

## Research Article

# The Skin Tissue of the Human Head Subjected to Thermal Diffusion

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We consider a problem of skin tissue of the human head subjected to thermal diffusion with relaxation time. The bounding surface of the tissue of the human head is subjected to a thermal shock. The chemical potential is also assumed to be a known function of time on the bounding plane. Laplace transform techniques are used and the results are obtained numerically using a numerical method for the inversion of the Laplace transform based on Tzou method. The temperature distribution and the concentration distribution are obtained and represented in figures. According to the results, the values of the time and the distance have significant effects on the temperature increment and the concentration. The values of the temperature increment and the concentration increase when the time increases and decrease when the distance increases.

## 1. Introduction

Biomechanics is the area of science where the laws, principles, and methods of mechanics are applied to the structure and function of the human body. Mechanics can be divided into two categories: statics, which is the study of stationary objects, and dynamics, which is the study of moving objects [1].

Some human trial studies have expressed that, in the short term, being subjected to cellular phones frequencies can cause such problems like exciting the brain cells when subjected to a wave [1], the possible occurrence of cataracts with continuous exposure weakening the neural behavioral and cognitive functioning, and possibly a disruption in the functionality of the nervous system [1]. Lindholm et al. [2] conducted a human trial to see the effects of short term radio frequency when the electromagnetic fields are subjected to preadolescents.

Ferreri et al. studied the mobile phone emissions and human brain excitability [3] and Keetley et al. studied the neuropsychological sequel of digital mobile phone exposure in humans [4], while Lin discussed the cataracts and personal communication radiation [5]. The effects of electromagnetic radiation of mobile phones on the central nervous system have been studied by Hossmann and Hermann [6] and the

thermal effects of radiation from cellular telephones have been studied by Wainwright [7].

The most important work regarding specific absorption rate and temperature distributions in human head subjected to mobile phone radiation at different frequencies was introduced by Wessapan et al. [8]. Elwassif et al. constructed the bioheat transfer model of deep brain stimulation-induced temperature changes [9]. Ley and Bayazitoglu analyzed the brain temperature distribution during deep hypothermic circulatory arrest in humans [10] and got the effect of physiology on the temperature distribution of a layered head with external convection [1].

The thermal wave model of bioheat transfer (TWMBT) equation is an energy balance equation that includes the heat caused by conduction, convection, metabolic heat generation, and the heat produced by radiation due to the cellular frequency [11]. The model incorporates a relaxation time to account for the lag time it takes for the radio frequency wave to respond to the heat penetrating through the tissue, that is, heat flux associated with the tissues [12, 13]. Biological experimental studies have shown that this value can range from 15 to 30 s [12, 14–20]. An additional relaxation time accommodating the phase lag of the temperature gradient is analytically studied.

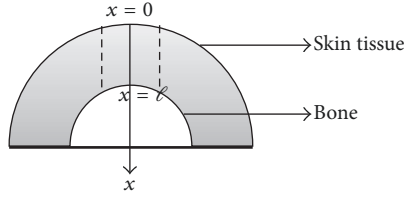


FIGURE 1: The human head.

Morimoto et al. [21] studied the time constants of the temperature elevations in human head and body models exposed to simulated radiation from dipole antennas, electromagnetic beams, and plane waves within frequency range considered to be from 1 to 30 GHz. Tang et al. discussed the thermal and vibrational characterization of human skin to find suitable and reproducible biomarkers for further clinical studies on intrinsic and extrinsic aging of dermis [22].

## 2. Formulation of the Problem

We consider a small bounded cross section of the skin tissue of the human head occupies the region  $0 \leq x \leq \ell$  subjected to thermal diffusion (such as a gas) in the upper plane of the skin tissue  $x = 0$  as in Figure 1, and this tissue is initially quiescent.

