Analysis of Temperature Distribution of Human Skin Tissue in Various Environmental Temperature with the Finite Volume Method

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***Abstract*— The purpose of this study is to model and simulate the biological heat transfer of human skin tissue at various environmental temperatures, and to determine the temperature distribution of each layer of skin tissue. The purpose of this research is to model and simulate the one-dimensional constant temperature distribution of human skin tissue at various environmental temperatures. The one-dimensional steady-state biological heat transfer equation is solved by modifying the Pennes equation solved by FVM. In this study, the temperature distribution of the skin tissue was simulated with 5, 10, and 20 points of change. The FVM results are verified with Deng, Z.S.'s analysis results. The results show that it is successful to use FVM to model the one-dimensional constant temperature distribution in human skin tissue, so the temperature distribution of skin tissue is often not analyzed under various environmental temperatures. When using Deng for FVM verification, the error rate of Z.S analysis results is only 0.9%, so the temperature distribution of skin tissue under various conditions is generally not analysed. Increasing the ambient temperature (25 to 34 °C) will increase the temperature of the skin's surface, making the gradient smaller. But this does not affect skin tissue damage, because it activates the body's metabolism.**

***Index Terms*—Bioheat transfer, temperature distribution, human skin tissue, finite volume method**

I. INTRODUCTION

The skin is the largest organ of the human body, and one of its functions is to help regulate body temperature. Human skin is composed of epidermis, dermis, and subcutaneous tissue. The epidermis is 0.6-1 mm thick and is the first and outer layer of the skin. It is the only skin layer that can be seen with the naked eye. The 14mm thick dermis is the second layer of skin after the epidermis. The dermis acts as a protector for the body, and the subcutaneous tissue contains the most fat to protect the body and help the body adapt to the external temperature. The thickness is 45 mm. [1, 2].

One of the functions of the skin is to regulate the thermal balance (thermoregulation), so it must be kept constant at around 37 ℃, which is the balance point of the body's heat production and dissipation. Extreme normal body temperature can affect the function of biological tissues and the entire body system. If the body temperature drops by 27 ℃ and rises by 42 ℃, death may occur. Therefore, the body temperature should be kept at around 37 ℃. No matter how the ambient temperature changes, the heat transfer in the blood vessels also helps to maintain a uniform core body temperature. Metabolism is another important heat source, which is a chemical process that occurs in organisms, maintains its structure, and maintains their respective environments [3]. Sweat evaporation is one of the effective parameters in the process of body temperature regulation, and it is the only way to dissipate heat when the ambient temperature is higher than normal body temperature (36.1-37.2℃) [4].

In the field of biomedical research useful for human life, knowledge of heat transfer is equally important. For one hundred years, people have been studying the effect of blood flow on heat transfer in living tissues. After Bernard proposed an experimental study in 1876, doctors, physiologists and engineers became interested in the mathematical modeling of the complex thermal interactions between the human vascular system. In 1948, HH Pennes [5] proposed a simple linear mathematical model based on experimental observations to describe the heat flow in the network.

Many researchers have developed alternative models to describe the perfusion rate and the difference between arterial blood temperature and local tissue temperature. Introduce the biological heat transfer equation model [5] to explain the influence of metabolism and blood perfusion on the energy balance of living tissues, as shown in equation (1):

$$\rho C\frac{dT}{dt} = k\frac{d^2T}{dx^2} + \omega_b\rho_b C_b(T_a - To_x) + Q_m \qquad (1)$$

Where:

$\rho c\frac{dT}{dt}$: heat storage; $k\frac{d^2T}{dx^2}$: thermal conduction; $\left(\omega_b\rho_b C_b\left(T_a - T_0(x)\right)\right)$: heat dissipation through the bloodstream; (Qm : heat generation

Several researchers modified the Pennes equation to predict the temperature distribution of human skin, including:

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Mathematical modeling is achieved through numerical analysis of skin bio-heat transfer, focusing on heat transfer through skin tissue [6, 7]. Studies have shown that metabolic heat production rate and blood perfusion rate will affect the increase in temperature. The temperature distribution of the dermal tissue layer is caused by various movements. Modified Pennes equation. In this study, Pennes equation was modified and solved by the finite element method [8, 9].

