Lectures Series in Propagation of Thermoelastic Waves on Skin Tissue

Lecture 1

hyperthermia

Dr. Najat A. Al-Ghamdi

Lecturer,

at Umm Al-Qura University, Dept. of Mathematics, Faculty of Sciences, Makkah, KSA

(E-mail: najatalghamdi@gmail.com)

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NONLINEAR BEHAVIOR AND THERMAL DAMAGE OF THERMAL LAGGING IN CONCENTRIC LIVING TISSUES SUBJECTED TO GAUSSIAN DISTRIBUTION SOURCE

Hamdy M. Youssef [1, 2], Najat A. Al-Ghamdi[3]
[1] Alexandria University, Dept. of Mathematics, Faculty of Education, Alexandria, Egypt
[2]Umm Al-Qura University, Dept. of Mechanics, Faculty of Engineering, Makkah, KSA
E-mail: youssefanne2005@gmail.com
[3] Umm Al-Qura University, Dept. of Mathematics, Faculty of Science, Makkah, KSA
E-Mail: najatalghamdi@gmail.com

ID: 4642

Certificate of Participation/Presentation

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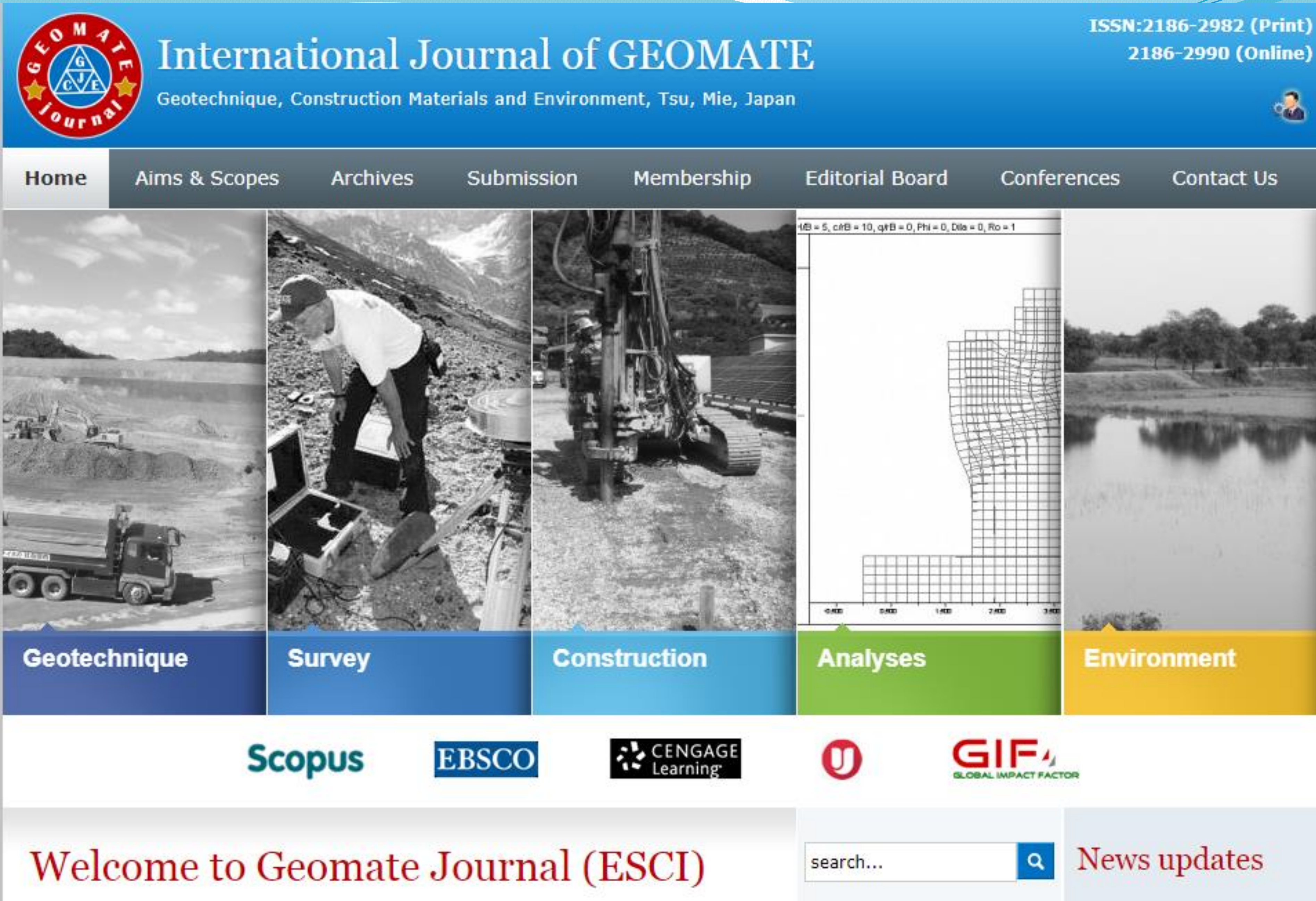
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Topics

Definition

- Hyper=Over
- Therm=heat
- ia=Suffix

- Hyperthermia is elevated body temperate to high temperatures *(up to 42°C) to* damage and kill cancer cells.
- It (also called thermal therapy or thermotherapy) is a kind of medical treatment in cancer therapy.