The heat transfer in living tissue is accompanied by blood perfusion and metabolic heat generation; the bioheat equation takes the following form [4]:

$$\begin{aligned} K \frac{\partial^2 T_s}{\partial x^2} &= \left( \frac{\partial}{\partial t} + \tau_1 \frac{\partial^2}{\partial t^2} \right) (\rho_c T_s + \alpha C) \\ &+ \left( 1 + \tau_1 \frac{\partial}{\partial t} \right) (\rho_p \omega_p c_p (T_s - T_b) - Q_{\text{met}} - Q_{\text{out}}), \end{aligned} \quad (1)$$

where  $T_s = T_s(x, t)$  is the temperature of the tissue,  $T_b$  is the blood temperature (constant),  $K$  is the thermal conductivity,  $\rho$  is the density of the skin tissue,  $\rho_p$  is the blood mass density,  $c_p$  is the specific heat of the blood,  $c_e$  is the specific heat of the skin tissue,  $\omega_p$  is the blood perfusion rate,  $Q_{\text{out}}$  is the external heat source,  $Q_{\text{met}}$  is the heat source due to metabolic heating,  $\alpha$  is a measure of thermodiffusion effect,  $\tau_1$  is the relaxation time of the skin tissue, and  $C = C(x, t)$  is the concentration of the diffusive material in the skin tissue.

The diffusion equations take the form

$$D \frac{\partial^2 P}{\partial x^2} = \left( \frac{\partial}{\partial t} + \tau_2 \frac{\partial^2}{\partial t^2} \right) C, \quad (2)$$

where  $\tau_2$  is the diffusion relaxation time,  $D$  is the diffusion coefficient, and  $P = P(x, t)$  is the chemical potential which satisfies

$$P = \beta C - \alpha (T_s - T_p), \quad (3)$$

where  $\beta$  is a measure of diffusive effect.

To simplify the equations in (1)–(3), we will use the following nondimension variables:

$$\begin{aligned} x' &= \sqrt{\frac{\omega_p \rho_p c_p}{K}} x, \\ (t', \tau_1', \tau_2') &= \frac{\omega_p \rho_p c_p}{\rho c} (t, \tau_1, \tau_2), \\ P' &= \frac{P}{\alpha T_p}, \\ C' &= \frac{\beta}{\alpha T_p} C, \\ \theta &= \frac{T_s - T_p}{T_p}, \\ (Q'_{\text{met}}, Q'_{\text{out}}) &= \frac{(Q_{\text{met}}, Q_{\text{out}})}{\omega_p \rho_p c_p T_p}. \end{aligned} \quad (4)$$

After applying the dimensionless variables, (1)–(3) take the forms

$$\begin{aligned} \frac{\partial^2 \theta}{\partial x'^2} &= \left( \frac{\partial}{\partial t'} + \tau_1' \frac{\partial^2}{\partial t'^2} \right) (\theta + a_1 C) \\ &+ \left( 1 + \tau_1' \frac{\partial}{\partial t'} \right) (\theta - Q_{\text{met}} - Q_{\text{out}}), \end{aligned} \quad (5)$$

$$\frac{\partial^2 P}{\partial x'^2} = a_2 \left( \frac{\partial}{\partial t'} + \tau_2' \frac{\partial^2}{\partial t'^2} \right) C, \quad (6)$$

$$P = C - \theta, \quad (7)$$

where  $a_1 = \alpha^2 / \rho \beta c$  and  $a_2 = K / \rho \beta c D$ .

We dropped the prime for simplicity.

We will consider the tissue has no external heat source ( $Q_{\text{out}} = 0$ ) and the heat source due to metabolic heating  $Q_{\text{met}}$  is constant; then we get

$$\begin{aligned} \frac{\partial^2 \theta}{\partial x'^2} &= \left( \frac{\partial}{\partial t} + \tau_1 \frac{\partial^2}{\partial t^2} \right) (\theta + a_1 C) \\ &+ \left( 1 + \tau_1 \frac{\partial}{\partial t} \right) (\theta - Q_{\text{met}}). \end{aligned} \quad (8)$$

By eliminating  $P$  between (6) and (7), we obtain

$$\frac{\partial^2 C}{\partial x'^2} - \frac{\partial^2 \theta}{\partial x'^2} = a_2 \left( \frac{\partial}{\partial t} + \tau_2 \frac{\partial^2}{\partial t^2} \right) C. \quad (9)$$

We will apply Laplace transform on (6) and (8) which is defined as

$$\bar{f}(x, s) = \int_0^\infty f(x, t) e^{-st} dt, \quad s > 0, \quad (10)$$

where  $C(x, t)|_{t=0} = \theta(x, t)|_{t=0} = \partial C(x, t) / \partial t|_{t=0} = \partial \theta(x, t) / \partial t|_{t=0} = 0$ .

