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Nonlocal heat conduction approach in biological tissue generated by laser irradiation

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Abstract. A novel nonlocal model with one thermal relaxation time is presented to investigates the thermal damages and the temperature in biological tissues generated by laser irradiations. To obtain these models, we used the theory of the non-local continuum proposed by Eringen. The thermal damages to the tissues are assessed completely by the denatured protein ranges using the formulations of Arrhenius. Numerical results for temperature and the thermal damage are graphically presented. The effects nonlocal parameters and the relaxation time on the distributions of physical fields for biological tissues are shown graphically and discussed.

Keywords: bioheat transfer; laplace transform; living tissues; nonlocal thermoelastic model; thermal relaxation time

1. Introduction

Cancer is a disease with high death rates and there is no definitive cure yet. Most types of cancer present as a solid tumor. Cancer cells can ultimately lead to cancer. There are already some common treatments such as chemotherapy, radiation therapy and the surgical removal of cancerous tumors, but all of them have many side effects and are not specific enough. In recent years, a new treatment called hyperthermia has been widely studied and several experiments show its high effectiveness while having fewer side effects. Hyperthermia is a heat treatment of cancer by raising the temperature of cancerous tumor cells in the human body considering that keeping the temperature above 42°C could cause necrosis of living human cells.

The nonlocal elastic theory was first advocated by Eringen (Eringen 1984a). After a period of 2 years, the theory of non-local thermoelasticity was explored by Eringen (1974). He reviewed the constitutive relations, the governing equations, the laws of equilibrium in continuum mechanic and the displacement equations/temperature under nonlocal elastic theory. The nonlocal elastic theory states that in case of translational motion, strain is the applied stress of the continuous body at a point x which depends not only on the strain point but also influenced by the strains of the body at every other region near this point x. Wang and Dhaliwal (1993) explained the uniqueness of the theory of non-local thermoelasticity. Eringen (1991) studied non-local electromagnetic solids and

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superconductivity under the theory of elasticity.

In 1948, Pennes (1948) investigated the distributions of temperature in the forearm skin temperature, which meant that the equation could be analyzed by different models usually used to get the solution of the heat transfer model for an infinite heat propagation based on classical Fourier thermal conduction. The skin tissues contain several phenomenological mechanizations like radiation and the perfusion of blood, metabolic heating generation and thermal conduction. Charny (1992) has presented the mathematical model of bioheat transfers. Andreozzi *et al*. (2019) discussed the heat transfer modeling in tumors. Marin (2010) presented some estimates on thermoelastic vibrations of dipolar materials. Hassan *et al*. (2018) studied the exploration of convective thermal transfers and flow characteristics synthesis. Marin (1996) studied the generalized solutions in the elasticity of micropolar materials with voids. The authors (Kumar and Gupta 2008, Marin *et al*. 2015, Lata *et al*. 2016, Ezzat and El-Bary 2017, Anya and Khan 2019, Khan *et al*. 2019, Lata and Kaur 2019, Sarkar *et al*. 2019, Alzahrani and Abbas 2020, Ezzat 2020, Hobiny and Abbas 2020, Hosseini 2020, Lata and Singh 2020, Rachedi *et al*. 2020, Saeed *et al*. 2020, Sarkar 2020, Sarkar *et al*. 2020a, b, Zhang *et al*. 2020, Hobiny and Abbas 2021a, Lata and Kaur 2021, Lata and Singh 2021) presented the solutions of several problems under generalized thermoelastic theories. Hobiny and Abbas (2021) have discussed the influences of fractional order bio-heat transfer model. Saeed and Abbas (2020) investigated the nonlinear dual phase lag bioheat transfer model in the spherical living tissue.

In this work, the analytical solution of temperature and the thermal damages of tissues are discussed. The nonlocal bioheat model with thermal relaxation times are applied to studying the propagations of thermal wave in living tissue. The effects nonlocal parameters and the relaxation time on the distributions of wave propagation of physical fields for tissues are shown graphically and discussed.

2. Mathematical model

Following Eringen (1984b, 2012) and Lord and Shulman (Lord and Shulman 1967), the basic equations for nonlocal bioheat equation in living tissue is given by (Xu *et al*. 2008, Ahmadikia *et al*. 2012, Kumar and Rai 2020)

$$K\frac{\partial^2 T}{\partial x^2} = \left(1-\zeta^2\frac{\partial^2}{\partial x^2}\right)\left(1+\tau_o\frac{\partial}{\partial t}\right)\left(\rho c\frac{\partial T}{\partial t} - Q_b - Q_m - Q_{ext}\right), \tag{1}$$