Important of Hyperthermia

- Hyperthermia is almost used with other forms of cancer therapy, such as radiation therapy and chemotherapy to treat cancer.
- Thermotherapy make cancer cells more motivate to radiation or harm other cancer cells that radiation cannot damage .

Purpose

- The goal of thermotherapy is to alter tissue temperature in a targeted region over time.
- The majority of thermotherapies are designed to deliver the thermal therapy to a target tissue volume with minimal impact on surrounding tissues.

feedback

Q1: What is hyperthermia?

a- fever
b- thermotherapy
c- thermoelastic

Q2: We can use hyperthermia with:

a- radiation and drugs for cancer.
b- cancer surgery.
c- radiation for cancer only.

Q3: The majority of thermotherapy is:

a- distributing the heat energy to the diseased tissue.
b- distributing the heat energy to the diseased tissue and surrounding it.
c- distributing the heat energy to the diseased tissue without affecting the healthy tissue.

Relationship between Hyperthermia and Mathematic

- **In 1948,** Pennes used mathematical model to describe temperature distribution in the living biological tissues. The model known as **the Pennes bio-heat transfer equation (PBT)**, and it remains used today.
- The connection between arterial blood and the heat transfer in a living tissue are taken.
- The Pennes bio-heat transfer equation (PBT) is based on **the classical Fourier's law**, taken into account a blood perfusion term, which is proportional to the volumetric rate of blood perfusion and the difference between the average arterial blood and tissue temperatures.
- **In 2006,** Youssef modified the theory of heat conduction which have been investigated by Chen and Gurtin, which depends upon two distinct temperatures, the conductive temperature and the thermodynamic temperature and the difference between these two temperatures is proportional to the heat supply.

Formulation of the Problem

In a magnetic fluid hyperthermia, magnetic particles are injected into at the center of tumor surrounded by the normal tissue and radially diffuse from the injected point in Gaussian distribution. For excitation of an alternating magnetic field, magnetic particles become the space-dependent heating sources in the tissue.

For t > o the heat is transferring in the radius direction symmetrically. The small tumor is regarded as a solid sphere with the radius *R*

The temperature distribution in the tumor tissue $0 \le r \le R$

The temperature distribution in the normal tissue $R \le r < h$

The energy conservation equation of bio-heat transfer is described in the context of the two-temperature model as:

$$\rho_i C_i \frac{\partial T_i^D(r,t)}{\partial t} = -\nabla \cdot q_i(r,t) - w_{bi} C_b \rho_p \left(T_i^D(r,t) - T_0\right) + \left(q_{mi}(r,t) + q_{ri}(r,t)\right), \quad i = 1,2$$

$$T_i^C(r,t) - T_i^D(r,t) = \beta_i \nabla^2 T_i^C(r,t), \quad i = 1,2$$

The second order DPL model can be rewritten as:

$$\left(1 + \tau_{qi}\frac{\partial}{\partial t} + \alpha_1 \frac{\tau_{qi}^2}{2}\frac{\partial^2}{\partial t^2}\right)\nabla \cdot q(r,t) = -K_i\left(1 + \tau_{Ti}\frac{\partial}{\partial t} + \alpha_2 \frac{\tau_{Ti}^2}{2}\frac{\partial^2}{\partial t^2}\right)\nabla^2 T_i^c(r,t), \quad i = 1,2$$

$$\left.\begin{array}{l} \text{1- DPL type I } (\alpha_1 = \alpha_2 = 0.0) \\ \text{2- DPL type II } (\alpha_1 = 1,\ \alpha_2 = 0) \\ \text{3- DPL type III } (\alpha_1 = \alpha_2 = 1) \end{array}\right\} \quad \left.\begin{array}{l} \beta_i = 0 \\ \beta_i \neq 0 \end{array}\right\} \begin{array}{l} \text{One-Temperature} \\ \text{Two-Temperature} \end{array}$$

Consider the following functions:

$$\theta(r,t)_i = r\left(T_i^{\,C} - T_0\right),\ \ \varphi_i(r,t) = r\left(T_i^{\,D} - T_0\right),\ i = 1,2$$