Hence, we get

$$\frac{\partial^2 \bar{\theta}}{\partial x^2} = (1 + \tau_1 s)(1 + s)\bar{\theta} + a_1(s + \tau_1 s^2)\bar{C} - \frac{Q_{\text{met}}}{s}, \quad (11)$$

$$\frac{\partial^2 \bar{C}}{\partial x^2} - \frac{\partial^2 \bar{\theta}}{\partial x^2} = a_2(s + \tau_2 s^2)\bar{C}.$$

By eliminating  $\bar{\theta}$  between the equations in (11), we obtain

$$\left[ \frac{\partial^4}{\partial x^4} - (\alpha_1 + \alpha_2 + \alpha_3) \frac{\partial^2}{\partial x^2} + \alpha_1 \alpha_3 \right] \bar{C} = 0, \quad (12)$$

and by eliminating  $\bar{C}$  between the equations in (11), we get

$$\left[ \frac{\partial^4}{\partial x^4} - (\alpha_1 + \alpha_2 + \alpha_3) \frac{\partial^2}{\partial x^2} + \alpha_1 \alpha_3 \right] \bar{\theta} = \alpha_4, \quad (13)$$

where  $\alpha_1 = (1 + \tau_1 s)(1 + s)$ ,  $\alpha_2 = a_1(s + \tau_1 s^2)$ ,  $\alpha_3 = a_2(s + \tau_2 s^2)$ ,  $\alpha_4 = \alpha_3 Q_{\text{met}}/s$ .

We can write the general solutions of (12) and (13) in the forms

$$\begin{aligned} \bar{\theta}(x, s) &= \gamma_1 e^{\lambda_1 x} + \gamma_2 e^{\lambda_2 x} + \beta_1 e^{-\lambda_1 x} + \beta_2 e^{-\lambda_2 x} + \frac{\alpha_4}{M}, \\ \bar{C}(x, s) &= \left( \frac{\lambda_1^2 - \alpha_3}{\lambda_1^2} \right) \gamma_1 e^{\lambda_1 x} + \left( \frac{\lambda_2^2 - \alpha_3}{\lambda_2^2} \right) \gamma_2 e^{\lambda_2 x} \\ &\quad + \left( \frac{\lambda_1^2 - \alpha_3}{\lambda_1^2} \right) \beta_1 e^{-\lambda_1 x} \\ &\quad + \left( \frac{\lambda_2^2 - \alpha_3}{\lambda_2^2} \right) \beta_2 e^{-\lambda_2 x}, \end{aligned} \quad (14)$$

where  $\gamma_1 = \gamma_1(s)$ ,  $\gamma_2 = \gamma_2(s)$ ,  $\beta_1 = \beta_1(s)$ ,  $\beta_2 = \beta_2(s)$  are parameters and  $\pm \lambda_1(s)$ ,  $\pm \lambda_2(s)$  are the roots of the characteristic equation

$$\lambda^4 - L\lambda^2 + M = 0, \quad (15)$$

where  $L = (\alpha_1 + \alpha_2 + \alpha_3)$ ,  $M = \alpha_1 \alpha_3$ .

