Journal of Coastal Life Medicine

journal homepage: www.jclmm.com

Original article doi: 10.12980/JCLM.3.2015J5-38

Two dimensional finite element method for metabolic effect in thermoregulation on human males and females skin layers

Saraswati Acharya[1], Dil Bahadur Gurung[1], Vinod Prakash Saxena[2]

[1]*Department of Natural Sciences (Mathematics), Kathmandu University Post Box 6250, Kathmandu, Nepal*

[2]*Sagar Institute of Research and Technology, Bhopal, India*

ARTICLE INFO

Article history:
Received 29 Apr 2015
Received in revised form 6 May, 2nd revised form 11 May 2015
Accepted 22 Jun 2015
Available online 15 Jul 2015

Keywords:
Metabolism
Finite element method
Crank-Nicolson technique
Bio-heat equation
Dermal layers

ABSTRACT

Objective: To deal the implication of metabolic reaction relying on dermal thicknesses of males and females for temperature distribution on the layers of dermal part at various atmospheric temperatures.

Methods: The mathematical model involving bioheat equation has been solved using finite element method and Crank-Nicolson technique to numerically investigate two dimensional temperature distributions. Initially, human dermal region under consideration is divided into six parts: stratum corneum, stratum germinativum, papillary region, reticular region, fatty layer and muscle part of subcutaneous tissue. Pennes bioheat equation is used considering the suitable physical and physiological parameters that affect the heat regulation in the layers. Computer simulation has been used for numerical results and graph of the temperatures profiles.

Results: Lower percentage of muscle mass and higher percentage of adipose tissue in subcutaneous part of females result lower metabolic rate compared to males. Metabolism is considered as a heat source within the body tissue. The study delineates that when the metabolic heat generation S increases, body temperature rises and when S decreases, it goes down. In higher ambient temperature T_∞ effect of S is lower as compared to lower T_∞.

Conclusions: Males and females would differ in their physiological responses in temperature distribution due to differences in metabolic heat production between genders. The thinner layers of males lead to higher values of skin temperature than thicker layer of females. Thickness plays a significant role in temperature distributions in human males and females body. Current understanding of human thermoregulation is based on male patterns; studies on women are still relatively rare and involve only small number of subjects. So it is still necessary for micro level study for temperature distribution model on the dermal layers of males and females.

1. Introduction

The body is divided into an inner core and outer cell, temperature is relatively uniform in the core and regulates within narrow limits, while cell temperature is permitted to vary. Heat is a natural byproduct of metabolism. It is constantly produces and continuously loss to the environment. When the quantity of heat production is equal to the amount of loss then homeostasis exists. If heat production and heat loss are not in balance, body temperature will rise or fall. Normal thermoregulatory function serves to maintain body temperature within a narrow range.

*Corresponding author: Saraswati Acharya, Department of Natural Sciences (Mathematics), Kathmandu University, Post Box 6250, Kathmandu, Nepal.
E-mail: saraswati.acharya@ku.edu.np

Thermal sensations are different among people even in the same environment. There is no absolute standard for temperature in human body. Temperature also depends on behavioral action such as altering clothing, altering activities posture or location, changing the thermostatic setting, opening windows, leaving a space. In the view of properties of skin and subcutaneous tissue (ST), the metabolic heat generation negligible in the epidermis and linearly varies with respect to the position in the dermis[1].

When measuring metabolic rates, many factors have to be taken into account. Each person has a different metabolic rate, and these rates can fluctuate when a person is performing certain activities or under certain environmental conditions. Even people who are in the same room can feel significant temperature differences due to their metabolic rates, which makes it very hard to find an optimal temperature for everyone in a given location. Food and drink habits may have an influence on metabolic rates, which indirectly influences thermal preferences. Body shape is another factor that affects thermal preference. Heat dissipation depends on body surface area. A tall and skinny person has a larger surface-to-volume ratio can dissipate heat more easily and can tolerate higher temperatures than a more rounded body shape[2,3].

Skin temperature is lower in females than in males. This attributes to the very obvious dimorphism in body structure, limb proportions, surface area, insulating muscle and fat mass, thickness distribution between males and females, which result in females maintaining lower skin temperatures. In general females have less body mass and less body surface area compared to males. Metabolic energy expenditure is proportional to body mass.

The males sex hormone testosterone can increase the metabolic rate about 10%–15%. But the females' sex hormone estrogen may increase the metabolic rate a small amount but usually not enough to be significant. Males usually have a higher metabolic rate than that of females of the same age because males tend to have a higher proportional of lean body mass than females of the same age. Conversely, females tend to have a higher proportional of fat cells and fat cells have a lower metabolic rate than lean muscle cells. But metabolic rate increases during pregnancy and lactation due to high energy requirement of producing fetal tissues than breast milk[4]. In general females have a metabolic rate about 5%-10% lower than males. The relationships for metabolic rate between human males and females at fat and muscle parts are represented by low and average levels as shown in Figure 1[5].

