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Study of Various Thermal Conductivity Layers in Bioheat Transfer Against Thermal Distribution on Human Skin with Finite Difference Method (FDM)

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Abstract: Development of science are often found with the connection between science and another that forms a brands new science. one among the new sciences is biomechanics with one among its scientific fields is bioheat transfer which is applied to human skin. one among the factors that influence the heat propagation of skin tissue is thermal conductivity because the ability of materials to conduct heat. the aim of this study was to work out the mathematical model of bioheat transfer with a one-dimensional finite difference method and therefore the effect of thermal conductivity on its temperature distribution. The model is often made with combine the Pennes H.H equation to the steady state then the chosen parameter entered into it. The results of the study were compared between the finite difference method and therefore the analytic method. The results of comparative studies indicate a rise in temperature distribution but between the 2 still have differences (error). Changes in environmental temperature affect the temperature distribution in human skin. While the thermal conductivity of various layers has no significant effect, the worth of temperature distributed between points increases regularly from the core of the body to the outer layer of human skin

Keywords: Bioheat transfer, finite difference, human skin, thermal conductivity

1. Introduction

The development of science is often found with the new relationship between science with others which will form a brands new science. one among the new sciences is biomechanics which is that the relationship between biology and mechanics. Mechanics were ready to explain and evaluate biology scientifically. A mathematical model of the method provides a more quantitative insight into the method by showing the consequences of varied process parameters [1]. One of the applications of biomechanics is heat transfer within the living tissue of the physical body (Human Tissue) which incorporates the organ system, blood flow, and thermal response of body tissue from external stimuli called bioheat transfer [2]. Calculation of heat transfer in body tissue aims to work out the mechanical phenomena within the scope of thermodynamics and biology in living things.

The heat balance equation addresses the interior and external factors that contribute to thermal balance [3]. The body tissue that's directly affected is that the outermost body tissue namely skin tissue. The skin functions as a generator, absorbent transmitter, radiator, conductor, and a hot exit. the equation is often wont to predict the consequences of frostbite, determine the depth of injury during a burn victim, and find the quantity of warmth lost through various parts of the body [1].

The skin, which is solid matter, experienced heat transfer in each layer by conduction. Human skin consists of three distinct layers: epidermis, dermis, and hypodermis, with varying degrees of specialization within each layer [4]. Heat transfer happened because atoms at higher temperatures vibrate and make silent atoms become vibrate. one of the factors

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influencing the heat propagation of human skin tissue is thermal conductivity [5]. Thermal conductivity is defined because of the ability of a cloth to conduct heat. Thermal conductivity is the nature of cloth and shows the quantity of heat flowing. skin tissue has various layers and every layer features a different thermal conductivity some researcher has researched bioheat transfer for instance [6] examined the analysis of one-dimensional transfer bioheat by the finite element method on the skin. during this study mathematical model of warmth transfer within the body of the human mean using the finite element method have made. The calculation results of the finite elements with analytic solutions were telling that the more points used, are going to be more precise the analytical results. Another example has been done by researchers using the non-Fourier fractional model et al. [7],[8],[9],[10] which surely cases explored the appliance [11],[12]. However, the calculation still uses parameters that are equated with water, and therefore the thermal conductivity parameter of the skin is merely considered one thermal conductivity.

2. Material and Methods

This study does the numerical analysis of mathematical models bioheat transfer on human skin with the thermal conductivity of the different layers as shown in Figure 1 using finite difference method, results identified from this study are model mathematics bioheat transfer on human skin by the finite difference method and the temperature distribution on the 5, 10, and 15 points

First prepare the tools needed for data processing, namely MATLAB. Continued with the mathematical model of bioheat transfer using the Pennes equation customized with boundary conditions the form length and the variation of thermal conductivity. After that insert the parameters in the calculation that have been determined include independent variables that used is the Environmental Temperature of 294 K as the temperature in the night of 296.86 K, as the temperature in the morning of 302.3 K as the temperature in the evening and amounts of points. The dependent variable observed in this study is the distribution of heat on the skin, the variables controlled in the research is the different thermal conductivity in each layer in the system of 310 K. After the process completes the calculation, results will be analyzed and made a discussion about heat transfer that occurs. Results on any point and temperature conditions will be compared with the analytical formula. Results will be analyzed and discussed to be concluded.