To get the parameters  $\gamma_1, \gamma_2, \beta_1, \beta_2$ , we will consider the upper plane of the tissue  $x = 0$  is subjected to thermal and chemical potential shock which depends on time only as follows:

$$\begin{aligned} \theta(0, t) &= f(t), \\ \theta(\ell, t) &= 0, \\ P(0, t) &= g(t), \\ P(\ell, t) &= 0. \end{aligned} \quad (16)$$

Applying Laplace transform on conditions (16), we get

$$\begin{aligned} \bar{\theta}(0, s) &= \bar{f}(s), \\ \bar{P}(0, s) &= \bar{g}(s). \end{aligned} \quad (17)$$

By using (7) and (17), we get

$$\bar{C}(0, s) = \bar{f}(s) + \bar{g}(s). \quad (18)$$

Applying the conditions in (17) and (18) on (14), we obtain the following system of linear equations:

$$\begin{aligned} \gamma_1 + \gamma_2 + \beta_1 + \beta_2 &= \bar{f}(s) - \frac{\alpha_4}{M}, \\ \left( \frac{\lambda_1^2 - \alpha_3}{\lambda_1^2} \right) \gamma_1 + \left( \frac{\lambda_2^2 - \alpha_3}{\lambda_2^2} \right) \gamma_2 + \left( \frac{\lambda_1^2 - \alpha_3}{\lambda_1^2} \right) \beta_1 \\ &\quad + \left( \frac{\lambda_2^2 - \alpha_3}{\lambda_2^2} \right) \beta_2 = \bar{f}(s) + \bar{g}(s), \\ \lambda_1 \gamma_1 e^{\lambda_1 \ell} + \lambda_2 \gamma_2 e^{\lambda_2 \ell} - \lambda_1 \beta_1 e^{-\lambda_1 \ell} - \lambda_2 \beta_2 e^{-\lambda_2 \ell} &= 0, \\ \left( \frac{\lambda_1^2 - \alpha_3}{\lambda_1} \right) \gamma_1 e^{\lambda_1 \ell} + \left( \frac{\lambda_2^2 - \alpha_3}{\lambda_2} \right) \gamma_2 e^{\lambda_2 \ell} \\ &\quad - \left( \frac{\lambda_1^2 - \alpha_3}{\lambda_1} \right) \beta_1 e^{-\lambda_1 \ell} - \left( \frac{\lambda_2^2 - \alpha_3}{\lambda_2} \right) \beta_2 e^{-\lambda_2 \ell} = 0. \end{aligned} \quad (19)$$

By solving the system above, we get

$$\begin{aligned} \gamma_1 &= \frac{\lambda_1^2 [\alpha_3 (\alpha_4 s - \bar{f}(s) M) - \lambda_2^2 (\alpha_4 s + \bar{g}(s) M)]}{\alpha_3 M (\lambda_2^2 - \lambda_1^2) (1 + e^{2\ell \lambda_1})}, \\ \gamma_2 &= \frac{\lambda_2^2 [\alpha_3 (\alpha_4 s - \bar{f}(s) M) - \alpha_1^2 (\alpha_4 s + \bar{g}(s) M)]}{\alpha_3 M (\lambda_1^2 - \lambda_2^2) (1 + e^{2\ell \lambda_2})}, \\ \beta_1 &= \frac{\lambda_1^2 e^{2\ell \lambda_1} [\alpha_3 (\alpha_4 s - \bar{f}(s) M) - \alpha_2^2 (\alpha_4 s + \bar{g}(s) M)]}{\alpha_3 M (\lambda_2^2 - \lambda_1^2) (1 + e^{2\ell \lambda_1})}, \\ \beta_2 &= \frac{\lambda_2^2 e^{2\ell \lambda_2} [\alpha_3 (\alpha_4 s - \bar{f}(s) M) - \lambda_1^2 (\alpha_4 s + \bar{g}(s) M)]}{\alpha_3 M (\lambda_1^2 - \lambda_2^2) (1 + e^{2\ell \lambda_2})}. \end{aligned} \quad (20)$$