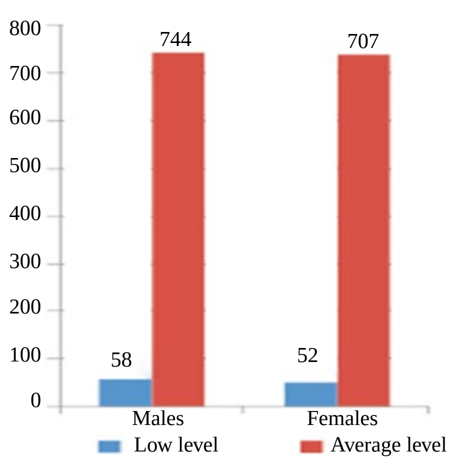

Figure 1. Two metabolic levels (w/m^3) of human males and females

Heat transfer problems are related in various discipline including biomedical sciences and have a role both in treatment and diagnosis. They can aid in predicting the time in the course of treatment or giving information on the temperature where thermometry is lacking. The balance between the heat generation and loss from the body to the environment is very important to maintain body core temperature.

It is very important to know how the human body will behave under different environmental conditions of temperature. Living organisms have to adapt and survive in a variety of environment conditions, including hot and cold climates. They are thermodynamic entities characterized by energy flows both within the body and its environment. The normal body temperature for a human is typically (37.0 ± 0.5) °C. The variation of 2 °C will cause pain but does not have serious effects on human life. A 41–42 °C fever will cause several convulsions and beyond this death will occur. On the other hand if the core temperature reaches 33 °C, the person will become unconscious. Below this level at approximately 28 °C cardiac fibrillation occur and death[6]. Therefore the careful regulation of body temperature is important for health.

Research on thermoregulation in human is extensive and has been limited to a homogeneous population consisting mainly of males. Earlier models have not attempted to delineate the differences in thermoregulation between males and females. So the present study focuses on mathematical model of the body temperatures in males and females due to metabolic reaction.

2. Materials and methods

The governing differential equation which represent the bio-heat transfer in the human skin can be written by the well known Pennes equation addressing the effect of conduction, blood perfusion and metabolism is given by Pennes1948[7].

$$\rho c \frac{\partial T}{\partial t} = \nabla.(K \nabla T) + \omega \rho_b c_b (T_a - T) + S \tag{1}$$

where ρ (kg/m^3) is the tissue density, c (J/kg °C) is the specific heat, T (°C) is the local tissue temperature, t is the time and from the skin surface to the body core respectively, K (w/m °C) is the tissue thermal conductivity, ω_b (m^3/s/m^3) is the blood perfusion, ρ_b (kg/m^3) is the density of blood, c_b (J/kg °C) is the specific heat of the blood, T_a (°C) is the arterial blood temperature, S (w/m^3) is the metabolic heat generation in the body.

In the two dimensional discretization of the dermal layers the thicknesses L has been taken along y–axis and the loss of heat from the outer surface of the body is exposed to the environment then the heat loss caused via convection, radiation and sweat evaporation. So the mixed boundary condition of heat flux from outer skin surface under study is given by:

$$\Gamma_1 : -K \left. \frac{\partial T}{\partial y} \right|_{at\ skin\ surface} = h_{conv}(T - T_\infty) + \sigma\varepsilon(T_\infty^4 - T^4) + LE \tag{2}$$

where h_{conv} (w/m^2 °C) represents heat transfer coefficient between skin and environment due to convection, T_∞ (°C) is the atmospheric temperature, σ (5.67×10^{-8} w/m^2 °C^4) is the Stefan Boltzmann constant, ε is emissivity of the skin surface emissivity of the surface, L (J/kg) is latent heat of evaporation and E (kg/m^2/s) is evaporative heat loss between skin surface and environment. The nonlinear radiation term in the boundary condition (2) is treated by using iterative procedure as follows:

$$\Gamma_1: -K\frac{\partial T_s}{\partial y}\Big|_{\text{at skin surface}} = [h_{conv}(T_s - T_\infty) + \sigma\varepsilon(T_s + T_\infty)(T_s^2 + T_\infty^2)](T_s - T_\infty) + LE \quad (3)$$

$$\Gamma_1: -K\frac{\partial T_s}{\partial y}\Big|_{\text{at skin surface}} = h_{cr}(T_s^n - T_\infty) + LE \quad (4)$$

where,

$$h_{cr} = h_{conv} + \sigma\varepsilon(T_s^{n-1} + T_\infty)(T_s^{n-1})^2 + T_\infty^2 \quad (5)$$

where T_s^n are skin surface temperature sequences for n = 1, 2, 3, … and T_s^0 represents an initial guess of temperature. The iteration is completed when the convergent condition is satisfied $\|T_s^n - T_s^{n-1}\| < \delta$, where δ is iteration tolerance[8].

The transport of heat within tissue occurs along normal to the skin surface from body core and hence we can assume negligible heat flux in x-direction. So the boundary conditions are assumed to be:

$$\Gamma_2: \frac{\partial T}{\partial x}\Big|_{x=0} = 0 \quad (6)$$

$$\Gamma_3: \frac{\partial T}{\partial x}\Big|_{x=W} = 0 \quad (7)$$

where W is the total width of the skin taken along x-direction. Also the human body maintains its core temperature at a uniform temperature at 37 °C. Therefore, the boundary condition at the inner boundary is taken as:

$$\Gamma_4: T(x, 0) = T_b = 37\,^\circ\text{C} \quad (8)$$

where, T_b is the body core temperature.