Uses the finite difference method to develop a mathematical model of the Pennes bio heating equation to estimate thermal damage caused by tissue crystallization in human skin and the subcutaneous tissue layer [10]. The results show that the thickness of the epidermis and dermis has a significant effect on temperature, while the initial temperature and blood perfusion have little effect. The change of the finite element method of the one-dimensional heat transfer model is based on the time-independent sweat response [11, 12]. The analysis shows that during the female luteal phase, when $T\infty$ is lower than core body temperature, the tissue temperature is lower than that of males.

Temperature distribution in muscle, tumor, fat, dermis, and subcutaneous tissue is studied by numerical analysis and analysis of various blood parameters and their management [13]. At the same time, the biological heat transfer equation with variable thermal conductivity is analyzed by the Laplace transform method, and it is found that the temperature of the network is significantly obtained from the variable parameter of the thermal conductivity, and the low score derived has a Laplace domain analytical solution. The biothermal equation is used to study the thermal damage of skin tissue during hyperthermia. [14, 15]. Similarly, the analytical solution of the hyperbolic biothermal equation under the strongly moving heat source and the exact solution of the Arrhenius equation in the Laplace transform domain, the hyperbolic biothermal model is simplified to the parabolic biothermal model when the thermal relaxation time is zero [16]. In addition, [17] studied the temperature change and the thermal damage to spherical tissues during hyperthermia, using the fractional derivative to simplify the parabolic biological heating model and the hyperbolic biological heating model.

The one-dimensional transfer finite element method is used to solve the biological heat transfer equation of the temperature distribution of the biological heat in the cylindrical living tissue, which is simple and accurate for the thermal behavior of biological systems and can be extended to the thermal behavior of biological systems. Thermal measurement parameters, temperature field reconstruction, and clinical treatment. and facial temperature [14-18, 19]

The thermal stress analysis of the body's limb area during periodic exercise and rest and the finite element method are used to predict the temperature distribution of the outer layer of the human body. Due to periodic physical exercise, the limbs of the two-dimensional case are thermally regulated [20, 21]. Although the analysis uses the burn biological heating equation based on the finite element method, it is found that conduction heat transfer causes greater damage to human tissues in radiation and radiation transfer. From the analysis of treatment, it is found that the fastest way to lower the body temperature is to use ice cubes, and the slowest way is to use air conditioners. The transferability of the biological heating equation is stable [22, 23]. From the biological heat transfer numerical model of human forearm active thermoregulation, the sensitivity of temperature field to metabolic heat production rate and arterial temperature is studied. The blood temperature and the internal temperature curve of the metabolic heat source [24, 25].

The Pennes biothermal equation is used to analyze the influence of various ambient temperatures, tissue thermal conductivity, metabolic rate, blood perfusion rate, and thermal coefficient of various parameters on the temperature distribution curve [26, 27]. Model and simulate the thermoregulatory response of the cold environment to predict and simulate the change in core body temperature of a specific individual [28, 29]. Studies have shown that heat exchange with the environment plays a key role in the thermal state of the human body.

Therefore, many researchers use the Pennes equation to describe skin heat transfer because it is simple and analytically solvable, and can be programmed as a finite difference method (FDM) model and a finite element method (FEM). In the research, a finite volume method (FVM) was proposed to study the temperature distribution of human skin in a dimensionally stable state due to the exposure of the outer surface of the skin to different environmental temperatures. This study manages the environmental temperature difference of human skin, assumes that the environment is friendly and one-dimensionally stable, and enters appropriate boundary conditions. The human skin temperature distribution obtained by FVM is an illustration of the thermal interaction between human tissue and perfused blood and its metabolic effects.