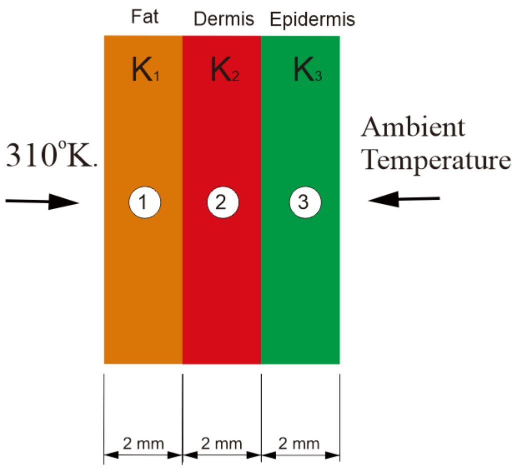

Fig. 1 Layers of Human skin

3. Model Description

The Pennes Equation [2] is widely used in analyzing heat transfer in living things. The equation has described the influence of blood perfusion in the temperature distribution of tissues. In general, one-dimensional Penne's equations as shown in equation (1).

$$\rho C_p \frac{\partial T}{\partial t} = -\frac{d}{dx}\left(k\frac{T_0(x)}{dx}\right) - \omega_b \rho_b C_b \left(T_a - T_0(x)\right) - Q_m \tag{1}$$

Under steady state, there is no stored heat [6], obtained equation (2).

$$-\frac{d}{dx}\left(k\frac{T_0(x)}{dx}\right) - \omega_b \rho_b C_b \left(T_a - T_0(x)\right) - Q_m = 0 \tag{2}$$

The equation (2) was solved using the Finite Difference Method (FDM) in the second-order $T_0(x)$ [5] can be stated as shown in equation (3):

$$\left.\frac{d^2T_0(x)}{dx^2}\right]_m \cong \frac{\left.\frac{dT_0}{dx}\right]_{m+1/2} - \left.\frac{dT_0}{dx}\right]_{m-1/2}}{\Delta x} = \frac{T_{m+1}-2T_m+T_{m-1}}{\Delta x^2} \tag{3}$$

When equation (2) is substituted using equation (3), obtained equation (4)

$$\left(k\frac{T_{m+1}-2T_m+T_{m-1}}{dx^2}\right) + \omega_b\rho_bC_b\left(T_a - T_0(x)\right) + Q_m = 0 \tag{4}$$

Table 1 - Equation symbol description

Symbol	Description	Unit
P	Tissue Density	Kg m^{-3}
C_p	Tissue Specific Heat	J $kg^{-1}K^{-1}$
T	Tissue Temperature	K
K	Thermal Conductivity	W m^{-1} K^{-1}
$T_0(x)$	Tissue Temperature in x	K
X	Distance	m
□$_b$	Blood Perfusion	S
ρ_b	Blood Density	kg m^{-3}
C_b	Blood Specific Heat	J kg^{-1} K^{-1}
T_a	Artery Temperature	K
Q_m	Metabolic Heat Generation	W m^{-3}

The equation (4) can be simplified as shown in equation (5)

$$\frac{1}{\Delta x^2}T_{m+1} + \left(-\frac{2}{\Delta x^2} - \frac{\rho\omega C}{k}\right)T_m + \frac{1}{\Delta x^2}T_{m-1} = -\frac{Q_m}{k} - \frac{\rho\omega C}{k}T_a \tag{5}$$

The human skin layer is defined in x = 0 to x = L using a total length of 6 mm. and in determining the distance at each point [5] using equation (6).

$$\Delta x = \frac{L}{N-1} \tag{6}$$

Thermal conductivity in more than one region uses:

$$K = \frac{k_1+k_2+k_3}{3} \tag{7}$$

At x = 6 mm there is the effect of convection from the environment to the epidermal skin layer so that at the point of temperature and convection point of the skin layer can be expressed by:

$$H_0\Delta T = H_0(T_{min} - T_{m-1}) \tag{8}$$

In the case of x = 6 mm the equation become*s*

$$\left(-H_0 - \frac{K}{\Delta x} - \frac{\rho\omega C}{2}\Delta x\right)T_{m-1} + \frac{K}{\Delta x}T_{m-2} = -\frac{Q_m}{2}\Delta x - \frac{\rho\omega C}{2}\Delta x(T_a) - H_0(T_{min}) \tag{9}$$