2.1. Skin geometry and assumption

The human skin is considered to have 6 major layers: stratum corneum, stratum germinativum, papillary region, reticular region, and fatty and muscle layers of ST. In the model the skin thickness has been considered as two dimensional rectangular skin and ST region. The diameter of skin along x-axis is 0.50 cm and the thickness along vertical axis (y-axis) is 0.90 cm for males and 1cm for females. Initially, the skin is divided into 180 nodal elements with triangular shape having total 114 nodes for males and 200 nodal elements with triangular shape having total 126 nodes for females. The stratum corneum, stratum germinativum, papillary region, reticular region and fatty layers of ST and muscle layer of ST are divided into 10, 10, 20, 30, 40, and 70 triangular elements for males and 10, 10, 20, 30, 50, and 80 triangular elements for females as shown in Figures 2 and 3.

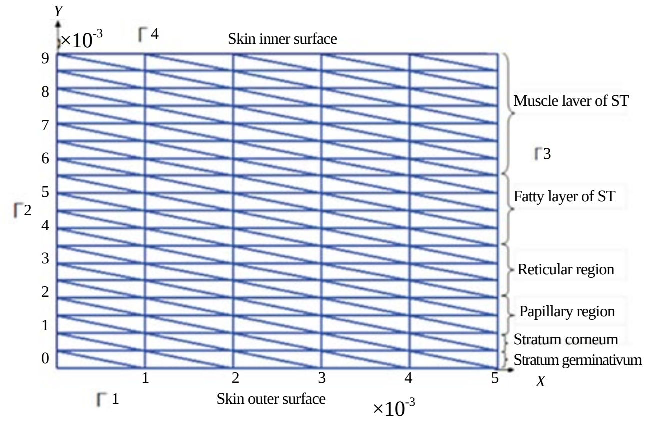

Figure 2. Schematic diagram of human males' skin layers.

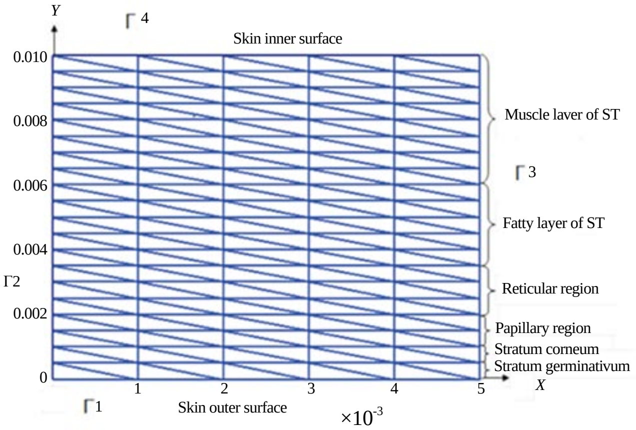

Figure 3. Schematic diagram of human females' skin layers.

Due to the minute's thickness of the region and for the simplicity of the calculation, the linear shape functions are considered to approximate the temperature profiles. So for general nodal element e we take[9].

$$T^{(e)} = C_1^{(e)} + C_2^{(e)}x + C_3^{(e)}y \quad (9)$$

where $C_1^{(e)}$, $C_2^{(e)}$ and $C_3^{(e)}$ are coefficients of $T^{(e)}$ depending upon the nodal values $T_i^{(e)}$, $T_j^{(e)}$ and $T_k^{(e)}$ of the typical element (e). The orientation of local nodal coordinate is taken as in Figure 4.

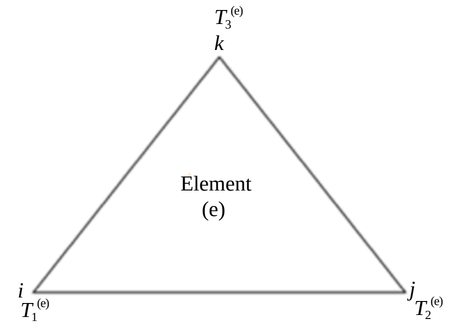

Figure 4. Triangular element.

2.2. Assumption of parameters[5,10]

Arterial blood temperature T_a have been considered zero in stratum corneum and stratum germinativum and $T_a = T_b$ in papillary region, reticular region, muscle layer of ST, fatty layer of ST and each of their subregions.

Blood perfusion has been considered zeros in stratum corneum and stratum germinativum. It has been considered as a function of depth in the layers lying between stratum germinativum, muscle layer of ST. But perfusion rate in each subregion of the six layers is considered same as its main layers.

Metabolic heat generation rate S has been taken zero in stratum corneum and it has been considered as a function in depth in the layers lying between stratum corneum and ST. But metabolic rate in each subregion of the six layers is considered same as its main layers. Uniform blood perfusion rate and metabolic heat for males and females have been considered in muscle layer of ST and its subregions.