Hence, we have

$$K_i\left(1 + \tau_{Ti}\frac{\partial}{\partial t} + \alpha_1\frac{\tau_{Ti}^2}{2}\frac{\partial^2}{\partial t^2}\right)\left(\frac{\partial^2 \varphi_i(r,t)}{\partial r^2}\right) =$$

$$\left(1 + \tau_{qi}\frac{\partial}{\partial t} + \alpha_2\frac{\tau_{qi}^2}{2}\frac{\partial^2}{\partial t^2}\right)\left(\begin{array}{l}\rho_i C_i\dfrac{\partial \theta_i(r,t)}{\partial t} + w_{bi}\rho_b C_b \theta_i(r,t) - \\ r q_{mi}(r,t) - r q_{ri}(r,t)\end{array}\right),\ \ i = 1,2.$$

$$\theta_i(r,t) = \varphi_i(r,t) - \beta_i\frac{\partial^2 \varphi_i(r,t)}{\partial r^2},\ \ i = 1,2$$


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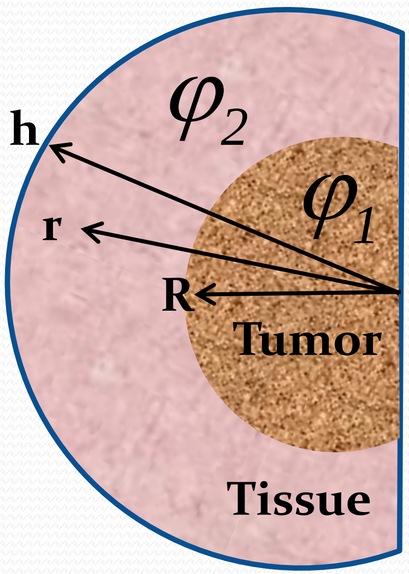
Tumor

Gaussian distribution $$q_{ri}(r,t) = q_0 H(t) e^{-(r_i^2/r_0)}, \; i = 1,2$$



$$\varphi_1(r,t)\Big|_{r=0} = 0, \; \varphi_1(R,t) = \varphi_2(R,t)$$

$$\frac{K_1}{r}\frac{\partial \varphi_1(r,t)}{\partial r}\bigg|_{r=R} = \frac{K_2}{r}\frac{\partial \varphi_2(r,t)}{\partial r}\bigg|_{r=R}$$

$$\varphi_2(r,t)\Big|_{r=h} = 0$$

r_0 is a parameter which determines how far the diffusion of the injected magnetic particles occurs

q_0 determines the maximum strength of the spatial heating source at the injection site

$H(t)$ is the unit step function

Applying Laplace transform $\overline{f}(s) = \int_0^\infty f(t) e^{-st} dt$

Thus, we get

$$\frac{\partial^2 \overline{\varphi}_i}{\partial r^2} - \lambda_i^2 \overline{\varphi}_i = -f_i r, \; i = 1,2$$

where

$$\lambda_i^2 = \frac{h_{qi}\left(\rho_i C_i\, s + w_{bi} C_b \rho_p\right)}{K_i h_{Ti} + \beta_i h_{qi}\left(\rho_i C_i\, s + w_{bi} C_b \rho_p\right)}, \qquad f_i = \frac{\overline{q}_{mi} + h_{qi}\overline{q}_{ri}}{\left[K_i h_{Ti} + \beta_i h_{qi}\left(\rho_i C_i\, s + w_{bi} C_b \rho_p\right)\right]}$$

$$h_{Ti} = \left(1 + s\tau_{Ti} + \alpha_1 \frac{s^2 \tau_{Ti}^2}{2}\right), \; h_{qi} = \left(1 + s\tau_{qi} + \alpha_2 \frac{s^2 \tau_{qi}^2}{2}\right)$$

$$\overline{q}_{ri}(r,s) = \frac{q_0}{s} e^{-(r_i^2/r_0)}, \qquad \overline{q}_{mi} = \frac{q_{mi}}{s}$$

The general solution

$$\bar{\varphi}_1(r,s) = c_{11}e^{-\lambda_1 r} + c_{12}e^{\lambda_1 r} + \frac{f_1}{\lambda_1^2}r, \;\; 0 \le r \le R,$$

$$\bar{\varphi}_2(r,s) = c_{21}e^{-\lambda_2 r} + c_{22}e^{\lambda_2 r} + \frac{f_2}{\lambda_2^2}r, \;\; R \le r < h$$

Apply the boundary and the continuity conditions

$$\left.\bar{\varphi}_1(r,s)\right|_{r=0} = 0, \;\; \bar{\varphi}_1(R,s) = \bar{\varphi}_2(R,s),$$

$$\left.\frac{K_1}{r}\frac{\partial\bar{\varphi}_1(r,s)}{\partial r}\right|_{r=R} = \left.\frac{K_2}{r}\frac{\partial\bar{\varphi}_2(r,s)}{\partial r}\right|_{r=R},$$

$$\left.\bar{\varphi}_2(r,s)\right|_{r=h} = 0$$

The thermal damage

Moritz and Henriques proposed that skin damage could be represented as a chemical rate process, which is calculated by using a first order Arrhenius rate equation. The measure of thermal damage Ω was introduced, and its rate were postulated to satisfy

$$\kappa(T) = \frac{d\Omega}{dt} = A\exp\left(-\frac{E_a/\eta}{T}\right) \Rightarrow \qquad \Omega = A\int_0^t \exp\left(-\frac{E_a/\eta}{T}\right)dt$$

