APPROXIMATING THE TEMPERATURES PROFILES FOR HUMAN SKIN TISSUE LAYERS DURING HEAT WAVE USING FINITE DIFFERENCE METHOD

by

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LIST OF ABBREVIATIONS

FDM	Finite Difference Method
FEM	Finite Element Method
FVM	Finite Volume Method
MET	Malaysia Meteorological Department
1D	One Dimensional

LIST OF SYMBOLS

ρ	Density
c	Specific heat
K	Thermal conductivity
S	Rate of metabolic heat generation of tissue
ρ_b	Blood density
m_b	Blood mass flow rate
c_b	Specific heat of the blood
T_A	Arterial blood temperature
T_b	Body core temperature
T_a	Atmospheric temperature
T_0	Normal skin temperature
h	Heat transfer equation
Δx	Spatial spacing
Δt	Time step
L	Latent heat of evaporation
E	Rate of sweat evaporation
ϕ_A	Tissue perfusion due to arterial blood
ϕ_v	Tissue perfusion due to venous blood

Menganggar Profil Suhu Untuk Lapisan Tisu Kulit Manusia Semasa Gelombang Haba Menggunakan Kaedah Beza Terhingga

ABSTRAK

Pada tahun 2016, Malaysia dilanda oleh gelombang haba sangat buruk. Sehingga hari ini, masih tiada kajian tentang kesan gelombang haba di Malaysia kepada lapisan-lapisan tisu kulit manusia. Oleh itu, kajian ini mempersembahkan aplikasi kaedah beza terhingga kepada kajian suhu termal tiga lapisan tisu kulit manusia yang dinamakan epidermis, dermis dan tisu subkutan. Persamaan Bioheat Pennes' telah digunakan untuk mewakili pengedaran termal di dalam lapisan tisu kulit. Ia diandaikan bahawa permukaan kulit terdedah kepada perbezaan suhu persekitaran. Kaedah beza terhingga digunakan untuk menganggarkan profil suhu lapisan tisu kulit manusia dengan bantuan perisian MATLAB. Pengiraan telah menunjukkan jangkaan keputusan yang mana suhu persekitaran memberi kesan kepada pengedaran suhu di dalam lapisan tisu kulit manusia. Pada setiap pertambahan 10℃ dalam suhu persekitaran, suhu di dalam epidermis, dermis dan tisu subkutan akan bertambah sebanyak 0.9℃, 0.8℃ dan 0.4℃, masing-masing.

Approximating The Temperatures Profiles for Human Skin Tissues Layers During Heat Wave Using Finite Difference Method

ABSTRACT

In 2016, Malaysia was stricken by a bad heat wave. Since today, there were no study yet on the effect of heat wave in Malaysia to human skin tissue layers. Therefore this study presents a Finite Difference Method application to the thermal study of three layers of human skin tissue namely epidermis, dermis and subcutaneous tissue. Pennes' bioheat equation used to represent the thermal distribution in human skin tissue layers. It is assumed that the surface of the skin expose to different surrounding temperature. Finite difference method is used to approximate the temperatures profiles for human skin tissue layers with the help of MATLAB software. The calculation showed an expected result which is surrounding temperature does effect the temperature distribution in human skin tissue layers. At each 10°C increase in surrounding temperature, the temperature in epidermis, dermis and subcutaneous tissue will increase around 0.9°C, 0.8°C and 0.4°C, respectively.

CHAPTER 1

INTRODUCTION

1.1 Introduction

According to the scientific report written by the Malaysian Meteorological Department (MET), the temperature in Malaysia indicate an increasing temperature trend in both Peninsular and East Malaysia. The average temperature in Malaysia is typically 27°C, but during the early March of 2016, temperatures have increased to more than 30°C. Moreover, on 12 March 2016, the temperature in the northern part of Malaysia has reached the fifth days marks of above normal temperatures. Hence, MET had declared a heat wave with Chuping, Perlis, recording 38.5℃, the highest in the country.