The results of the model will be compared with the results of analytic formulas [13]

$$T_0(x) = T_0 + \frac{\left(T_c - T_a - \frac{Q_{met}}{\omega_b\rho_bc_b}\right)\left(\sqrt{A}\cosh(\sqrt{A}x) + \frac{h}{k}\sinh(\sqrt{A}x)\right)}{\sqrt{A}\cosh(\sqrt{A}L) + \frac{h}{k}\sinh(\sqrt{A}L)} \frac{\frac{h}{K}\left(T_s - T_b - \frac{Q_{met}}{\omega_b\rho_bc_b}\right)\sinh\left(\sqrt{A}(L-x)\right)}{\sqrt{A}\cosh(\sqrt{A}L) + \frac{h}{K}\sinh(\sqrt{A}L)} \tag{10}$$

Where: $A = \omega_b\rho_bc_bk^{-1}$

4. Tissue Properties

Based on literature studies conducted on previous Bioheat Transfer research, secondary data have been obtained and following the provisions of human samples aged 20-30 years and healthy.

Table 2 - Skin tissue properties

Tissue Properties	Symbol	Value	Unit	Reference
Thermal Conductivity of Epidermis	K_1	0.235	$Wm^{-1} K^{-1}$	[14]
Thermal Conductivity of Dermis	K_2	0.445	$Wm^{-1} K^{-1}$	[14]
Thermal Conductivity of Fat	K_3	0.268	$Wm^{-1} K^{-1}$	[15]
Heat convection coefficient between skin & surrounding	H_0	10	$Wm^{-2}K^{-1}$	[13]
Surrounding air temperature Minimum	T_{min}	294	K	[16]
Surrounding air temperature average	T_{avg}	296.86	K	[16]
Surrounding air temperature Maximum	T_{max}	302.3	K	[16]
The arterial temperature	T_a	310	K	[6]
Body core temperature	T_c	310	K	[6]
Metabolic heat generation	Q_m	1190	$W m^{-3}$	[17]
Specific heat of blood	c_b	3840	$J Kg^{-1} K^{-1}$	[18]
Density of blood	ρ_b	1060	$Kg m^{-3}$	[19]
The blood perfusion	ω_b	0.000508	s^{-1}	[13]

5. Result and Discussion

5.1 Mathematical Model

Mathematical models are often created by modifying equations (2) to regulate the research conditions. In steady conditions are often made with the absence of heat loss. Determining the worth of the equation using the finite difference method which replaces the derivative within the equation . The mathematical model is tailored to the conditions experienced by the skin. These conditions provide the addition of convection from the environment at the skin surface x = 6 mm as shown in equation (12), while in the skin layers as shown in equation (11).

at x< 6 mm

$$\frac{1}{\Delta x^2}(T_{m+1}) + \left(-\frac{2}{\Delta x^2} - \frac{\rho\omega C}{k}\right)(T_m) + \frac{1}{\Delta x^2}(T_{m-1}) = -\frac{Q_m}{k} - \frac{\rho\omega C}{k}(T_a) \tag{11}$$

at x=6mm

$$\left(-H_0 - \frac{K}{\Delta x} - \frac{\rho\omega C}{2}\Delta x\right)(T_{m-1}) + \frac{K}{\Delta x}(T_{m-2}) = -\frac{Q_m}{2}\Delta x - \frac{\rho\omega C}{2}\Delta x(T_a) - H_{0.}(T_{min}) \tag{12}$$