A is a material parameter (frequency factor)

E_a is the activation energy

η is the universal gas constant

T is the Kelvin temperature

Numerical Results

To determine the distribution $\varphi_i\left(r,t\right)$ of each layer, a Riemann-sum approximation method will be used to obtain the numerical results in which, any function in Laplace domain can be inverted to the time domain as (Tzou Method):

$$f(t)=\frac{e^{\varepsilon t}}{t}\left[\frac{1}{2}\,\bar{f}\left(\varepsilon\right)+\mathrm{Re}\sum_{n=1}^{N}\left(-1\right)^{n}\,\bar{f}\left(\varepsilon+\frac{i\,n\pi}{t}\right)\right]$$

For faster convergence $\varepsilon t \approx 4.7$

The value of $\dfrac{\varphi_1\left(r,t\right)}{r}$ $at\ r=0$ is undefined and it must be replaced by its limit as

$$\left.\frac{\varphi_1\left(r,t\right)}{r}\right|_{r=0}=\lim_{r\to 0}\frac{\varphi_1\left(r,t\right)}{r}=\left.\frac{d\varphi_1\left(r,t\right)}{dr}\right|_{r=0}$$

$$q_0 = 6.15\times10^6 \ W/m^3$$

$$\rho_b C_b = 4.18\times10^6 \ J/m^3/K$$

$$r_0 = 0.75\times R$$

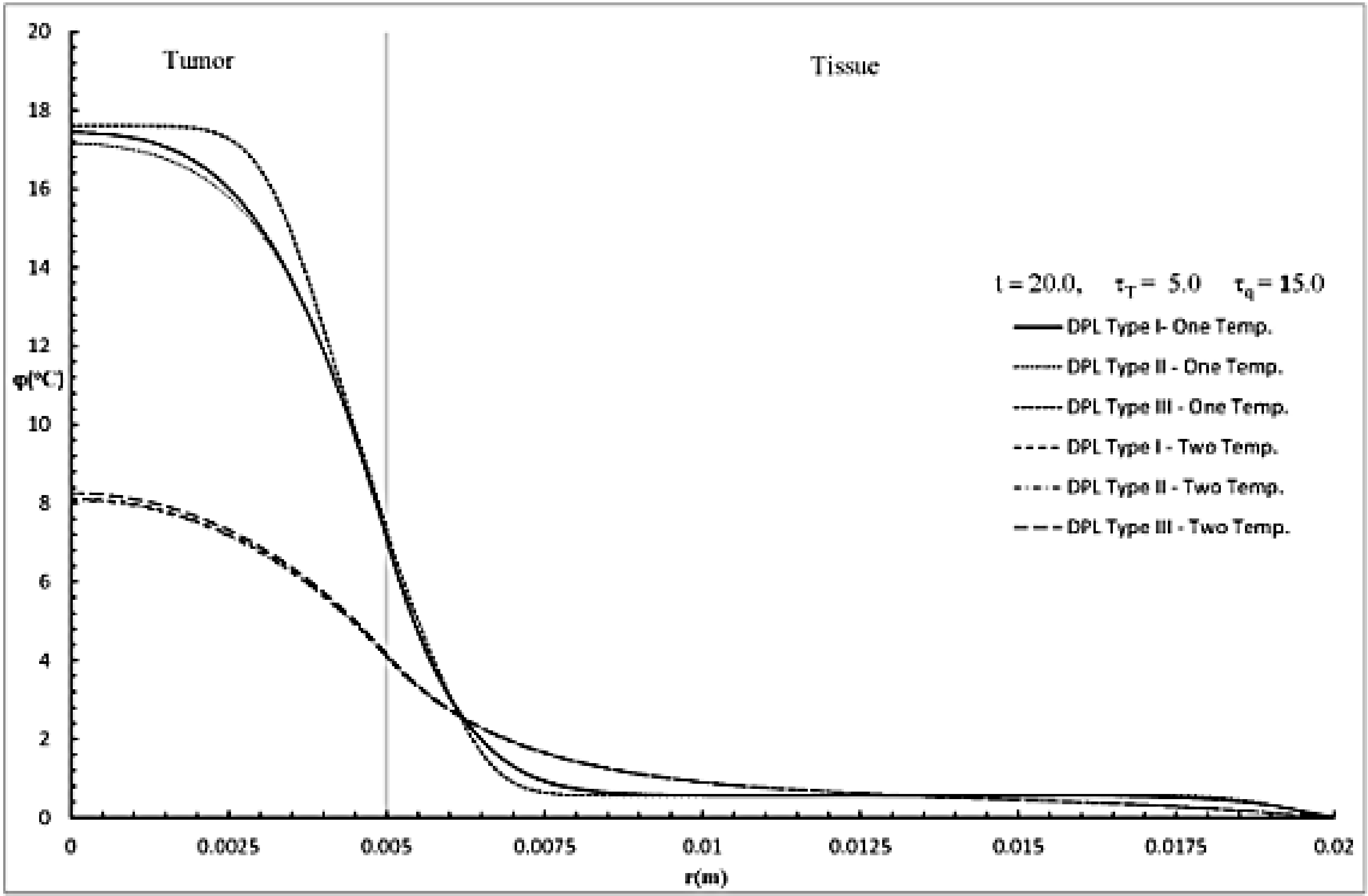
$$h = 4.0\times R$$

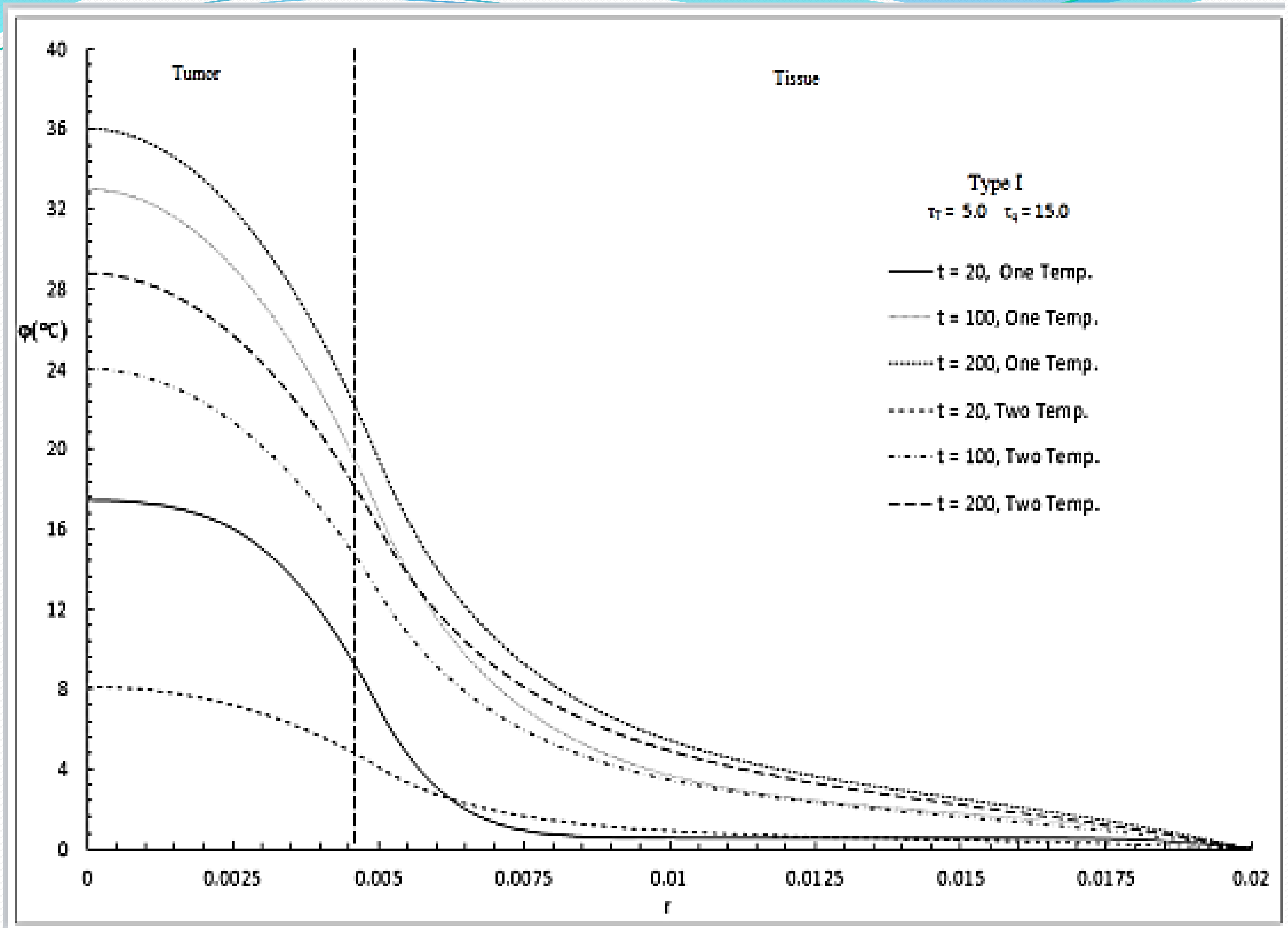
$$R = 0.005 \ m$$

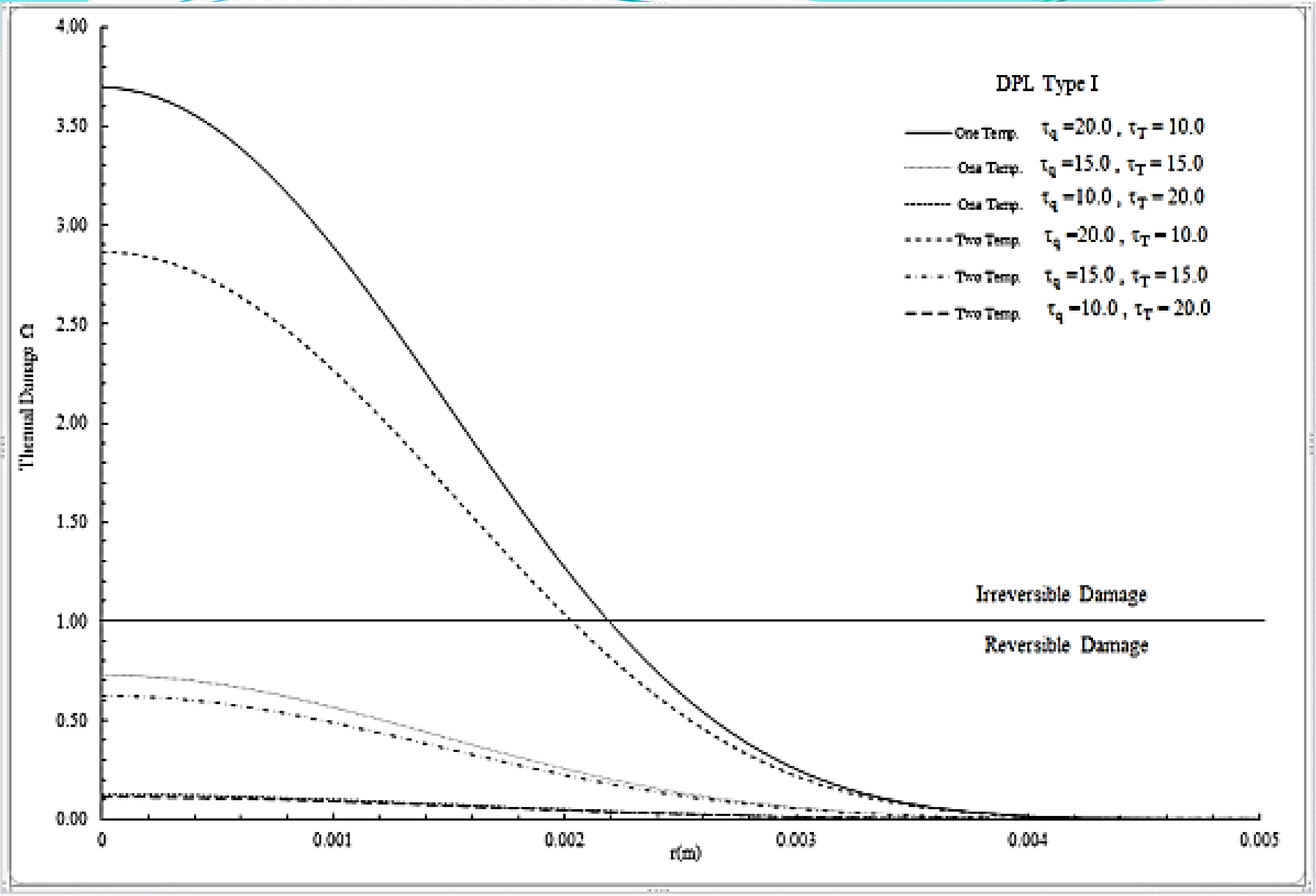
Table1: Properties of Tumor-Tissue Model