When the surrounding temperatures changes, the skin temperature will also changes. In opposite to the body core temperature, the skin temperature increases and decreases with the surrounding temperature. Moreover, skin are made of three layers which are epidermis, dermis and subcutaneous tissue. Besides, skin also plays a key part in retaining the thermal homeostasis of the body (Lehmuskallio, Hassi & Kettunen, 2002). Normally, a human body temperature will stays consistent as 37℃. If the temperature is higher than 40℃, the body will experience hyperthermia along with hot, dry skin, and central nervous system dysfunction (Fisher-Hubbard, Sung, Hubbard & Hlavaty, 2016).

Pennes' bioheat equation is one of the most used models to simulate the heat flow in biological tissues for the one dimensional case. Although the Pennes' bioheat model is developed based on the experimental analysis of the human forearm, it can be used to quantitatively calculate the rate of heat transfer in any perfused tissues. Many authors have used Pennes' bioheat equation to develop mathematical models of heat transfer in living tissues so that it becomes well known as the bioheat transfer equation (Shih, Kou, Liauh & Lin, 2002). This model has proved to be quiet accurate in predicting the temperature in vascularized tissues with small vessels, and has been widely used in several biomedical applications (Bhowmik, Repaka & Mishra, 2014).

The Pennes' bioheat equation has been solved numerically by several methods such as Finite Volume Method (FVM), Finite Element Method (FEM), and Finite Difference Method (FDM) (Ng & Chua, 2000; Khanday & Saxena, 2009; Gurung, Saxena & Adhikary, 2009; Agrawal, Adlakha & Pardasani, 2010; Khanday, Aijaz & Rafiq, 2015; Fu, Weng & Yuan, 2014; Orndoff, Ponomarev, Dai & Bejan, 2017; Najar & Khanday, 2016; Khanday, Nazir, Khalid & Rasool, 2016). Finite difference method is chosen since it is very easy to worked out with less errors (Khanday & Hussain, 2015)

1.2 Problem Statement

Heat wave has always been a serious issue facing by Malaysian for the last few years (Suparta & Yatim, 2017). In 2016, the heat wave even caused a few death among Malaysian (Hasnan, 2016). There were many research done by scholars in this field. However, most of the research done were focusing on the effect of the heat wave towards the body. Since skin is the largest organ of human body (Xu & Lu, 2011), it is very interesting to understand the effect of heat wave towards the skin. Recently, some researchers were focusing on the extreme cold weather and its effect to skin (Khanday & Hussain, 2015). But, no researches attempt to address the implication of extreme hot weather and its effect to skin. Therefore, this study will help us to obtain more understanding for the effect of heat wave towards human skin by using three layer model.

1.3 Research Objectives

The main objective is to estimate the temperature profiles of human skin with a bioheat transfer equation using a three layer model. In order to achieve main objective, the following sub-objectives will be performed:

i. To discretize 1D Pennes' bioheat transfer equation on three layer tissues model by using finite difference method (FDM).

ii. To construct computational algorithm of FDM Pennes' bioheat transfer model and procedure for solving 1D Pennes' bioheat transfer equation.

iii. To validate the result obtained with Finite Element Method.

iv. To predict the temperature of the skin layers during heat wave in Malaysia.

1.4 Research Scopes

i. The discretization of domain will focus only on three layer model.

ii. The body core temperature remains constant, $T_b = 37$°C.

iii. The thickness of the skin layer is considered to be 0.5cm.

iv. The skin layer is exposed to the surrounding temperature for 20 minutes as the temperature remain almost constant afterwards.

1.5 Significant of The Study

The finite difference method which will be used to solve the Pennes' bioheat transfer equation in this study will guide other researcher to find the discrete values of temperature profiles at nodal points. Furthermore, this calculations will also beneficial in medical sciences and tissue engineering. With growths in microwave, laser and other technology, various thermal methods have been expanded and applied to the treatment or disease involving skin tissues. In order to kill or thermally denaturize the necrotic cells, precise monitoring the increasing or decreasing in temperature of targeted skin area during thermal treatment methods are required.

Other than applications in biomedical, this study may be beneficial to the advances connected to space and armed forces operations. In space travel and some military operations, astronauts and military personnel might faced with some extreme environments. Besides, skin certainly plays an important role as the layer between the human body and the outside worlds. Hence, it is crucial to equip astronauts and military personnel with an advanced outfits to shield them from severe environment temperature.