5.2. The Temperature Distribution of Human Skin Using the Finite Difference Method

Temperature distribution data with a one-dimensional Finite Difference Method (FDM) show the effects of points used in finite difference methods. Figures 3, 4, and 5 show temperature distribution in three cases at the ambient temperature of 294 K (Tmin), 296.86 K (Tavg), and 302.3 K (Tmax) using the Finite Difference Method (FDM). The x-axis shows the space between points (meters) while the y-axis shows the temperature (K). Temperature may be a measure of the warmth or cold of an object. Distance point used is 0.0015 meters at 5 points, 0.000666667 meters in 10 points, and 0.00042857 meters at 15 points. Within the temperature distribution of 5 points distribution is seen on the surface and at the top , the distribution is that the lowest than the opposite points. the leads to the 10-point distribution look more evenly distributed where the row ranks have begun to seem with values between 5 points and 15 points. The results from the 15 points case look high and evenly distributed than the point with the very best in starting to the top that approaching the blood heat value at 310 K. The temperature distribution produced at the five points isn't more accurate than the results at 10 point. and therefore the results at 10 points aren't more accurate than the results at 15 points. This shows the worth of accuracy will increase with increasing points used. that's because the finite difference method that utilizes the points within the left and right areas that are calculated. Thus, increasing the amount of points within the finite-difference analysis increases the accuracy of the info obtained.

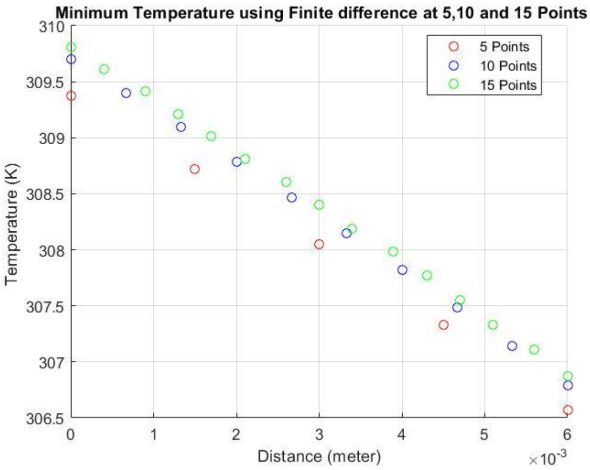

Fig. 3- Relationship between 5, 10, and 15 points Distance to Temperature at Tmin temperature using the finite difference method

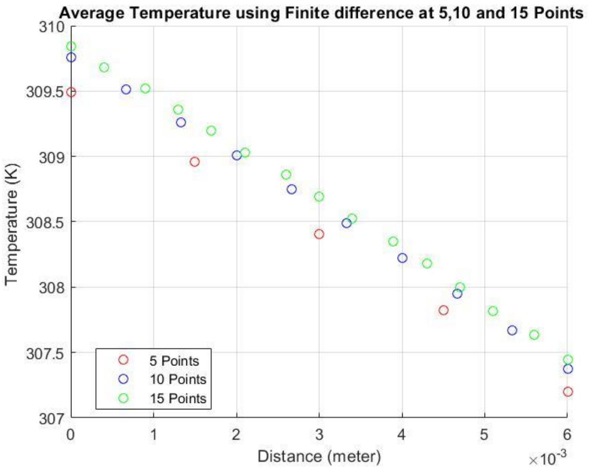

Fig - 4 Relationship between 5, 10, and 15 points Distance to Temperature at Tavg temperature using the finite difference method

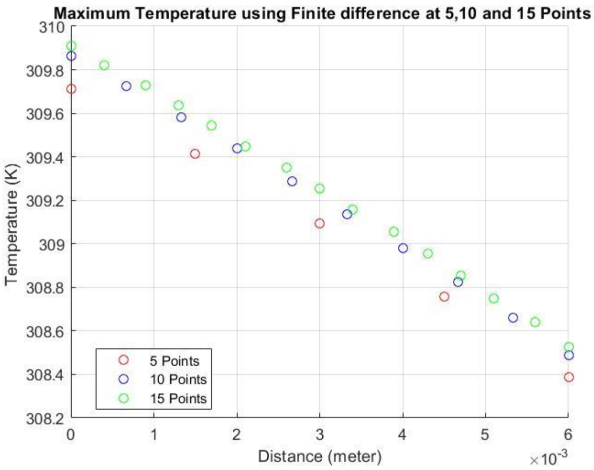

Fig. -5 Relationship between 5, 10, and 15 points Distance to Temperature at Tmax temperature using the finite difference method

5.3 Error Comparison from the Finite Difference Method and Analytical Method in Temperature Distribution

The Errors percentage were obtained from a comparison of the Finite Difference Method to the analytical formula in equation (1).