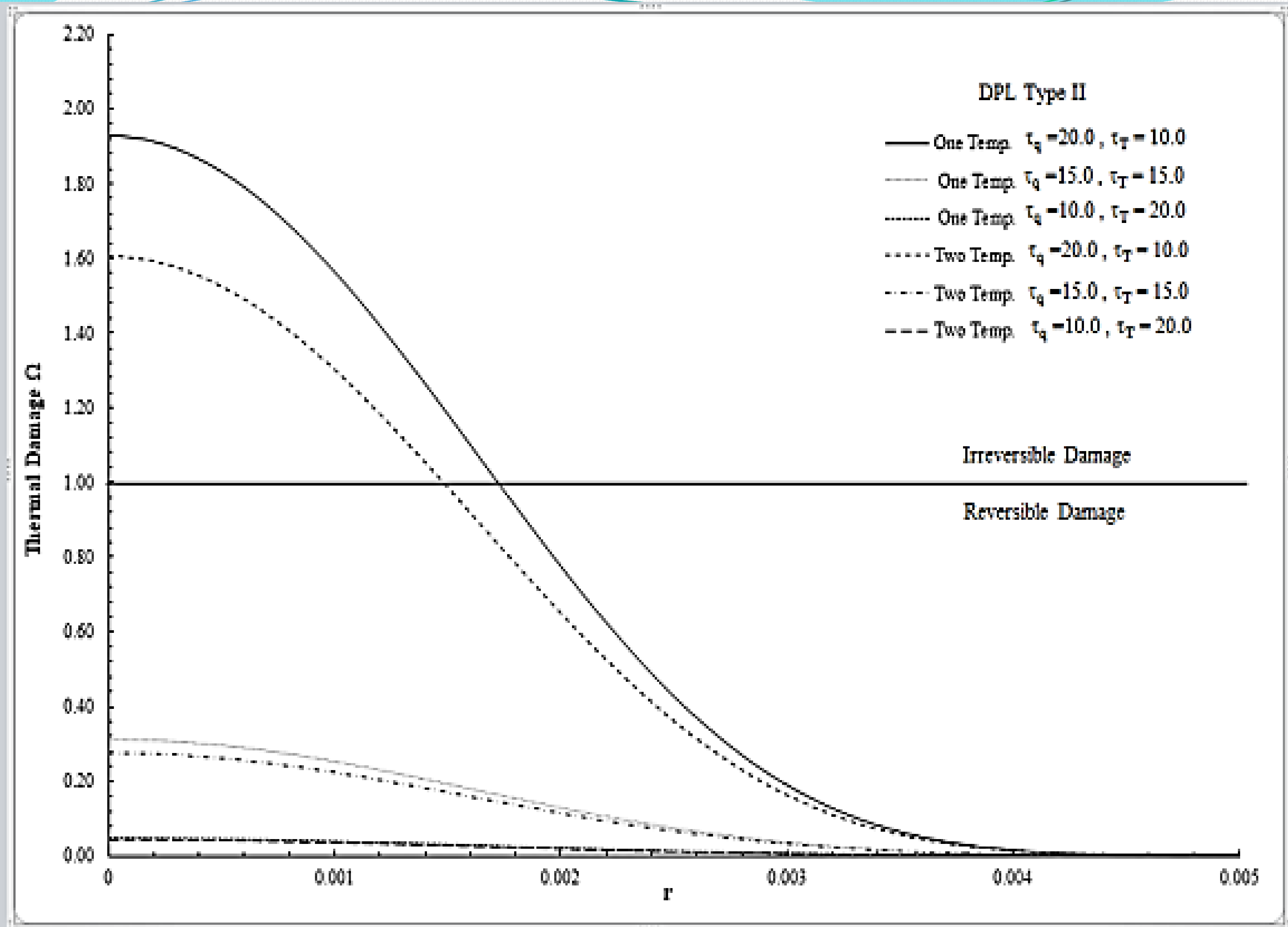
Parameter	Unit	Tumor	Tissue
K	W/mK	0.778	0.642
ρ	kg/m^3	1660	1000
C	$J/kg\,K$	2540	3720
w_b	$m^3/s/m^3$	0.0064	0.0064
T_0	^{o}C	37	37
q_m	W/m^3	29000	450
x	m	0.005	0.02
β	m^{-2}	0.000001	0.000001