2.3. Mathematical solution of the model

The governing equation (1) together with boundary conditions is transformed into the variational form as:

$$I = \frac{1}{2}\iint_{\Omega} K\left[\left(\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{dy}\right)^2\right) + \omega\rho_b c_b (T_a - T)^2 - 2ST - \rho c\frac{\partial T^2}{\partial t}\right]d\Omega + \frac{1}{2}\int_{\Gamma_1}[h_{cr}(T - T_\infty)^2 + LET]\, d\Gamma_1 \quad (10)$$

where Ω is the domain of the region of dermal part considered and $\Gamma 1$ is the outer skin boundary. Now express the function I as a sum of E elemental quantities $I^{(e)}$ as

$$I = \sum_{e=1}^{E} I^{(e)} \quad (11)$$

where,

$$I^{(e)} = \frac{1}{2}\iint_{\Omega^{(e)}} K^{(e)}\left[\left(\left(\frac{\partial T^{(e)}}{\partial x}\right)^2 + \left(\frac{\partial T^{(e)}}{dy}\right)^2\right) + \omega^{(e)}\rho_b c_b (T_a - T^{(e)})^2 - 2S^{(e)}T^{(e)} - \rho c\frac{\partial T^{(e)2}}{\partial t}\right] d\Omega^{(e)} + \frac{1}{2}\int_{\Gamma_1^{(e)}}[h_{cr}(T^{(e)} - T_\infty)^2 + LET^{(e)}]\, d\Gamma_1^{(e)} \quad (12)$$

where, $\Omega^{(e)}$ is the domain of the nodal element (e) and $\Gamma_1^{(e)}$ is the boundary of outer skin element. Equation (12) is broken into five parts:

$$I^{(e)} = I_K^{(e)} + I_w^{(e)} - I_S^{(e)} + I_t^{(e)} + I_h^{(e)} + I_E^{(e)} \quad (13)$$

where,

$$I_K^{(e)} = \frac{1}{2}\iint_{\Omega(e)} K^{(e)}\left[\left(\left(\frac{\partial T^{(e)}}{\partial x}\right)^2 + \left(\frac{\partial T^{(e)}}{\partial y}\right)^2\right)\right] d\Omega^{(e)}$$

$$I_w^{(e)} = \frac{1}{2}\left[\iint_{\Omega(e)} \omega^{(e)}\rho_b c_b (T_a - T^{(e)})^2\right] d\Omega^{(e)}$$

$$I_S^{(e)} = \frac{1}{2}\left[\iint_{\Omega(e)} 2S^{(e)} T^{(e)}\right] d\Omega^{(e)}$$

$$I_t^{(e)} = \frac{1}{2}\left[\iint_{\Omega(e)} \rho c \frac{\partial T^{(e)\,2}}{\partial t}\right] d\Omega^{(e)}$$

$$I_h^{(e)} = \frac{1}{2}\int_{\Gamma_1^{(e)}}\left[h_{cr}(T^{(e)} - T_\infty)^2\right] d\Gamma_1^{(e)}$$

$$I_E^{(e)} = \frac{1}{2}\int_{\Gamma_1^{(e)}}\left[LET^{(e)}\right] d\Gamma_1^{(e)}$$

For the minimization of the function I, we have

$$\frac{\partial I}{\partial T_i} = \sum_{e=1}^{E}\frac{\partial I^{(e)}}{\partial T_i} = 0,\ i = 1, 2, ..., N \quad (14)$$

Using (12) and (14), we get,

$$\frac{\partial I}{\partial T_i} = \sum_{e=1}^{E}\frac{\partial I^{(e)}}{\partial T_i} = \sum_{e=1}^{E}\frac{\partial}{\partial T_i}(I_K^{(e)} + I_w^{(e)} - I_S^{(e)} + I_t^{(e)} + I_h^{(e)} + I_E^{(e)} = 0 \quad (15)$$

Now to minimize equation (15), let us differentiate it with respect to each nodal temperature, except as the core boundary and set the derivative equal to zero. The equation (15) leads to a linear system of differential equations of the type:

$$C\dot{T} + P\overrightarrow{T} = B \quad (16)$$

Now Crank-Nicolson method is applied to solve the system equation (16) with respect to time with the following relation:

$$\left\{C + \frac{\Delta t}{2}P\right\}\{T\}^{(i+1)} = \left\{C - \frac{\Delta t}{2}P\right\}\{T\}^{(i)} + \Delta t B \quad (17)$$

Where Δt is the time interval and $\{T\}^{(i)}$ is the nodal temperature T and n^{th} time step. The equation (17) repeatedly solves to get the nodal temperature.

3. Results

For the numerical analysis males inner skin and fat metabolic level have been considered as S = 744 w/m^3 and 58 w/m^3 and females inner skin and fat metabolic level have been considered as S = 707 w/m^3 and 52 w/m^3 respectively. The values of Table 1 have been assigned to each physical and physiological parameter in each subregion of dermal part[5,8,10].

Table 1

Parameter values used in model.

Parameter	Value
$K^{(1)}$ (w/m °C)	0.20934
$K^{(2)}$ (w/m °C)	0.20934
$K^{(3)}$ (w/m °C)	0.31401
$K^{(4)}$ (w/m °C)	0.31401
$K^{(5)}$ (w/m °C)	0.41868
L (J/kg)	2.4×10^6
h (w/m^2 °C)	6.2802
ρ (kg/m^3)	1050
c (J/kg °C)	3475.044
M (w/m^3 °C)	1255.67

The superficial epidermis is approximately 75-150 μm in thickness. The second layer is the dermis which is approximately 1–4 mm. The third layer is ST which is composed of loose fatty connective tissue. The thickness of ST varies considerably over the surface of the body[11]. The thickness of subcutaneous part varies with age, sex, race, endocrine and nutritional status of the individual. It acts as an insulating layer and a protective cushion and constitutes amount 10% of the body weight[12]. The thicknesses of dermal layers considered in this model were presented in Table 2.