where τ_o is the thermal relaxation time, ζ is the nonlocal parameter, c is the heating specific of tissues, T is the tissue temperature, k is the tissues thermal conductivity, t is the time, ρ is the mass density of tissues, Q_m is the metabolic heating generations in skin tissues, Q_b is the blood perfusion heating sources, c_b is the blood specific heating, Q_{ext} point to the heat generated per unit volume of tissue and ω_b is the rate of blood perfusions. The laser heating sources are expressed by Gardner *et al*. (1996) by

$$Q_{ext}(r,t) = I_o\mu_a\left[U(t) - U(t-\tau_p)\right]\left[C_1 e^{-\frac{k_1}{\delta}x} - C_2 e^{-\frac{k_2}{\delta}x}\right], \tag{2}$$

where μ_a is the coefficients of absorption, I_o is the intensity of laser, τ_p is the laser exposure time, δ is the penetrations depth, $U(t)$ is the unit step functions, k_1, k_2, C_1 and C_2 are the functions of diffuse reflectance R_d and they are mentioned as in Gardner *et al*. (1996) where the depth of penetration can be defied as

$$\delta = \frac{1}{\sqrt{3\mu_a\big(\mu_a + \mu_s(1-g)\big)}}, \tag{3}$$

where μ_s is the scattering coefficient and g is the anisotropy factor. While Q_b refer to the heating source of blood perfusions which is expressed by

$$Q_b = \omega_b \rho_b c_b (T_b - T), \tag{4}$$

where c_b is the blood specific heat, ρ_b is the blood mass density, ω_b is the rate of blood perfusion and T_b is the blood temperature. We consider an unbounded domain of living tissues with a thickness L and it's both directions thermally isolated have been proposed.

3. Application

Now, the initial condition and boundary condition are given by follow

$$T(x,0) = T_b, \qquad \frac{\partial T(x,0)}{\partial t} = 0. \tag{5}$$

While the problem boundary conditions are given as

$$-K\frac{\partial T(0,t)}{\partial x} = 0, \qquad -K\frac{\partial T(L,t)}{\partial x} = 0. \tag{6}$$

For conveniences, the dimensionaless parameters are defined as

$$\begin{aligned} &\mathrm{T}' = \frac{\mathrm{T}-\mathrm{T}_o}{T_o}, \quad (t',\tau_o',\tau_p') = \frac{k}{\rho c L^2}(t,\tau_o,\tau_p), \quad f_r = \frac{L^2 I_o \mu_a}{kT_o}, \quad f_m = \frac{L^2 Q_m}{kT_o}, \\ &x' = \frac{x}{L}, \quad (k_1',k_2') = \frac{L}{\delta}(k_1,k_2), \quad f_b = \frac{\rho_b \omega_{bo} c_b L^2}{k} \end{aligned} \tag{7}$$

In terms of these non-dimensional parameters in (7), the basic Eq. (3) with initial (5) and boundary (6) condition are written as (for its convenience, the dashes are neglected)

$$\frac{\partial^2 T}{\partial x^2} = \left(1 + \tau_o\frac{\partial}{\partial t}\right)\left(1 - \zeta^2\frac{\partial^2}{\partial x^2}\right)\left(\frac{\partial T}{\partial t} - f_b(T_b - T) - f_m - f_r\varphi(x,t)\right), \tag{8}$$

$$T(x,0) = 0, \qquad \frac{\partial T(x,0)}{\partial t} = 0, \tag{9}$$

$$\frac{\partial T(0,t)}{\partial x} = 0, \qquad \frac{\partial T(L,t)}{\partial x} = 0 \tag{10}$$

4. Laplace transforms

The Laplace transform for any functions $F(x,t)$ are defined by Debnath and Bhatta (2014)

$$\bar{F}(x,s) = L[F(x,t)] = \int_0^\infty F(x,t)e^{-st}dt, \tag{11}$$

where s is the Laplace transforms parameter. Hence, by using the initial conditions (9) and the definition (11) in the Eq. (8) therefore the Eqs. (8) and (10) can be replaced as

$$\frac{d^2\bar{T}}{dx^2} = m_1\bar{T} - m_2 - m_3 e^{-k_1 x} - m_4 e^{-k_2 x}, \tag{12}$$

$$\frac{d\bar{T}(0,p)}{dx} = 0, \qquad \frac{d\bar{T}(L,p)}{dx} = 0, \tag{13}$$

where $m_1 = \frac{s_1}{(1+\zeta^2 s_1)}$, $m_2 = \frac{s_2}{(1+\zeta^2 s_1)}$, $m_3 = \frac{s_3(1+\zeta^2 k_1^2)}{(1+\zeta^2 s_1)}$, $m_4 = \frac{s_4(1+k_2^2\zeta^2)}{(1+\zeta^2 s_1)}$, $s_1 = (1+s\tau_o)(f_b + s)$, $s_2 = \frac{f_m}{s}$, $s_3 = \frac{f_r C_1}{s}(1-e^{-s\tau_p})$ and $s_4 = -\frac{f_r C_2}{s}(1-e^{-s\tau_p})$.