1.6 Thesis Outline

The first chapter of this dissertation is started with an introduction to the problem, the problem statement, research objectives involved in this study, research scopes and the significant of the research. The second chapter is about literature review of this study. This chapter is started by an overview about heat wave in Malaysia. Then, the chapter is continued to the skin layers and introducing the equation used in this study. The chapter is then proceeded to the numerical methods used by many other authors. Next, the third chapter is about the methodology used in this study. This chapter begin with the discretization process for Pennes' bioheat equation and the initial condition, boundary condition and step sizes used in this study. After that, this chapter move to the general grid scheme for explicit finite difference method as well as the grid scheme for Pennes' bioheat equation. This chapter is ended with the description of methodology phase of this study. Meanwhile, the fourth chapter is about the results and discussion related to this study. This chapter is consist of validation of finite difference method and the results for Pennes' bioheat equation. Finally, the last chapter is about the conclusion and recommendations for further study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will discuss the heat wave in Malaysia, the skin layers, Pennes' bioheat equation and numerical computation involving the equations.

2.2 Heat Wave

According to a statement made by the Datuk Seri Wilfred Madius Tangau, the Minister of Science, Technology and Innovations (MOSTI) in Bernama (2016), the weather below 35°C is categorized as Level 0. Meanwhile, an alert Level 1 is considered if the temperature is between 35°C to 37°C for three straight days. Next, if the temperature higher than 37°C for three straight days, MOSTI will declare heatwave and schools will be close. The worst level is Level 3 where the temperature exceeds 40°C for three straight days making the Prime Minister to declare a state of emergency. The average temperature in Malaysia is usually 27°C, but during the early of March of 2016, temperatures have escalated to more than 30℃. Moreover, on 12 March, after five days in a row of above normal temperature, The Malaysian Meteorological Department (MET) had announced a heat wave. The states that severely involved were among the northern region of Peninsular Malaysia. More alarming, a scientific report written by MET had stated that the temperature in Malaysia shows an increasing temperature trend in both Peninsular and East Malaysia. This shows that heat wave will eventually become one of the natural disasters in Malaysia.

Inevitably, when the surrounding temperatures changes, the skin temperature will also changes. The effect of skin temperature and sensory states can be represented in Table 2.1 (Gagge & Nishi, 2011)

Table 2.1: The effect of skin temperature and sensory states

Skin temperature	State
Above 45	Rapid tissue damage
43-41	Threshold of burning pain
41-39	Threshold of transient pain
39-35	Sense of hot
37-35	Initial sense of warm
34-33	Neutral temperature sense at rest, comfortable

Therefore, this study will be used to identify the temperature profiles for the skin when the surrounding temperature changes and its effect to skin.

2.3 Skin

Normally, a human body temperature will stays consistent and around $37°C$. If the temperature is higher than $40°C$, the body will experience hyperthermia along with hot, dry skin, and central nervous system dysfunction (Fisher-Hubbard et al, 2016).

Meanwhile, hypothermia is caused by the decreasing in temperature below $35°C$. In an extremely cold environment, the skin can suffer from frostbite, trench foot and chilblains (Khanday, 2013). When the ambient temperature is very low, the tissue death at the skin and deep tissues will occur depending on its severity (Khanday & Hussain, 2015).

Thermal homeostasis is the capability of the human body to conserve the body temperature even when the surrounding temperature changes (Page & Shear, 1988). In opposite to the core temperature, the skin temperature increases and decreases with the surrounding temperature. Hence, the skin temperature is the main temperature to describe the heat loss from the body to its surrounding (Guyton & Hall, 2006).

Skin is composed of three layers and has an important job in sustaining the thermal homeostasis of the body (Lehmuskallio et al, 2002). Figure 2.1 shows the skin layers in human body.