II. Methodology

A. One-Dimensional Steady-State Biological Heat Transfer Equation

The one-dimensional steady state of the human skin biological heat transfer equation is shown in equation (2) to predict the temperature distribution. Human skin tissue is usually composed of three layers: epidermis, dermis, and subcutaneous tissue [30], as shown in Fig. 1.

$$k\frac{d^2T(x)}{dx^2} + \omega_b\rho_b C_b[T_a - T(x)] + Q_m = 0 \qquad (2)$$

Here, ρ, c, k, and Qm represent the density, specific heat, thermal conductivity, and metabolic heat generation rate in the tissue, respectively. T (x) and Ta represent the temperature of the tissue and arterial blood, respectively. In addition, mb and cb are the mass flow of blood and the specific heat of blood, respectively.

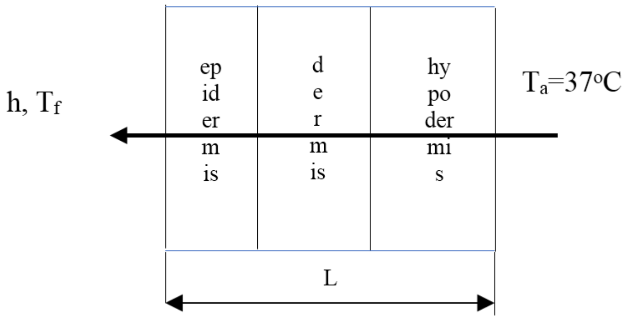


Figure 1. The human skin

B. Boundary Condition

Due to heat loss from the outer surface caused by convection, the boundary condition of the outer surface is given by [23]:

$$-k\frac{dT}{dx}\bigg]_{x=0} = h\left(T - T_f\right) \tag{3}$$

Among them, the environmental heat transfer coefficient, T_f is the atmospheric temperature.

The core of the body is kept at a uniform temperature Ta. Therefore, the boundary condition of the interior limit is given by Ta (x = L) = 37°C.

C. Domain Discretization

The thickness of the human skin layer is measured vertically from the outer surface of the human skin to the core of the body. For one-dimensional modeling, Fig. 2 is a schematic diagram of the human skin layer, divided into 16 parts [31].

Now the area of the skin is divided into 5, 10 and 20, and the distance is x1, x2, x3, x4, x5; x1, x2, x3, x4, x5, x6, x7, x8, x9, x10; x1, x2, x3, X4, x5, x6, x7, x8, x9, x10, x11, x12, x13, x14, x15, x16, x17, x18, x19, x20. The distance points of elements are nodes like shown in Fig. 2. Assuming the thermal conductivity of the human skin layer is constant

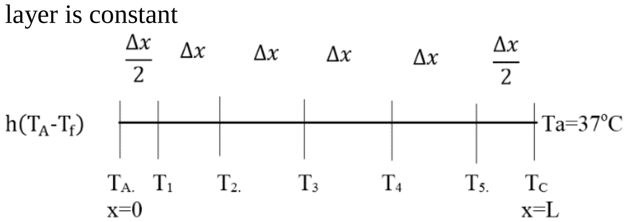


Figure 2. The distance points of each element

D. Finite Volume Method of the Bioheat Transfer Equation

The first step of the Finite Volume Method (FVM) is the integration of equation (2) over a control volume is shown in equation (4):

$$\int_{Adx} \frac{d^2T_0(x)}{dx^2} Adx + \int_{Adx} \omega_b\rho_b C_b[T_a - T_o(x)]\, Adx + \int_{Adx} Q_m Adx = 0 \tag{4}$$

Here A is the cross-sectional area of the control volume face, ΔV is the volume differential.

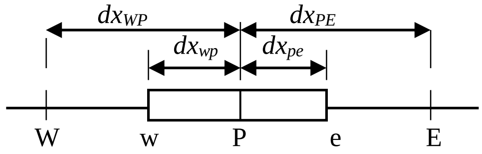


Figure 3. Boundary condition

By modifying equation (4) by entering the boundary conditions in Fig. 3, equation (4) is obtained which can be wont to obtain temperatures at x_2 to x_{n-1}, simplicity, obtained as shown in equation (5)

$$\left(k\frac{1}{dx_{PE}} + \frac{k}{dx_{WP}}\right)T_P = \frac{k}{dx_{WP}}T_W + \frac{k}{dx_{PE}}T_E + \omega_b\rho_b C_b T_a dx + Q_m dx - \omega_b\rho_b C_b T_P dx \tag{5}$$