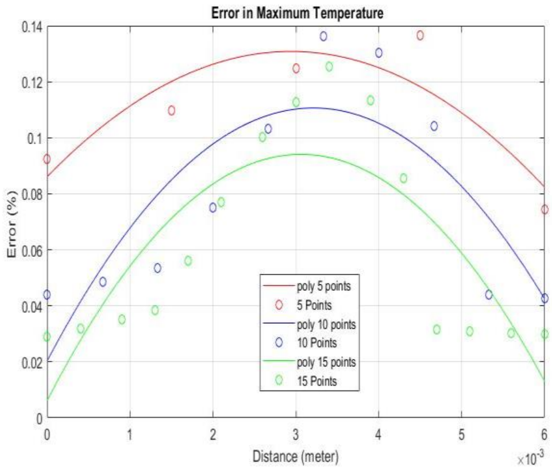

Fig. -6. Error in 5,10 and 15 points temperature distribution results with the maximal ambient temperature

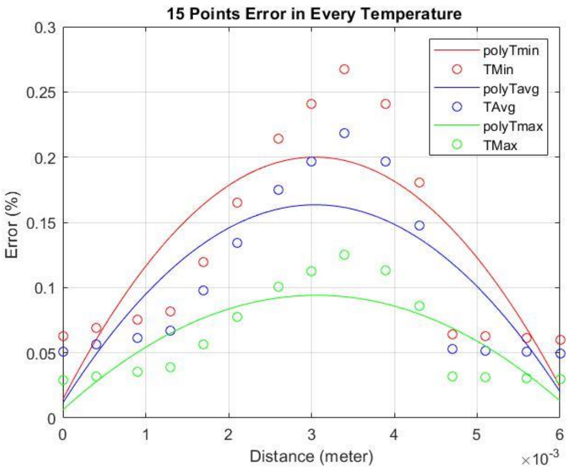

Fig.- 7. Error in 15 points temperature distribution results with three ambient temperature conditions

Figure 6 shows the error of temperature distribution within the 5,10 and 15 points case of the finite difference to analytical methods at ambient temperatures 302.3 K (T max). While figure 7 illustrates the error of temperature distribution end in the 15 points at the ambient temperature of 294 K (T min), 296.86 K (T avg), and 302,3 K (T max). The x-axis showing the space between points (meters) while the y-axis shows the error (%). Figure 6 shows the error within the temperature distribution of 5.10 and 15 points obtained from the share difference between the Finite Difference Method and therefore the analytical formula. within the three graphs, there was a rise and reduce at maximum ambient temperature (T max) the very best error value was obtained at 5 points with a mistake tendency of 0.13% followed by 10 points of 0.11% and 15 points with 0.09%. validation of analytical and experimental results are often valid and used if a mistake percentage of but 15% is obtained [20]. By watching the results of errors that exist within the temperature distribution of 5.10 and 15 points but 15%, the experimental results are valid. that's because the finite difference mathematical model has been conditioned to the particular condition during a steady-state and includes convection parameters outside the skin to finish the model.

Figure 7 explains the quantity of error within the temperature distribution of 15 points from the share between the Finite Difference method and analytical formulas in three environmental temperature conditions. The three graphs have a mistake tendency below 0.2% with the very best error achieved by a graph with a minimum ambient temperature while rock bottom error is reached by a maximum ambient temperature. With a mistake value below 0.2%, the mathematical model may be a finite difference valid and appropriate. this will occur because the environmental temperature plays a task within the amount of warmth transfer that's available and flows to the skin. The calculation will determine the initial value of the temperature received on the surface of the skin. the upper the temperature of the environment, the better it's for the body to take care of its blood heat.

5.4 Effect of Thermal Conductivity Layers in Bioheat Transfer Against Temperature Distribution in Human Skin Using the One-Dimensional Finite Difference Method

This study shows the effect of thermal conductivity on the use of the one-dimensional finite-difference in determining the temperature distribution of the human skin layer and the effect of points used in the finite difference method. In figures 8, 9, and 10 show the connection between temperature and point distance within the skin layer using the finite difference method. The x-axis showing the space between points (meters) while the y-axis shows the temperature (K). Temperature may be a measure of the heat or cold of an object. Distance point used is 0.0015 meters at 5 points, 0, 000666667 meters in 10 points, and 0,00042857 meters at 15 points. The image above shows that in three environmental conditions graph gradually drops through layers to the outer (epidermis).