Thus, we have the solution of the problem in the Laplace transform domain in the form

$$\begin{aligned} \bar{\theta}(x, s) &= \frac{\lambda_2^2 [\alpha_3 (\alpha_4 s - \bar{f}(s) M) - \alpha_1^2 (\alpha_4 s + \bar{g}(s) M)]}{\alpha_3 M (\lambda_1^2 - \lambda_2^2) (1 + e^{2\ell \lambda_2})} \\ &\quad \cdot e^{\lambda_1 x} \\ &\quad + \frac{\lambda_1^2 [\alpha_3 (\alpha_4 s - \bar{f}(s) M) - \alpha_2^2 (\alpha_4 s + \bar{g}(s) M)]}{\alpha_3 M (\lambda_1^2 - \lambda_2^2) (1 + e^{2\ell \lambda_2})} e^{\lambda_2 x} \\ &\quad + \frac{\lambda_1^2 e^{2\ell \lambda_1} [\alpha_3 (\alpha_4 s - \bar{f}(s) M) - \alpha_2^2 (\alpha_4 s + \bar{g}(s) M)]}{\alpha_3 M (\lambda_2^2 - \lambda_1^2) (1 + e^{2\ell \lambda_1})} \\ &\quad \cdot e^{-\lambda_1 x} \\ &\quad + \frac{\lambda_2^2 e^{2\ell \lambda_2} [\alpha_3 (\alpha_4 s - \bar{f}(s) M) - \lambda_1^2 (\alpha_4 s + \bar{g}(s) M)]}{\alpha_3 M (\lambda_1^2 - \lambda_2^2) (1 + e^{2\ell \lambda_2})} \\ &\quad \cdot e^{-\lambda_2 x} + \frac{\alpha_4}{M}, \end{aligned}$$

$$\begin{aligned}
\bar{C}(x, s) = & \left( \frac{\lambda_1^2 - \alpha_3}{\lambda_1^2} \right) \\
& \cdot \frac{\lambda_1^2 [\alpha_3 (\alpha_4 s - \bar{f}(s) M) - \lambda_2^2 (\alpha_4 s + \bar{g}(s) M)]}{\alpha_3 M (\lambda_2^2 - \lambda_1^2) (1 + e^{2\ell\lambda_1})} e^{\lambda_1 x} \\
& + \left( \frac{\lambda_2^2 - \alpha_3}{\lambda_2^2} \right) \\
& \cdot \frac{\lambda_2^2 [\alpha_3 (\alpha_4 s - \bar{f}(s) M) - \alpha_1^2 (\alpha_4 s + \bar{g}(s) M)]}{\alpha_3 M (\lambda_1^2 - \lambda_2^2) (1 + e^{2\ell\lambda_2})} e^{\lambda_2 x} \\
& + \left( \frac{\lambda_1^2 - \alpha_3}{\lambda_1^2} \right) \\
& \cdot \frac{\lambda_1^2 e^{2\ell\lambda_1} [\alpha_3 (\alpha_4 s - \bar{f}(s) M) - \alpha_2^2 (\alpha_4 s + \bar{g}(s) M)]}{\alpha_3 M (\lambda_2^2 - \lambda_1^2) (1 + e^{2\ell\lambda_1})} \\
& \cdot e^{-\lambda_1 x} + \left( \frac{\lambda_2^2 - \alpha_3}{\lambda_2^2} \right) \\
& \cdot \frac{\lambda_2^2 e^{2\ell\lambda_2} [\alpha_3 (\alpha_4 s - \bar{f}(s) M) - \lambda_1^2 (\alpha_4 s + \bar{g}(s) M)]}{\alpha_3 M (\lambda_1^2 - \lambda_2^2) (1 + e^{2\ell\lambda_2})} \\
& \cdot e^{-\lambda_2 x}.
\end{aligned} \tag{21}$$

### 3. Inverse Laplace Transforms

To get solutions in the time domain, the Riemann-sum approximation method is used to obtain the numerical results. In this method, any function in Laplace domain can be inverted to the time domain as follows:

$$h(t) = \frac{e^{\kappa t}}{t} \left[ \frac{1}{2} \bar{h}(\kappa) + \operatorname{Re} \sum_{n=1}^N (-1)^n \bar{h} \left( \kappa + \frac{in\pi}{t} \right) \right], \tag{22}$$

where  $\operatorname{Re}$  is the real part and  $i$  is the imaginary number unit. For faster convergence, many numerical experiments have shown that the value of  $\kappa$  satisfies the relation  $\kappa t \approx 4.7$ .