Table 2

Thicknesses of dermal layer. (m).

Gender	l_1	l_2	l_3	l_4	l_5	l_6
Female	0.0005	0.0010	0.0020	0.0035	0.0060	0.0100
Male	0.0005	0.0010	0.0020	0.0035	0.0055	0.0090

In below Figures 5-16 and Tables 3 and 4, T_{SC} represents the outer skin steady nodal temperature of stratum corneum, T_{SG} denotes interface steady nodal temperature between stratum corneum and stratum germinativum, T_{PR} denotes interface steady nodal temperature between stratum germinativum and papillary layer, T_{RL} denotes interface steady nodal temperature between papillary layer and reticular layer, T_{FS} denotes interface steady nodal temperature between reticular layer and fatty part of ST and T_{MS} denotes interface steady nodal temperature between fatty and muscle part of ST respectively.

There is no variation of temperature along the width of the skin boundary. This is due the assumptions of no outward flow of heat across the boundaries Γ_2 and Γ_3 as in Figures 2 and 4 (equations (6) and equations (7)). This happens in the case of perfect thermal insulation in the temperature distribution about the boundaries Γ_2 and Γ_3. The transport of heat within tissue occurs only along downwards from the skin surface to the body core.

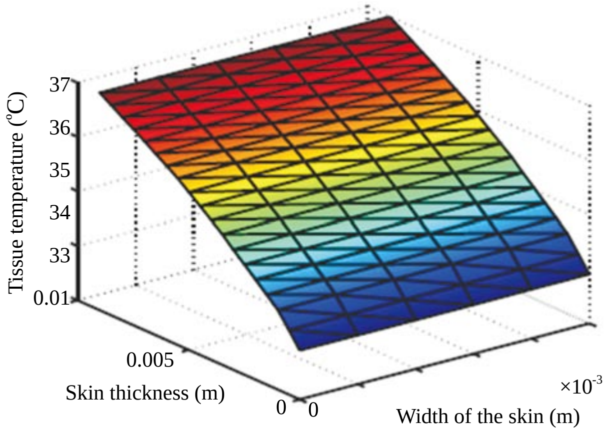

Figure 5. Tissue temperatures of males at $T_\infty = 15\,^{\circ}C$ and E = 0 kg/m^2/s.

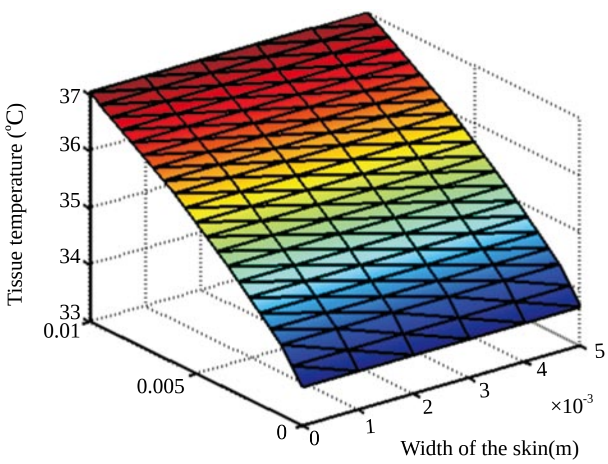

Figure 6. Tissue temperatures of females at $T_\infty = 15\,^{\circ}C$ and E = 0 kg/m^2/s.

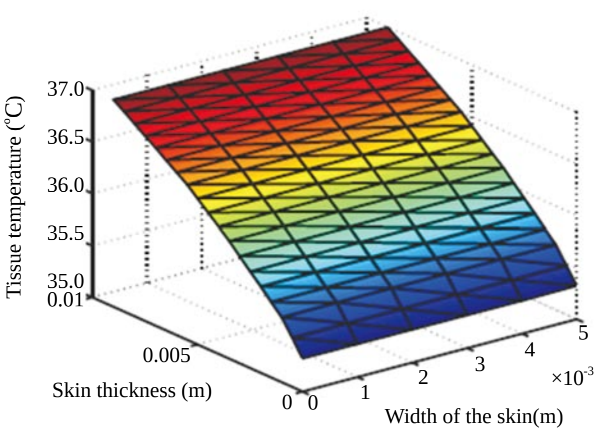

Figure 7. Tissue temperatures of males at $T_\infty = 25\,^{\circ}C$ and E = 0 kg/m^2/s.

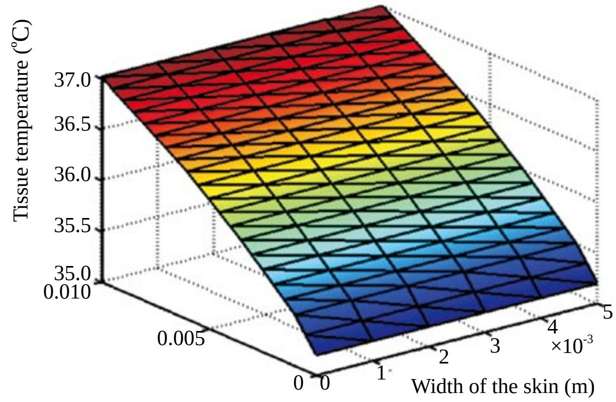

Figure 8. Tissue temperatures of females at $T_\infty = 25\,^{\circ}C$ and E = 0 kg/m^2/s.