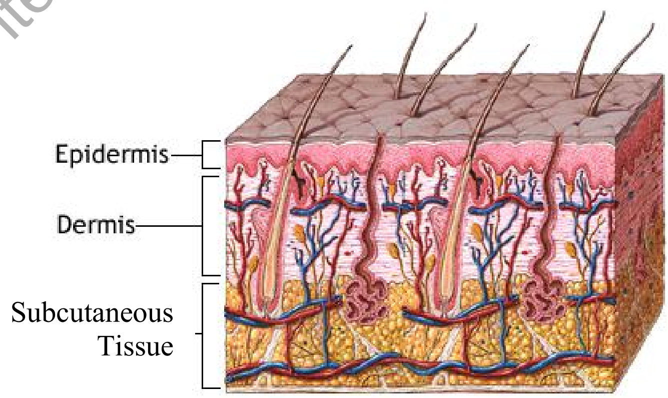

Figure 2.1: Human skin layers (Gurung et al, 2009)

Based on Figure 2.1, the skin layers has been divided into three separate layers namely epidermis, dermis and subcutaneous tissue and the subscripts *e, d* and *s* stand for the parameters assigned to these layers respectively. The physiological and parametric behaviour of these regions is given below (Guyton & Hall, 2006):

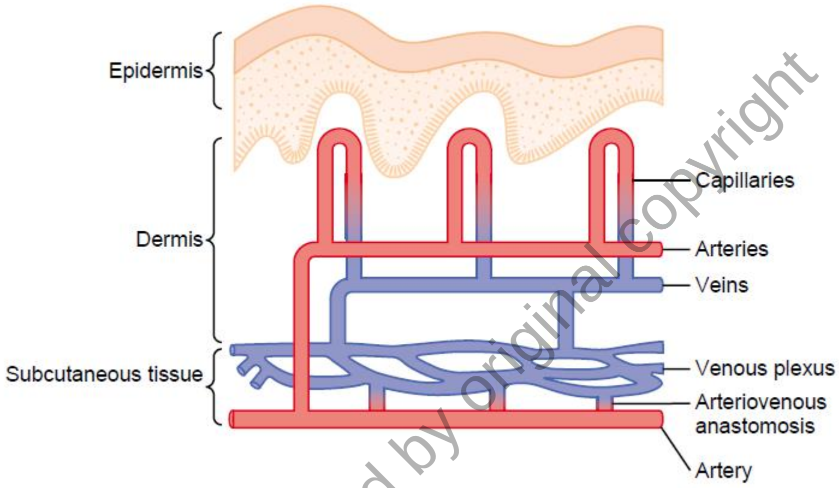

Figure 2.2: Blood vessels in skin tissue layers (Guyton & Hall, 2006)

The first layer is known as epidermis layer. Based on Figure 2.2, there are no blood vessels in epidermis layer, so there is no blood flow and hence very minimal metabolic activity. Therefore, $K_e =$ constant, $M_e = 0$, $S_e = 0$ where *K, M* and *S* are the thermal conductivity, blood flow and metabolic heat of the tissue respectively. Meanwhile, the subscript *e* represents the epidermis layer.

The second layer is the dermis layer. There are plenty of blood vessels in this layer and becomes almost steady in subcutaneous tissue. Hence, the value of the thermal conductivity, blood flow and metabolic activity are the highest in subcutaneous tissue and the lowest in epidermis layer. As a result, the values of these biophysical constants in dermis is considered as the mean value of that in epidermis and subcutaneous tissue, which are $K_d = \frac{K_s + K_e}{2}$, $M_d = \frac{m}{2}$, $S_d = \frac{s}{2}$ where the subscript d represents the dermis layer.

The subcutaneous tissue also known as hypodermis is the lowest layer in three layer skin. Its function is to regulate the body temperature and also provide protection for the inner organs and bones. Compared to dermis, subcutaneous tissue contains larger blood vessels and nerves. The values of the parameters in the subcutaneous tissue are assumed to be $K_s =$ constant, $M_s = m$, and $S_s = s$ where the subscript s represents the subcutaneous tissue layer.

2.4 Pennes' Bioheat Equation

Back in mid twentieth century, thermal injury was one of the famous problem that most authors want to investigate on. In 1947, Henriques and Moritz devised the Arrhenius burn integration damage function that was then been used broadly. By using this injury function, prediction of the cumulative damage received during a burn was made possible. They suggested that the damage to the skin could be described like a chemical rate process, that could be calculated by applying a first order Arrhenius rate equation, by which damage is related to the protein denaturation rate (κ) and exposure time (τ) at a given absolute temperature (T).