Meanwhile, to urge the temperature at x1 and x_n (x_5, x_{10}, and x_{20}), integration is carried out, at point 1 which is restricted by environmental conditions (convection coefficient of heat transfer and ambient temperature), then obtained as shown in equation (6)

$$\left(\frac{k}{dx}\right)T_P = \frac{k}{dx}T_E + 0.T_W + (\omega_b\rho_b C_b T_a + Q_m)dx - \omega_b\rho_b C_b T_P dx - \frac{k}{dx/2}T_P + k\frac{T_A}{dx/2} \tag{6}$$

At point n (x_5, x_{10}, and x_{20}) which boundary condition of the arterial temperature (T_C=T_a=37°C), was obtained equation (7)

$$\left(\frac{k}{dx}\right)T_P = \frac{k}{dx}T_E + 0.T_W + (\omega_b\rho_b C_b T_a + Q_m)dx - \omega_b\rho_b C_b T_P dx - \frac{k}{dx/2}T_P + k\frac{T_B}{dx/2} \tag{7}$$

From equations (5), (6), and (7) was obtained as shown in Table I.

TABLE I. COEFFICIENTS OF A_W, A_E, S_P AND S_U

Points	A_W	A_E	A_P	S_P	S_U
1	0	$\frac{k}{dx}$	$\left(\frac{k}{dx} + \frac{2k}{dx} + Bdx\right)$	$-\omega_b\rho_b C_b dx - \frac{k}{dx/2}$	$(\omega_b\rho_b C_b T_a + Q_m)dx + k\frac{T_A}{dx/2}$
2 to n–1	$\frac{k}{dx}$	$\frac{k}{dx}$	$\left(\frac{k}{dx} + \frac{k}{dx} + \omega_b\rho_b C_b dx\right)$	$-\omega_b\rho_b C_b dx$	$(\omega_b\rho_b C_b T_a + Q_m)dx$
n	$\frac{k}{dx}$	0	$\left(\frac{k}{dx} + \frac{2k}{dx} + \omega_b\rho_b C_b dx\right)$	$-\omega_b\rho_b C_b\, dx - \frac{k}{dx/2}$	$(\omega_b\rho_b C_b T_a + Q_m)dx + k\frac{T_C}{dx/2}$

III. Result and Discussion

In this study, the predicted temperature of human skin was solved by the finite volume method using the biological equation of heat transfer. The surface of the human skin is defined as x = 0, and the nucleus of the human body is at x = L. A previous study [9] showed that the internal skin tissue temperature generally remains constant at a short distance of 10 mm from the skin surface, so the long domain L = 10 mm (0.01 m). For the analysis, some estimates of the properties of the network are made [9], as shown in Table II.

TABLE II. Thermophysical Parameter Values

Tissue Properties	Symbols	Values	Unit
Thermal conductivity of the tissue	K	0,5	W/m°C
Heat convection coefficient between skin & surrounding	h_0	10	W/m²°C
Surrounding air temperature	T_f	25; 28; 31; 34	℃
The arterial temperature	T_a	37	℃
Body Core temperature	T_C	37	°C
Metabolic heat generation	Q_m	420	W/m³
Specific heat of the tissue	C	4200	J/kg ℃
Specific heat of blood	c_b	4200	J/kg ℃
Density of tissue	ρ	1000	kg/m³
Density of blood	ρ_b	1000	kg/m³
The Blood perfusion	ω_b	0.0005	ml/s/ml

The one-dimensional steady state of the human skin biological heat transfer equation is solved using the Finite Volume Method (FVM), and the condition values and network attributes are input (Table III). The discretization process obtains the equations of each node 1 to 5, as shown in Fig. 3. Substituting numerical values gives Δx = 0.01 / 5 = 0.002, so each discretization coefficient is sufficient. It's easy to decipher. These values are given in Table II. The skin tissue surface temperature (TA) is obtained using equation (3): $h\ (T_f - T_A) = k\ ((T_a - T_A))\ /\ dx$). Four environmental temperatures [9] were selected, namely: cold temperature (T_f = 25 °C), normal temperature (T_f = 28°C) and warm temperature (T_f = 31°C), and hot temperature of (T_f = 34℃) to obtain the temperature superficial. of the skin tissue, are respectively T_A = 35℃, T_A = 35.5℃, T_A = 36℃ and T_A = 36.5℃. Substitute the values of the thermophysical parameters in Table II in Table I, and the results are shown in Table III.