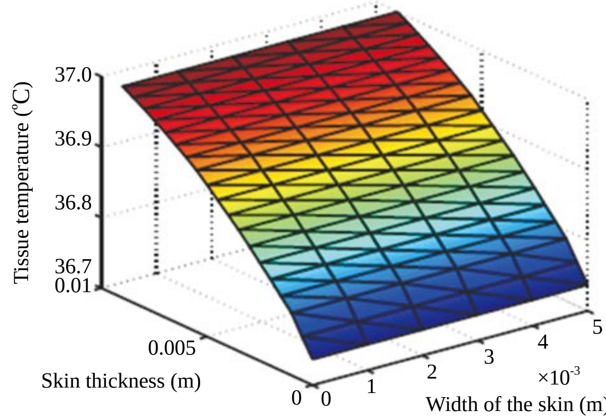

Figure 9. Tissue temperatures of males at $T_\infty = 35\,^{\circ}C$ and E =0 kg/m^2/s.

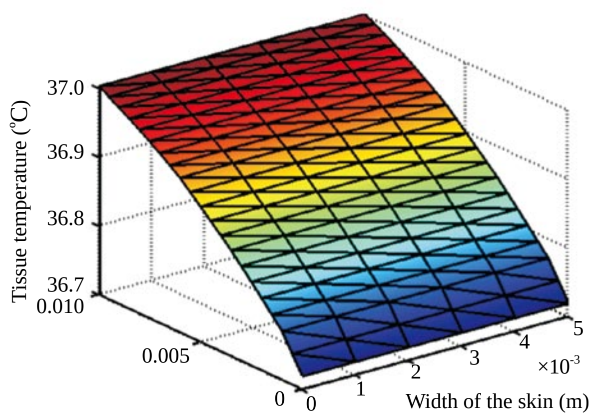

Figure 10. Tissue temperatures of females at $T_\infty = 35\,^{\circ}C$ and E = 0 kg/m^2/s.

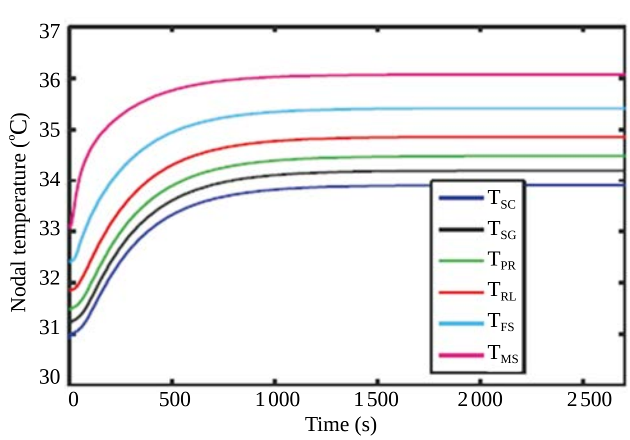

Figure 11. Nodal temperatures of males at $T_\infty = 15\,^{\circ}C$ and E = 0 kg/m^2/s.

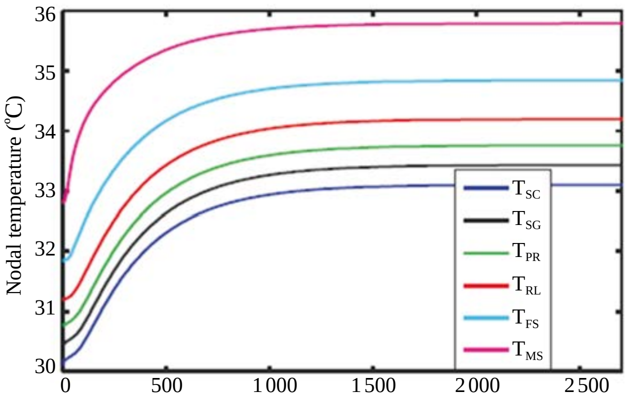

Figure 12. Nodal temperatures of females at $T_\infty = 15\ ^\circ\mathrm{C}$ and E = 0 kg/m^2/s.

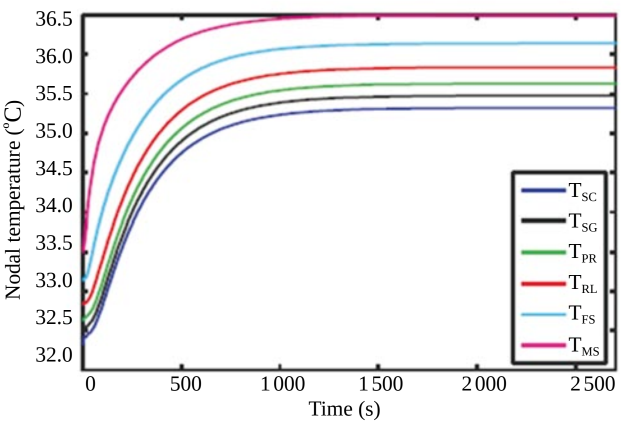

Figure 13. Nodal temperatures of males at $T_\infty = 25\ ^\circ\mathrm{C}$ and E =0 kg/m^2/s.