Next, Pennes had created a bioheat transfer equation in reference to the analysis after making an experiment on human forearm (Pennes, 1948). For simplicity of the modeling analysis, Pennes has made three assumptions that the rate of heat production by tissue, the volume flow of blood per unit volume of tissue per second and the tissue specific thermal conductivity were all considered uniform throughout the forearm. Although the Pennes' bioheat model is developed based on the experimental analysis of the human forearm, it can be used to quantitatively calculate the rate of heat transfer in any perfused tissues (Shih, Kou, Liauh & Lin, 2002). Countless authors had adopted this equation to create mathematical models regarding heat transfer in living tissues so that it becomes well known as the bioheat transfer equation (Shih, Kou, Liauh & Lin, 2002).

Pennes (1948) proposed the mathematical model for the flow of heat in biological tissues for the one dimensional case, which is given by

$$\rho c \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2} + \rho_b m_b c_b (T_A - T) + S \tag{2.1}$$

where ρ stand for the tissue density; c the specific heat of the tissue ; T the tissue temperature ; t the time ; K the thermal conductivity ; ρ_b the blood density ; m_b the flow rate of the blood mass ; c_b the blood specific heat ; T_A the temperature of arterial blood and S the metabolic heat generation rate of tissues respectively.

There are a lot of studies made for solving Pennes' bioheat equation. Pal and Pal (1990) worked on the predicting the human skin's and subcutaneous tissues' temperature profiles by using confluent hypergeometric together with Airy's functions. The solutions shows the inter-relationships between interface temperatures, metabolic heat production, thermal conductivities, blood perfusion, ambient temperature and thickness of various layers of subcutaneous tissues.

This model is one of the simplest and oldest blood perfusion models that was being used in many medical and biological applications (Bhowmik, Singh, Repaka & Mishra, 2013). Examples of these applications are to estimate the characteristics of tumor inside breast and brain, hyperthermia, brain hypothermia, tissue ablation, radiofrequency tumor ablation, microwave tumor ablation, thermal therapy, cryosurgery, thermal imaging, skin burns and fabric protection against skin burn (Bhowmik, Repaka & Mishra, 2014).

2.5 Numerical Methods

The Pennes' bioheat equation has been solved numerically by several methods such as Finite Element Method (FEM), Finite Volume Method (FVM) and Finite Difference Method (FDM) (Ng & Chua, 2000; Khanday & Saxena, 2009; Gurung, Saxena & Adhikary, 2009; Agrawal, Adlakha & Pardasani, 2010; Khanday, Aijaz & Rafiq, 2015; Fu, Weng & Yuan, 2014; Orndoff, Ponomarev, Dai & Bejan, 2017; Najar & Khanday, 2016; Khanday, Nazir, Khalid & Rasool, 2016).

One of the method used to solve Pennes' bioheat equation is by using Finite Element Method (FEM) as done by Ng and Chua (2000) where they have done their study on three layers skin model to investigate the impact that skin layers has after being exposed to a contact heat source. Another noteworthy work in Finite Element Method is the work done by Khanday and Saxena (2009), where they produced a mathematical model to investigate the regulation of temperature for human head in relatively low temperature by using variational finite element method. Since human body has the head as the most important organ, any irregularity to the regulation of temperature will cause the brain to be faulty. They had applied Pennes bioheat equation on four layers model namely brain, cerebrospinal fluid (CSF), skull and scalp.

Contrary to Khanday and Saxena (2009), Gurung, Saxena and Adhikary (2009) investigated the temperature distributions in one dimensional unsteady state case for three layers model with quadratic shape functions using finite element method. As an extension to this study, Agrawal, Adlakha and Pardasani (2010) used three dimensional finite element method to investigate the heat flow in epidermis, dermis and subcutaneous tissue by elliptical and tapered shape human limbs. After that, Khanday, Aijaz and Rafiq (2015) applied variational finite element method to numerically estimate the pattern of fluid distribution in five layers skin tissue with different metabolic rates.

Another method to solve Pennes' bioheat equation is by using Finite Volume Method. Fu, Weng and Yuan (2014) used a finite volume method to model the transient heat together with mass transfer in three layers skin tissue, with regards on water diffusion and vaporization effect on the temperature of the skin. The outcome of the study shows two different effects on tissue temperature. The temperature of the epidermis layer will decrease if there are heat loss because of water vaporization and water diffusion. However, the temperature in subcutaneous tissue will increase and damage the skin due to heat from blood perfusion and water diffusion.