The thermal conductivity of various layers has no significant effect. the worth of temperature distributed between points increases regularly from the core of the body to the outer layer of human skin. that's because the finite difference method that utilizes points within the area before and after. The thermal conductivity of various skin layers plays a task within the finite difference method. Differences in conductivity values during a layer resulting load at the purpose before. there's a change in thermal conductivity where some extent is suffering from another point in order that the results obtained are evenly shaped. Changes in environmental temperature affect the temperature distribution in human skin. the higher the ambient temperature, the higher the temperature distribution in the skin layer. so that the body will respond through the thermoregulation process to maintain heat balance in the body

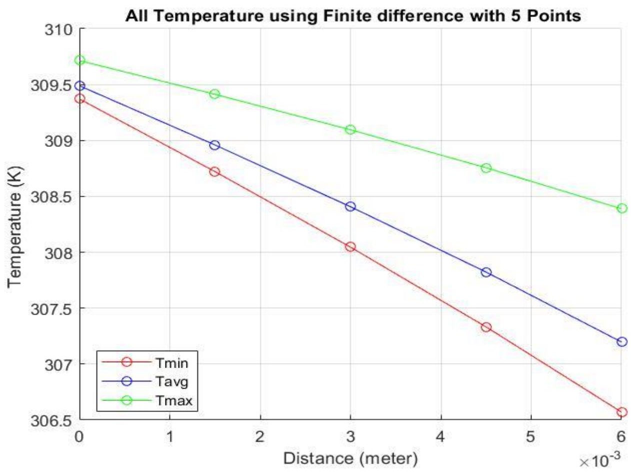

Fig.- 8. Graphic Relationship of the 5-point Distance to Temperature at 3 ambient temperature conditions

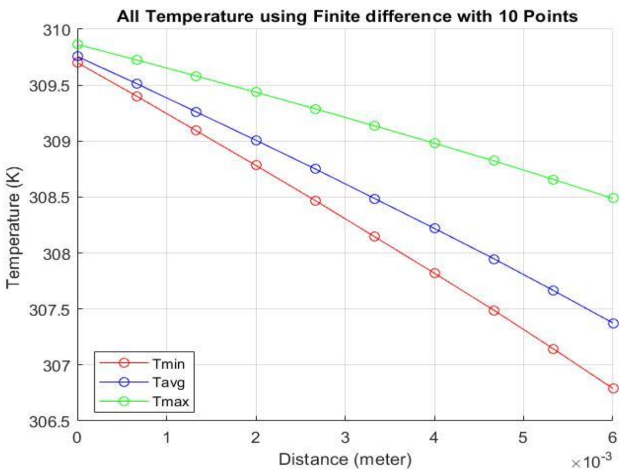

Fig.- 9. Graphic Relationship of 10-point Distance to Temperature at 3 ambient temperature conditions

6. Conclusion

1. The errors percentage of temperature distribution of 5.10 and 15 points about 0.11 % of results of FDM compared analytic solution.
2. Changes in environmental temperature affect the temperature distribution in human skin
3. The thermal conductivity of various layers has no significant effect, the worth of temperature distributed between points increases regularly from the core of the body to the outer layer of human skin

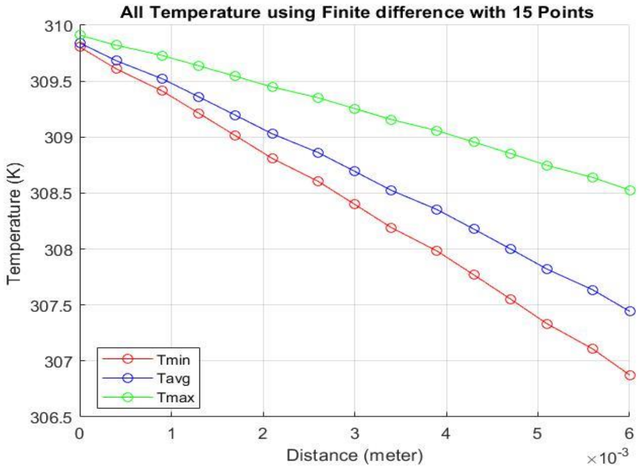

Fig.- 10. Relationship between 15 points distance to Temperature at 3 ambient temperature conditions