We considered that the functions on the boundary in (16) will be defined as a shock in the following forms:

$$f(t) = g(t) = \omega H(t), \tag{23}$$

where  $\omega$  is constant (the intensity of the shock) and  $H(t)$  is the Heaviside unit step function.

By using Laplace transform, (23) takes the form

$$\bar{f}(s) = \bar{g}(s) = \frac{\omega}{s}. \tag{24}$$

### 4. The Numerical Values

The following properties of a skin tissue are used in the numerical analysis [1–5]:

$$\rho = 1190 \text{ kg/m}^3,$$

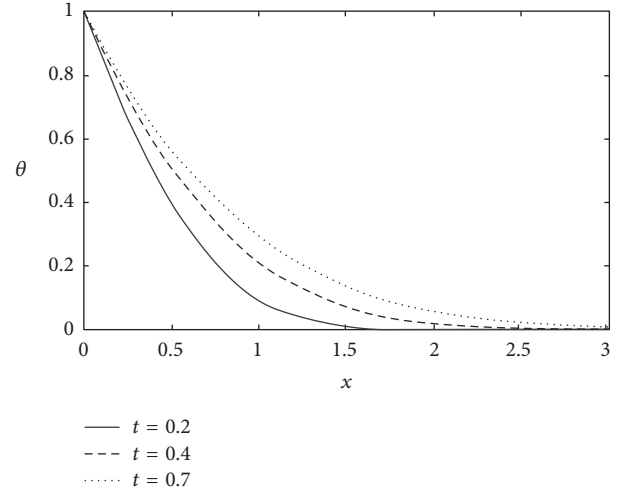


FIGURE 2: The temperature increment distribution at different values of time.

$$K = 0.235 \text{ W/mK},$$

$$c_e = 3600 \text{ J/kg K},$$

$$\rho_p = 1060 \text{ kg/m}^3,$$

$$c_p = 3770 \text{ J/kg K}$$

$$\omega_p = 0.5 \text{ kg/m}^3 \text{ s},$$

$$Q_m = 33800 \text{ W/m}^3,$$

$$q_o = 5000 \text{ W/m}^3,$$

$$T_p = 310 \text{ K},$$

$$\ell = 0.002 \text{ m},$$

$$D = 0.85 \times 10^{-8},$$

$$\alpha = 1.2 \times 10^4,$$

$$\beta = 0.9 \times 10^6,$$

$$Q_{\text{met}} = 5.46 \times 10^{-5},$$

$$\tau_1 = 0.002,$$

$$\tau_2 = 0.02,$$

$$a_1 = 32.098,$$

$$a_2 = 7.171 \times 10^{-6}.$$

(25)

Figures 2 and 3 represent the temperature increment distribution and the concentration distribution, respectively, with a wide range of the thickness of the layer of the tissue when  $0 \leq x \leq 3$  and at different values of time  $t = (0.2, 0.4, 0.7)$ . Those figures show that the value of the time has a significant effect on the temperature increment and

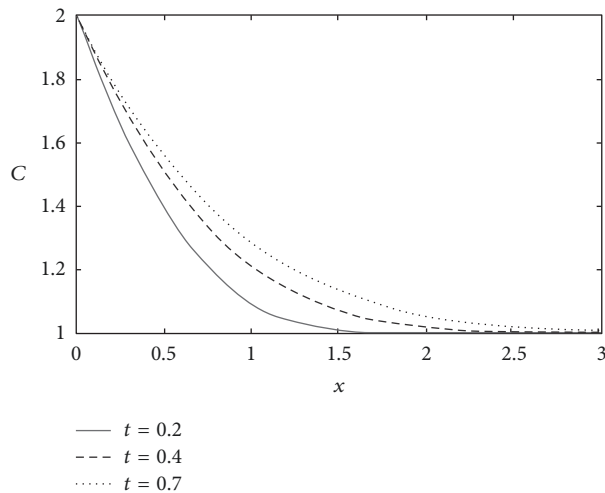


FIGURE 3: The concentration distribution at different values of time.