TABLE III. The Coefficient of Each Discretized Equation

Nodes point	a_W	a_E	S_u	S_P	a_P
1	0	250	17500	-500	750
2	250	250	156,24	-4.2	504.2
3	250	250	156,24	-4.2	504.2
4	250	250	156,24	-4.2	504.2
5	250	0	18656,2 4	-504.2	754.2

From Table III, the resulting set of algebraic equations and maybe rearranged become as shown in Fig. 3.

$$\begin{bmatrix} 750 & -250 & 0 & 0 & 0 \\ -250 & 504.2 & -250 & 0 & 0 \\ 0 & -250 & 504.2 & -250 & 0 \\ 0 & 0 & -250 & 504.2 & -250 \\ 0 & 0 & 0 & -250 & 754.2 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \end{bmatrix} = \begin{bmatrix} 17500 \\ 156.24 \\ 156.24 \\ 156.24 \\ 18656.24 \end{bmatrix}$$

Figure 4. The algebraic equation

Fig. 4 shows the algebraic equation to obtain steady-state temperature distribution in each situation. For T_A = 35℃ and T_C = Ta = 37℃ (arterial temperature), we can obtain: T_1 = 35.216℃; T_2 = 35.648℃; T_3 = 36.055℃; T_4 = 36.442℃ and T_5 = 36.816℃. In the same way, the temperature distributions of various ambient temperatures are obtained (T_f = 28, 31 and 34℃). In this study, the temperature of human skin tissue is also calculated through the 10 and 20 node points. In the same way, use 5 nodes to get the human skin tissue temperature, as shown in Fig. 4.

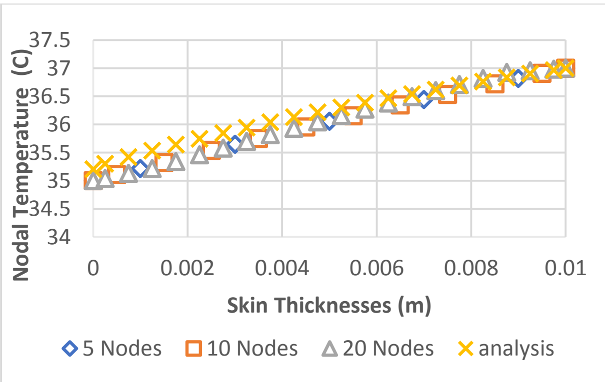
A. Model Verification

Model verification is performed by comparing the FVM results with the analysis results [32], as shown in equation (11), using the values of the thermophysical parameters in Table II

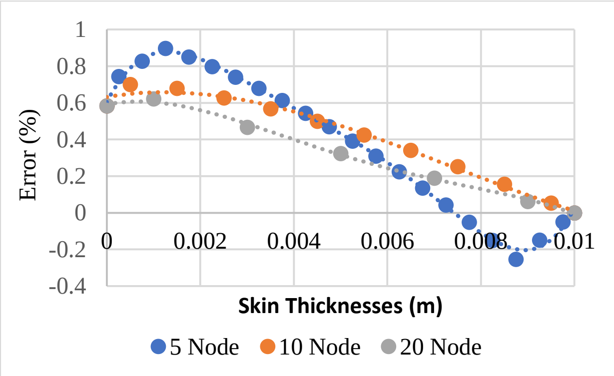
$$T(x) = T_b + \frac{Qm}{\omega_b \rho_b c_b} + \frac{\left(T_c - T_b - \frac{Qm}{\omega_b \rho_b c_b}\right)\left(\sqrt{A}\cosh(\sqrt{A}x) + \frac{h_0}{k}\sinh(\sqrt{A}x)\right)}{\sqrt{A}\cosh(\sqrt{A}L) + \frac{h_0}{k}\sinh(\sqrt{A}L)} + \frac{\frac{h_0}{k}\left(T_f - T_b - \frac{Qm}{\omega_b \rho_b c_b}\right)\sinh\left(\sqrt{A}(L-x)\right)}{\sqrt{A}\cosh(\sqrt{A}L) + \frac{h_0}{k}\sinh(\sqrt{A}L)} \quad (8)$$