The complementary solution $\bar{T}_c$ of the associated homogeneous Eq. (12) can be given by

$$\bar{T}_c(x,s) = A_1 e^{\sqrt{m_1}x} + A_2 e^{-\sqrt{m_1}x}, \tag{14}$$

where A_1 and A_2 are constants. While, the particular solution $\bar{T}_p$ of the non-homogeneous Eq. (12) can be given as

$$\bar{T}_p(x,s) = \frac{m_2}{m_1} + \frac{m_3 e^{-xk_1}}{m_1 - k_1^2} + \frac{m_4 e^{-xk_2}}{m_1 - k_2^2}. \tag{15}$$

Hence, the general solution $\bar{T}$ of the non-homogeneous Eq. (12) are the sum of the above two solutions as follow

$$\bar{T}(x,s) = A_1 e^{\sqrt{m_1}x} + A_2 e^{-\sqrt{m_1}x} + \frac{m_2}{m_1} + \frac{m_3 e^{-xk_1}}{m_1 - k_1^2} + \frac{m_4 e^{-xk_2}}{m_1 - k_2^2}. \tag{16}$$

For the final solution of temperature distribution, a numerical inversion scheme adopted the general solution of the temperature distributions, Stehfest (1970) numerical inversion scheme are taken. In this scheme, the Laplace transforms inverse for $\bar{F}(x,s)$ can be approximated as

$$F(x,t) = \frac{ln(2)}{t}\sum_{n=1}^{N} V_n \bar{F}\left(x, n\frac{ln(2)}{t}\right), \tag{17}$$

where

$$V_n = (-1)^{\left(\frac{N}{2}+1\right)} \sum_{p=\frac{n+1}{2}}^{min\left(n,\frac{N}{2}\right)} \frac{(2p)!\,p^{\left(\frac{N}{2}+1\right)}}{p!\,(n-p)!\left(\frac{N}{2}-p\right)!\,(2n-1)!}, \tag{18}$$

where N is the term number.

5. Evaluation of thermal injuries

The accurate prognosis of thermal injuries to living tissues are valuable for thermotherapy. The evaluations of burn are one of the ultimate great attributes in sciences the bioengineering in biological tissue. To quantify thermal damages, the approach which modified by Moritz-Henriques (Henriques and Moritz 1947, Moritz and Henriques 1947) have employed. The non-dimensional measures of thermal damages index Ω can be defined by

$$\Omega = \int_0^t B e^{-\frac{E_a}{RT}} dt, \tag{19}$$

where R is the universal gas constant, E_a is the activation energy and B is the frequency factor.

6. Conclusions

For numerical example, the biological tissues were the selection for target of numerical estimations to test the performances of proposed bioheat transfers under nonlocal thermal conduction model. The values of constants for skin tissues-like material are given by Noroozi and Goodarzi (2017)

$\rho_b = 1060(kg)(m^{-3})$, $\omega_b = 1.87 \times 10^{-3}(s^{-1})$, $c = 4187\ (J)(kg^{-1})(k^{-1})$,
$T_b = 35.7$ ℃, $\rho = 1000(kg)(m^{-3})$, $c_b = 3860\ (J)(kg^{-1})(k^{-1})$,
$k = 0.628\ (W)(m^{-1})(k^{-1})$, $L = 0.03(m)$, $Q_m = 1.19 \times 10^3(W)(m^{-3})$,
$E_a = 6.28 \times 10^5$ (J)(mol^{-1}), $T_o = 36.5$ ℃, $B = 3.1 \times 10^{98}(s^{-1})$,
$R = 8.313$ (J)(mol^{-1})(k^{-1}).

The calculations have been made by MATLAB(R2019) software and the results are graphically demonstrated as in Figs. 1-6. In these figures, the calculation was carried out when $T_o = 35.7°C$. Fig. 1 displays the variations of temperature with distance x for four different values of nonlocal parameter ($\zeta = 0{,}0.001, 0.0015\ \ 0.002$). Fig. 2 reveals the variations of temperature with the time

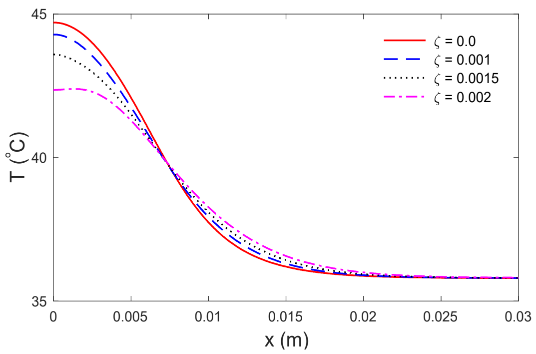

Fig. 1 The variation of temperature along the distance for several values of the nonlocal parameter