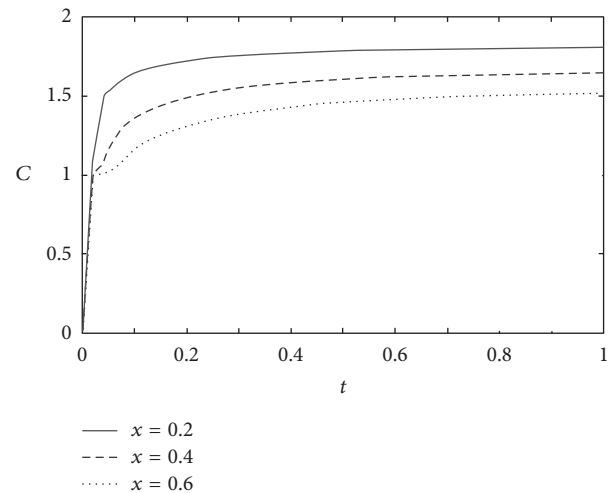


FIGURE 5: The concentration distribution at different values of distance.

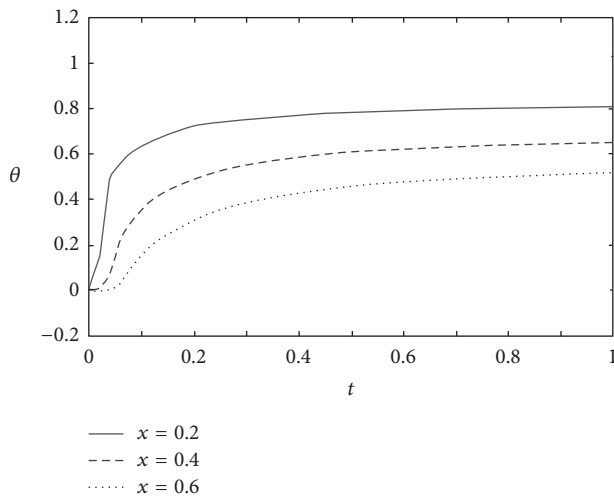


FIGURE 4: The temperature increment distribution at different values of distance.

the concentration. The values of the temperature increment and the concentration increase when the time increases and decrease when the distance increases. The thermal and the concentration waves have finite speeds of wave propagation which agrees with the real physical behavior.

Figures 4 and 5 represent the temperature increment distribution and the concentration distribution, respectively, with a wide range of the time when  $0 \leq t \leq 1.0$  and at different values of distance  $x = (0.2, 0.4, 0.6)$ . Those figures show that the value of the distance has a significant effect on the temperature increment and the concentration. The values of the temperature increment and the concentration increase when the distance decreases and go to the steady state position when the time increases. Moreover, the steady state positions start first in the nearest distance. The steady states of the thermal wave and the concentration wave occur almost at the same instance.

## Conflicts of Interest

The funding mentioned in Acknowledgments did not lead to any conflicts of interest regarding the publication of this manuscript.

## Acknowledgments

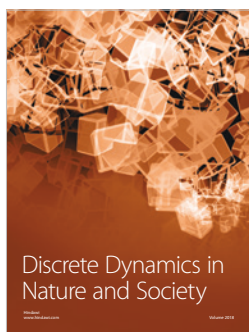
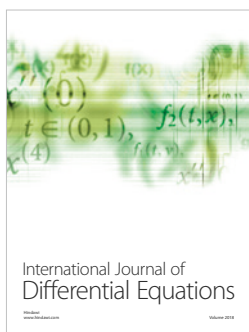
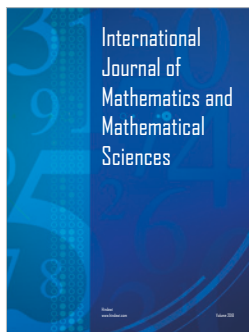
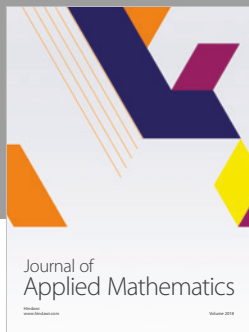
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