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References

[1] Ashim, K.D. (2017) Heat and mass transfer a biological context second edition. New York: CRC Press
[2] Pennes, H.H. (1948) Analysis of tissue and arterial blood temperature in the resting human forearm, Journal of Applied Physics Volume 1 pp 93-122
[3] Tansey, E. A., & Johnson, C. D, (2015). Recent advances in thermoregulation. Advances in Physiology Education, 39(3),39-48
[4] Wong, R., Geyer, S., Weninger, W., Guimberteau, J.-C., & Wong, J. K. (2015). The dynamic anatomy and patterning of skin. Experimental Dermatology, 25(2), 92–98
[5] Cengel, Y. A., & Afshin, J, (2015). Heat and mass transfer: a practical approach fifth edition New York: McGraw-Hill
[6] Nashima, B., Anup, S., Moshju, A., & Choudhury, A.A.R, (2013) IOSR Journal of Engineering (IOSRJEN) Volume 3, PP 43-49
[7] Forghani, P., Ahmadikia, H., & Karimipour A. (2015), Non-Fourier boundary conditions effects on the skin tissue temperature response, Heat Transfer-Asian Research pp1-20
[8] Ezzat, M.A., AlSowayan, N. S., Al-Muhiameed, Z. I. A., & Ezzat, S. M., (2014). Fractional modeling of pennes' bioheat transfer equation. Heat and Mass Transfer, 50(7), 907–914
[9] Nantu, S, (2016). A novel Pennes' bioheat transfer equation with memory-dependent derivative. Mathematical Models in Engineering. Volume 2. 151-157
[10] Assunta, A., Luca, B., Marcello, l., Claudio, T., & Giuseppe, V, (2019). Bioheat transfer in a spherical biological tissue: a comparison among various models. Journal of Physics: Conference Series
[11] Kashcooli, M., Salimpour, M. R., & Shirani, E., (2017). Heat transfer analysis of skin during thermal therapy using thermal wave equation. Journal of Thermal Biology, volume 64, 7–18
[12] Chu, K. F., & Dupuy, D.E, (2014) Thermal ablation of tumours: biological mechanisms and advances in therapy Nature Reviews Cancer volume 14 199-208
[13] Deng, Z.S., & Liu, J, (2002). Analytical study on bioheat transfer problems with spatial or transient heating on skin surface or inside biological bodies, Journal of Biomechanical Engineering, Volume 124 pp 638–649
[14] Stanko, S., & Đani, J, (2013) A system for model-based quality assessment of burn-protective garments (Case Studies in Control: Putting Theory to Work). (London: Springer Science & Business Media) Chapter 9 pp 257-285

[15] Waldemar, W., Sergil, P.S., & Maksat, K, (2019) Model of skin tissue heat transfer in the conditions of cryosurgical impact (Information technology on medical diagnostics II). (London :Taylor and francis group) pp 297-305
[16] Badan meteorology, klimatologi dan geofisika. (2020). Data Harian Temperatur. [online] Available at: http://dataonline.bmkg.go.id/ [Accessed 10 Feb. 2020]
[17] Rajneesh, K., Anil, K.V., & Suniti, G, (2017). Analytical solution of bioheat transfer equation with variable thermal conductivity in skin. International journal of Engineering Research and Development Volume 14 PP 11-17
[18] Riyadh. W.Y.H, (2020) Foundation of bioelectromagnetic (BioElectroMagnetics: Human Safety and Biomedical Applications). (United State :CRC press) Chapter 2
[19] Duck, F. A., (2013), Physical properties of tissue: a comprehensive reference book, New York: Academic press
[20] Febri, D.I, (2017). Pemodelan bioheat transfer pada jaringan manusia berbasis finite element method.Bogor Master Thesis Bogor Agricultural University (IPB), Bogor, Indonesia