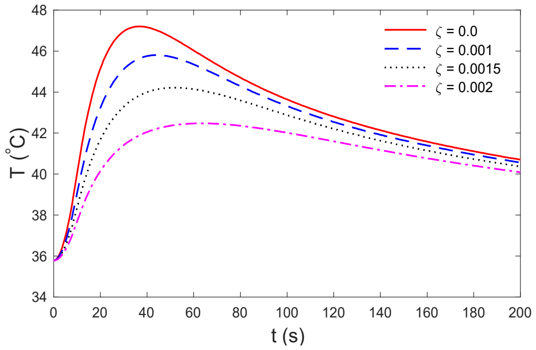

Fig. 2 The history of temperature at skin surface for several values of the nonlocal parameter

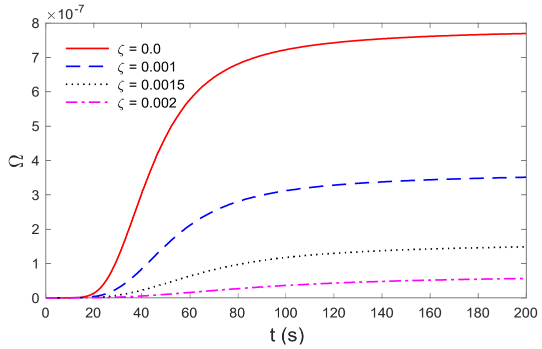

Fig. 3 The variations of thermal damages for several values of the nonlocal parameter at skin surface $x = 0$

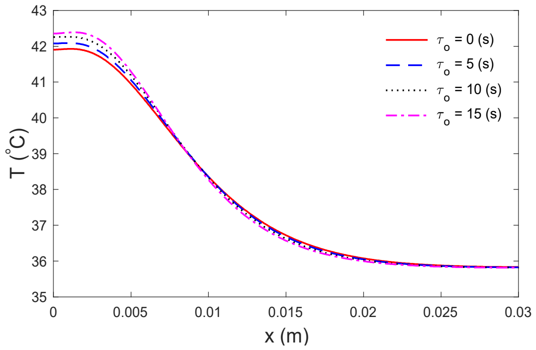

Fig. 4 The variations of temperature along the distance for several values of the thermal relaxation time

t for four different values of nonlocal parameter ($\zeta = 0{,}0.001{,}0.0015{,}0.002$). It is clear from the plot that with an increase in value of nonlocal parameter, there is a decrease in the numerical values of temperature, which shows that nonlocal parameter ζ have decreasing effects on the temperature. Fig. 3 shows the variations of surface thermal damages through the time t for four different values of nonlocal parameter ($\zeta = 0{,}0.001{,}0.0015{,}0.002$). It is observed that the thermal damages have high values under the local model and it decreases with the increasing nonlocal

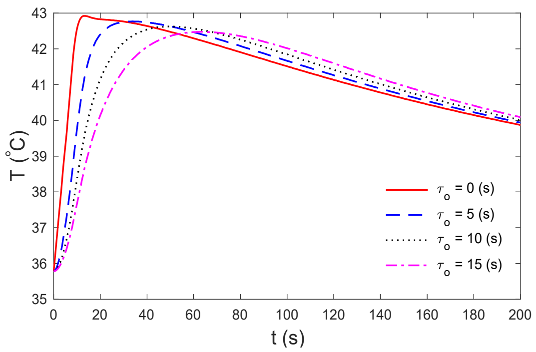

Fig. 5 The history of temperature at skin surface for several values of the thermal relaxation time

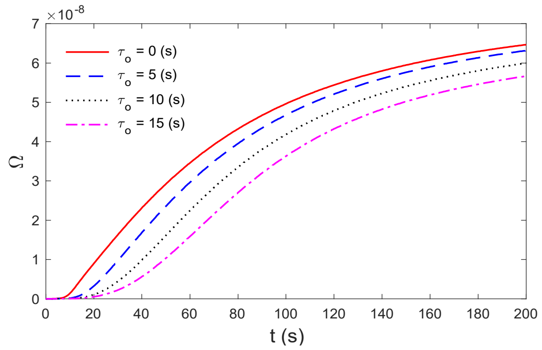

Fig. 6 The variations of thermal damages at skin surface for several values of the thermal relaxation time

parameter. Figs. 4, 5 and 6 show the effects of thermal relaxation time on the temperature and the thermal damages under nonlocal model. It is noticed that the temperature and thermal damages decreases with the increasing of thermal relaxation time. As expected, the nonlocal parameter has great effects on the distributions of field quantities.

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