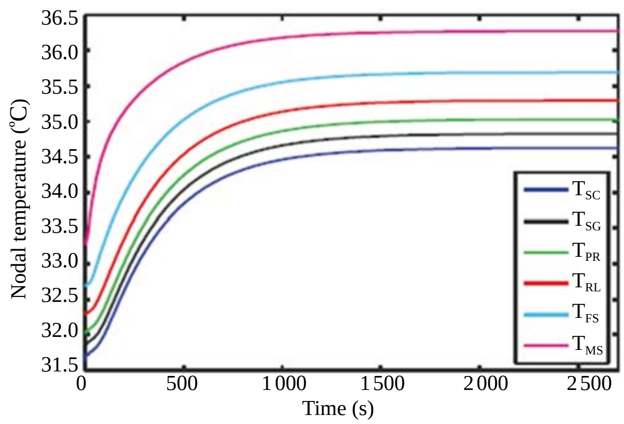

Figure 14. Nodal temperatures of females at $T_\infty = 25\ ^\circ\mathrm{C}$ and E = 0 kg/m^2/s.

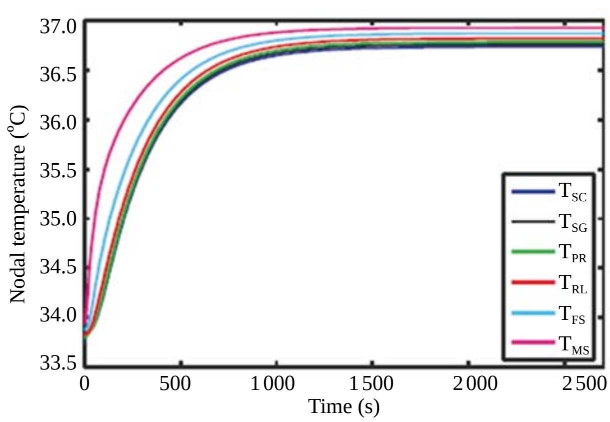

Figure 15. Nodal temperatures of males at $T_\infty = 35\ ^\circ\mathrm{C}$ and E = 0 kg/m^2/s.

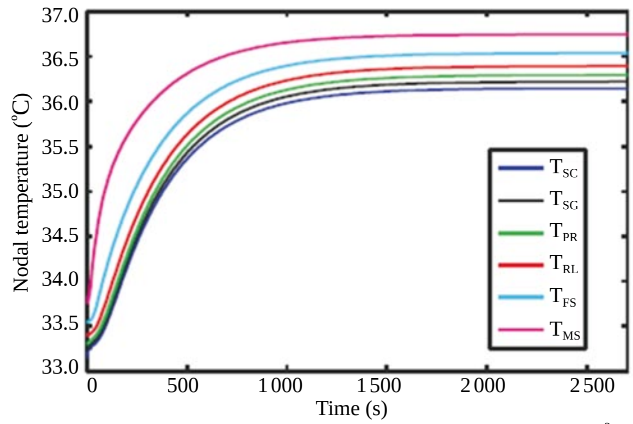

Figure 16. Nodal temperatures of females at $T_\infty = 35\ ^\circ\mathrm{C}$ and E = 0 kg/m^2/s.

Table 3

Steady state nodal temperatures of males. (°C).

Ambient temperature T_∞	Steady state temperature of males					
	T_{SC}	T_{SG}	T_{PR}	T_{RL}	T_{FS}	T_{MS}
15	33.90	34.19	34.47	34.85	35.41	36.07
25	35.32	35.48	35.63	35.84	36.14	36.50
35	36.74	36.77	36.79	36.83	36.88	36.94

Table 4

Steady state nodal temperatures of females. (°C).

Ambient temperature T_∞	Steady state temperatures of females					
	T_{SC}	T_{SG}	T_{PR}	T_{RL}	T_{FS}	T_{MS}
15	33.67	33.95	34.23	34.60	35.15	35.96
25	35.20	35.35	35.50	35.70	36.00	36.44
35	36.73	36.75	36.78	36.81	36.86	36.93

3.1. Steady state results

The results of the analysis for metabolic effect in temperature distribution at the interfaces of the dermal subregions are presented through the graphs in Figures 5 to 10 for males and females dermal layers in steady state case. The observed tissue nodal temperatures of males and females were presented in Tables 3 and 4.

3.2. Unsteady state results

The results of the analysis for metabolic effect in nodal temperature distribution at the interfaces of the dermal subregions are presented through the graphs in Figures 11 to 16 for males and females dermal layers in unsteady state case.

Figures 11, 13 and 15 represents the tissue nodal temperatures of males and Figures 12, 14 and 16 represents the females tissue nodal temperatures in two dimensional case.

The males tissues nodal temperatures $T_{SC}\ T_{SG}\ T_{PR}\ T_{RL}\ T_{FS}$ are increased by around 0.26 °C and 0.11 °C for tissue nodal temperature of T_{MS} in comparison to females at $T_\infty = 15\ ^\circ\mathrm{C}$ and E = 0 kg/m^2/s. Likewise the males tissue nodal temperature $T_{SC}\ T_{SG}\ T_{PR}\ T_{RL}\ T_{FS}$ are raised by around 0.14 °C and 0.6 °C for tissue nodal temperature of T_MS in comparison to females at $T_\infty = 25\ ^\circ\mathrm{C}$ and E = 0 kg/m^2/s.