With $A = \omega_b \rho_b c_b k^{-1}$.

Fig. 5 (a) is the expression of the temperature distribution, using the precise values of the relevant parameters to understand the changes in ambient temperature. By comparing the FVM model with the results of the analysis, the extent of the FVM model used to predict the precise temperature distribution in a variety of settings is analyzed [13]. It can often be seen from Fig. 5 (b) that there is an honest agreement between the analysis results and the FVM, indicating that the percentage of error is very small, less than 0.9%.



(a)



(b)

Figure. 5 (a) Comparison of FVM with Deng, Z.S [29] analysis solutions (b) % error comparing FVM with Deng, Z.S [29] analysis solutions

B. Steady-State Analysis of Human Skin Tissue Temperature Distribution

The skin tissue temperature distribution is derived from the steady-state FVM of different ambient temperatures (T_f = 25; 28; 31; 34°C) and convection coefficient (h_f = 10 W/m^{2}K)), as shown in Figs. 6 (a), 6 (b) and 6 (c).

Equation (2) illustrates the influence of blood metabolism on the temperature distribution of human skin tissue. So the temperature distribution of the network is a bit different. For steady-state analysis, taking into account the influence of convection, it is generally necessary to determine the surface temperature of the skin tissue. Figs. 6(a), 6(b) and 6(c) show the steady-state temperature distribution in the skin tissue of each node. This shows that the temperature of the skin surface is around 35 ℃, which is suitable for humans. After entering the body tissue, due to internal metabolic heat and perfusion, the temperature further rises, consistent with equation (1). But the core temperature remains constant at 37 ℃ [4,7,9,10].

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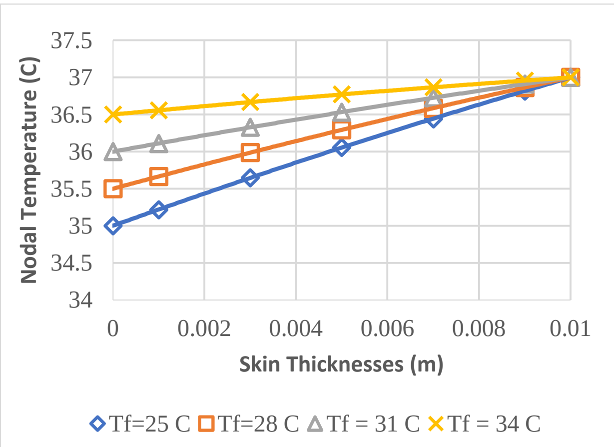

Figure 6 (a). Temperature distribution in human skin tissue various environmental temperatures to 5 nodes point

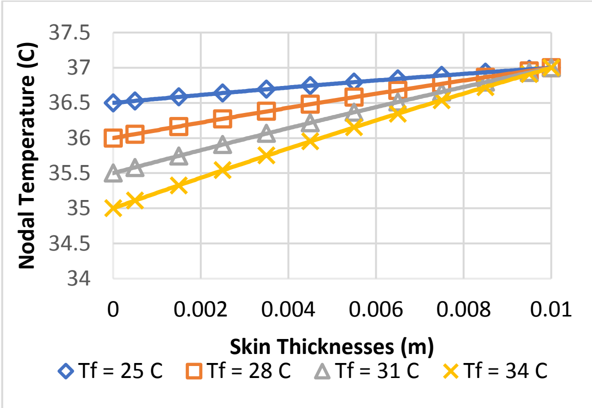

Figure 6 (b). Temperature distribution in human skin tissue various environmental temperatures to 10 nodes point