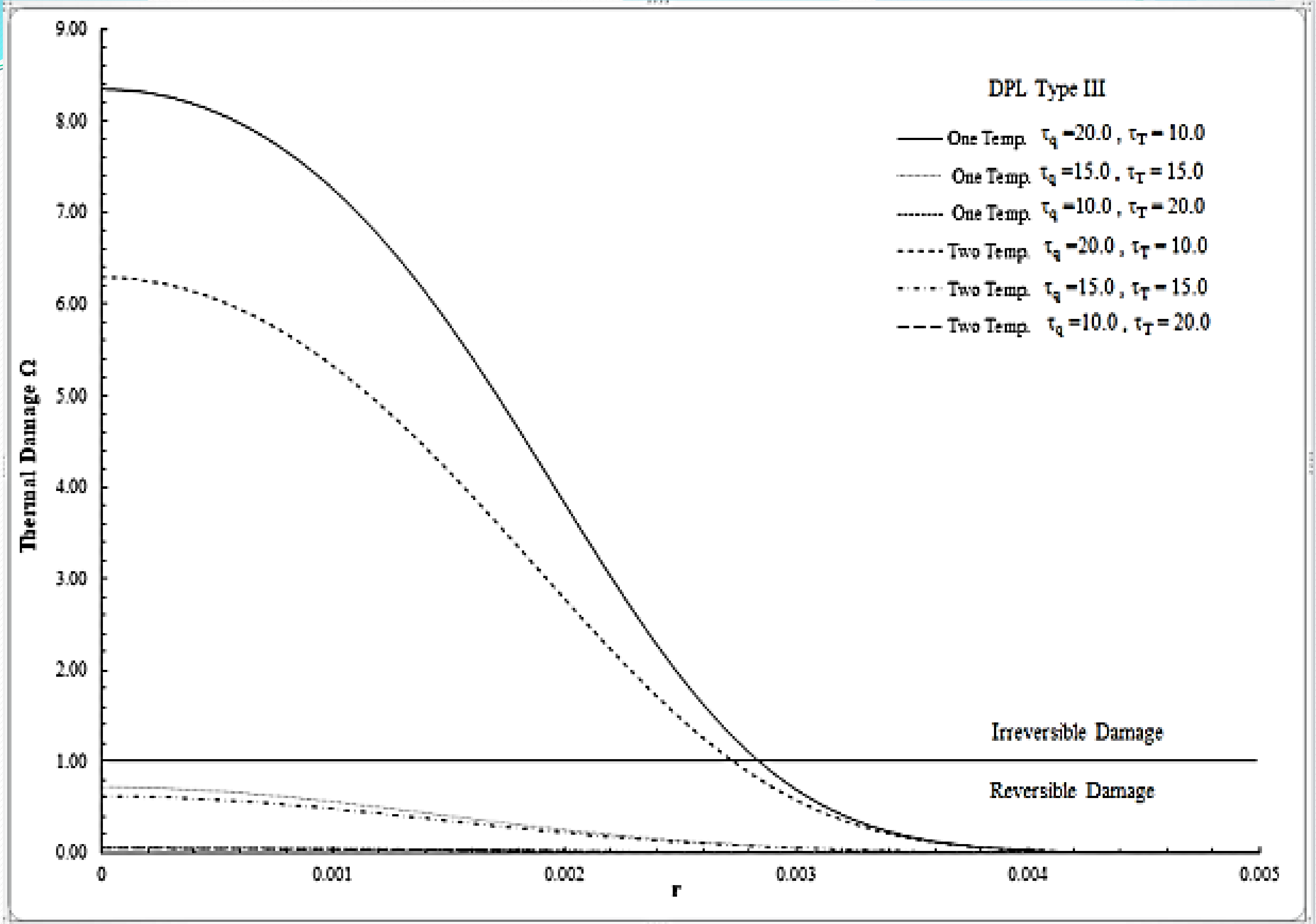
Figures


Tumor
Tissue
t = 20.0, τT = 5.0 τq = 15.0
DPL Type I- One Temp.
DPL Type II - One Temp.
DPL Type III - One Temp.
DPL Type I - Two Temp.
DPL Type II - Two Temp.
DPL Type III - Two Temp.
φ(°C)
r(m)
0
2
4
6
8
10
12
14
16
18
20
0
0.0025
0.005
0.0075
0.01
0.0125
0.015
0.0175
0.02


Tumor
Tissue
Type I
τT = 5.0 τq = 15.0
t = 20, One Temp.
t = 100, One Temp.
t = 200, One Temp.
t = 20, Two Temp.
t = 100, Two Temp.
t = 200, Two Temp.
φ(°C)
r
0
4
8
12
16
20
24
28
32
36
40
0.0025
0.005
0.0075
0.01
0.0125
0.015
0.0175
0.02


DPL Type I
One Temp. τ_q =20.0 , τ_T = 10.0
One Temp. τ_q =15.0 , τ_T = 15.0
One Temp. τ_q =10.0 , τ_T = 20.0
Two Temp. τ_q =20.0 , τ_T = 10.0
Two Temp. τ_q =15.0 , τ_T = 15.0
Two Temp. τ_q =10.0 , τ_T = 20.0
Irreversible Damage
Reversible Damage
Thermal Damage Ω
r(m)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
0.001
0.002
0.003
0.004
0.005


DPL Type II
One Temp. τq =20.0 , τT = 10.0
One Temp. τq =15.0 , τT = 15.0
One Temp. τq =10.0 , τT = 20.0
Two Temp. τq =20.0 , τT = 10.0
Two Temp. τq =15.0 , τT = 15.0
Two Temp. τq =10.0 , τT = 20.0
Irreversible Damage
Reversible Damage
Thermal Damage Ω
r
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
0.001
0.002
0.003
0.004
0.005


DPL Type III
One Temp. τq =20.0 , τT = 10.0
One Temp. τq =15.0 , τT = 15.0
One Temp. τq =10.0 , τT = 20.0
Two Temp. τq =20.0 , τT = 10.0
Two Temp. τq =15.0 , τT = 15.0
Two Temp. τq =10.0 , τT = 20.0
Irreversible Damage
Reversible Damage
Thermal Damage Ω
r
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
0.001
0.002
0.003
0.004
0.005

Conclusion

1- The parameters of the relaxations times have significant effects on the temperature increment and the value of the damage.

2- The two-temperature parameter has significant effects on the temperature increment and the value of the damage.

3- Dual-phase-lag heat conduction model of type III offers more irreversible damage than type I, then Type II.

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Thank you