The males tissues nodal temperatures $T_{SC}\ T_{SG}\ T_{PR}\ T_{RL}\ T_{FS}$ are increased by around 0.02 °C and 0.01 °C for tissue nodal temperature of T_{MS} in comparisons to females at T_∞ = 35 °C and E = 0 kg/m^2/s.

4. Discussion

Shivering is the main source of internal heat production when T_∞ falls below 37 °C. An increase in oxygen consumption is usually indicative of a rise in metabolic rate. Since shivering is a rapid involuntary contraction of muscle, oxygen consumption is used as an indicator for shivering. The metabolic effect is negligible when T_∞ greater than 37 °C. So in this study only we have taken atmospherics temperature T_∞ = 15 °C, 25 °C, 35 °C[5].

It can be observed from the above two dimensional analysis that males have slightly higher tissue temperature than females. This is because males have higher metabolic rate in comparison to females. Moreover, we observe that in case of higher atmospheric temperatures, the effect of metabolic rate in temperature distribution is less in comparison to low atmospheric temperature. The significance effects of metabolism are observed at low atmospheric temperatures. At low temperature the blood vessels constrict, which in turn decrease heat carried by the blood to the surface, causing increase the metabolic heat effect to keep the body core temperature constant.

When metabolic heat is positive, body temperature rises and when it is negative, it goes down. Higher T_∞ effects of metabolic heat in temperature variation of tissue is lower as compared to lower T_∞. Males and females would different in their physiological responses in temperature distribution due to differences in metabolic heat production between genders. In our study the thinner layers of males lead to higher values of skin temperature than thicker layer of females. Thickness play significance role for temperatures distribution in human male and female body[5].

In conclusion present study shows that a two-dimensional variational finite element model and simulated steady and transient temperature differences between males and females due to metabolic reaction. The model has incorporated more feasible layers and has taken significant biophysical parameters in case of human males and females. Males and females would differ in their physiological responses in temperature distribution due to differences in metabolic heat production between sexes. Furthermore, we observed that the thicknesses play significant role for temperatures distribution in human males and females' body. The thinner layers lead to higher values of skin temperature than thicker layer. Also the significant effect in temperature distribution in males and females due to metabolism is seen being thicker skin layer of females. The subcutaneous fat in females contributes thicker skin layers than males. But in case of same thickness of skin layers in males and females, the metabolic effect does not alter significantly in temperature distribution in males and females body. The purpose of the study is to determine heat responses in body tissue due to metabolic heat production according to gender differences. The results of the above figures clearly establish that such difference exists.

Study of heat transfer through the skin tissue is very important. It is essential for understanding of biological processes and also for many clinical applications such as cancer occurs epidermis, dermis, and ST, laser irradiation. The work may be useful to the researcher to study the genderwise thermoregulation.

Conflict of interest statement

We declare that we have no conflict of interest.

References

[1] Saxena VP, Pardasini KR, Agarwal R. Unsteady state heat flow in epidermis and dermis of a human body. *Proc Indian Acad Sci Math Sci* 1988; **98**: 71-80.

[2] Kingma B, Frijns A, van Marken Lichtenbelt W. The thermoneutral zone: implications for metabolic studies. *Front Biosci (Elite Ed)* 2012; **4**: 1975-85.

[3] Cryan PM, Wolf BO. Sex differences in the thermoregulation and evaporative water loss of a heterothermic bat, *Lasiurus cinereus*, during its spring migration. *J Exp Biol* 2003; **206**: 3381-90.

[4] Guyton AC, Hall JE. *Text book of medical physiology*. Amsterdam: Elsevier; 2009, p. 75-256.

[5] Acharya S, Gurung DB, Saxena VP. Effect of metabolic reactions on thermoregulation in human males and females body. *Appl Math* 2013; **4**(5A): 39-48.

[6] Smith CE. *A* transient three-dimensional model of the human thermal system[dissertation]. Manhattan: Kansas State University; 1991.

[7] Pennes HH. Analysis of tissue and arterial blood temperature in the resting human foream. *J Appl Physiol (1985)* 1998; **85**: 5-34.

[8] Acharya S, Gurung DB, Saxena VP. Human males and females body thermoregulation: perfusion effect analysis. *J Therm Biol* 2014; **45**: 30-6.

[9] Gurung DB, Saxena VP. Transient temperature distribution in human dermal part with protective layers at low atmospheric temperature. *Int J Biomath* 2010; **3**: 439-45.

[10] Acharya S, Gurung DB, Saxena VP. Transient temperature distribution in human males and females body due to variation in perfusion effect. *Int J Appl Math* 2014; **29**: 1263-70.

[11] Odland GF. Structure of the skin. In: Goldsmith LA, editor. *Physiology, biochemistry and molecular biology of the skin*. Oxford: Oxford University Press; 1991.

[12] Burton JL, Cunliffe WJ. Subcutaneous fat. In: Champion RH, Burton JL, Ebling FJG, editors. *Textbook of dermatology*. 5th ed. Oxford: Blackwell Scientific Publications; 1992, p. 2135-76.