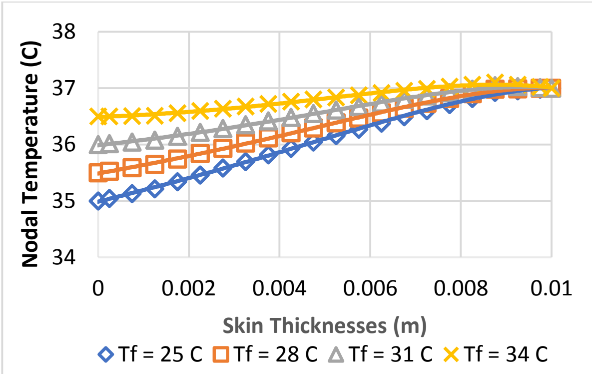

Figure 6 (c). Temperature distribution in human skin tissue various environmental temperatures to 20 nodes point

Ambient temperature plays an important role in the temperature distribution in the human body. Since evaporation occurs in the body at high temperatures, keeping other parameters fixed, take a temperature between 25 and 34 ℃ to observe the effect of ambient temperature on skin tissue [14]. Therefore, core temperature and skin temperature are the two most important indicators of the thermophysiological response of the human body [8]

Several temperature curves are observed in Figs. 6 (a), 6 (b), and 6 (c). The main ambient temperature has the temperature of the skin tissue surface is much higher than the low ambient temperature. These figures indicate that the temperature value in the partial layer of the dermis increases with increasing atmospheric temperature [8,9]. This shows that if the atmospheric temperature is lower than the core temperature of the body, the body temperature decreases from the center of the body to the surface of the skin [23]. This indicates that metabolism and blood perfusion effects will cause the temperature in the dermis and subcutaneous tissue to increase, which is the result of blood energy transfer. This temperature rise is regulated by the dermis, so it will not kill the skin tissue [4,9]

At cold room temperature (T_f = 25 - 28°C), the body temperature is almost always higher than room temperature, and the heat is always lost through the skin, causing The surface temperature of skin tissue can reach 35 ℃. Therefore, inside the body, the temperature difference between the fat of the skin and the skin itself is indeed very large, for example, 37 ℃ sectioning is performed at a room temperature of 25 ℃. The surface temperature of human skin may also vary from place to place. Skin tissue is extremely sensitive to the effect of tissue temperature, which is very different from the temperature of 37 ℃. Therefore, even if the ambient temperature changes drastically, the body will try to process the heat of the blood. This is usually achieved by maintaining a balance between the heat lost by the body and the heat received by the body from external changes in the body [10, 14].

For humans whose ambient temperature is around 25 - 34 ℃, the skin surface temperature fluctuates around 35 - 36.5 ℃, while the core temperature fluctuates around 37 ℃. Therefore, the gradient between the core temperature and the skin temperature is sufficient to remove active Excess metabolic heat in the tissue. When the ambient temperature decreases, the gradient between the skin temperature and the ambient temperature increases (as shown in Figures 6(a), 6(b), and 6(c)), which leads to an increase in heat dissipation through thermal convection, resulting in a decrease in skin temperature [9,11,12].

IV. Conclusion

This research successfully established a biological heat transfer model that uses the basic Pennes equation to solve the finite volume method, which describes the temperature distribution in human skin tissue. The model was validated using the results of the analysis and FVM, and a very small percentage of error (<0.9%) was obtained. This shows that the created model can be used to calculate the temperature distribution of human skin tissue at various ambient temperatures. The finite volume method has been used to simulate the temperature distribution in skin tissue with 5-node, 10-node, and 20-node changes. The increase in the ambient temperature in the skin tissue leads to an increase in the surface temperature of the skin and does not affect the healthy tissue due to the metabolism of the active tissue.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Slamet Wahyudi conducted the research, prepared the draft manuscript, analyzed the data, and approved the final version while Femiana Gapsari collected the data and wrote the manuscript.

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