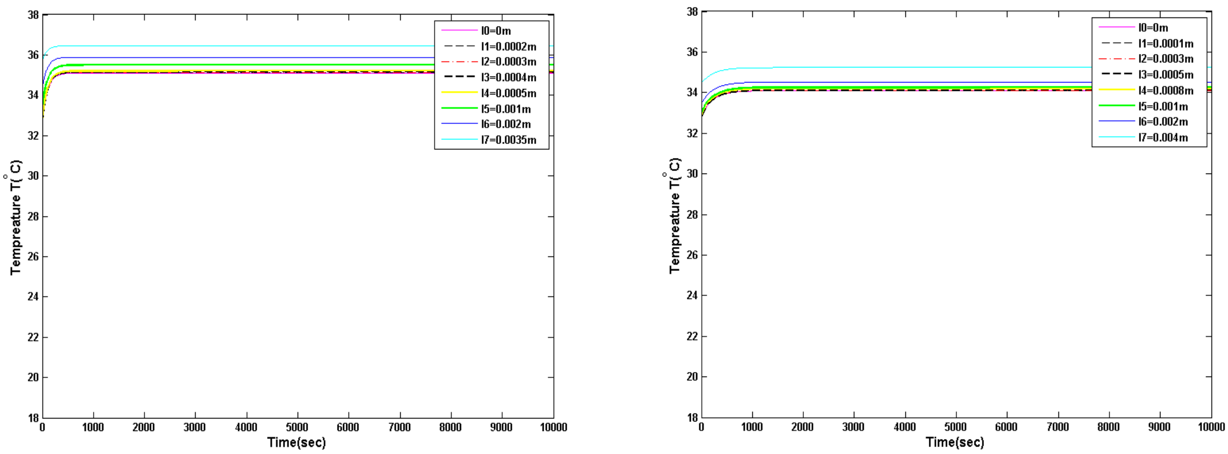
(a) (b)

Figure 4
Temporal Temperature Variation at atmospheric temperature 20°C on different nodal points for (a) SET I (b) SET II



(a) (b)

Figure 5
Temporal Temperature Variation at atmospheric temperature 85°C on different nodal points for (a) SET I (b) SET II



(a) (b)

Figure 6
Temporal Temperature Variation at atmospheric temperature 90°C on different nodal points for (a) SET I (b) SET II

CONCLUSION

The present study provides an insight on temperature distribution in human skin affected by ambient temperature. The model can be used for predicting skin temperature response in extreme cold and extreme hot conditions. The one dimensional unsteady state finite element model seems more realistic. Though there are so many layers in the human skin, we have taken only eight layers of dermal parts: stratum corneum, stratum lucidum, stratum graulosum, stratum spinosum, stratum germinativum, papillary region and reticular region and subcutaneous tissue. The theoretical results obtained here for temperature profile of skin under different ambient conditions are in good agreement with the biological and physical facts. These results may be useful for biomedical scientists and physiologists to detect the various abnormalities occur in human skin due to heat flow.

CONFLICT OF INTEREST

Conflict of interest declared none.

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