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Research Article

Mathematical Modeling of the Physics of Blood Flow along a Constricted Artery during Treatment of Cancer using Hyperthermia

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Abstract

A numerical investigation of a unidirectional unsteady flow of blood and heat transfer through an artery with a stenotic condition during heat therapy has been performed aiming at determining the dynamics of fluid (blood) flow and heat transfer. Blood is treated to obey the Newtonian law of viscosity. The arterial wall is considered to be rigid due to the presence of stenosis. Heat transfer has been studied under the presence of external heat source that is used to raise body temperature during treatment under hyperthermia. The formulated model equations have been solved using finite difference scheme and simulations are done using MATLAB software. Velocity and temperature profiles have been plotted subject to varying some flow parameters such as Reynolds number, Pranditl number, Eckert number and heat the source parameter. Skin friction and Nusselt number have been plotted to see their varying behavior during heat therapy. A validation of this formulation is shown by comparing the current findings with those from the existing literature.

Nomenclature

Re: Reynolds Number; e: Non-dimensional Stenotic Height; Pr: Prandtl Number; Ec: Eckert Number; Q: Heat Source Parameter; Sc: Schmidt Number; K_R: Chemical Reaction Parameter; u_z: Dimensional Radial Velocity; w: Non-Dimensional Radial Velocity; t: Dimensional Time; τ: Non-Dimensional Time; C: Concentration; D: Diffusion Parameter; $R(z)$: Dimensional Geometry of Stenosis

1. Introduction

Cancer is a disease that kills millions of people all over the world. The disease involves the unusual growth of the cells in the human body. Scientists have managed to find ways of combating the disease [1] pointed out, that despite the development of diagnostic techniques and multiple novel therapies, the death rate of cancer patients has not changed substantially for decades. Besides, there is no single mechanism to cure cancer; instead, a combination of various modalities is to be involved for better results [2]. There are some prevalent treatments such as chemotherapy, radiotherapy and surgical ablation of cancerous tumors already but all of them have many side effects, and they do not have enough accuracy [3]. Recently, the estimation of transient temperatures in biological tissues has been under the focus of researchers [4,5] pointed out that the Hyperthermia is a promising approach to cancer therapy because it not only kills cancer cells directly, but it also activates anti-cancer immunity as an indirect effect. Hyperthermia in the clinical context of a radiosensitiser for superficial tumours is defined as temperatures that are above normal physiological conditions, ranging from 40 °C to 45 °C [6]. In the similar manner [2], describes the term hyperthermia the elevation of temperature of a part of the body at a temperature more than that of the normal body temperature and maintaining it for a specific time duration.

Carrying out mathematical modeling of fluid (blood) flow during such heat therapy is important as it does not only add knowledge but also helps in predicting the abnormality

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condition of the body. In recent years, studies that involve blood flow along a constricted artery have been widely carried out. Besides In term of cost, hemodynamic modelling is a cheap alternative for physicians for predicting the outcome of alternative treatment plans for patients, which can be utilized to predict the risk of disease [7]. Numerical simulation of blood flow in a stenosed carotid artery using different rheological models was also studied by [8]. The geometry of the constriction was considered to follow a bell-shaped Gaussian distribution.

[9] modelled and simulated the flow of blood with magnetic nanoparticles as a carrier for targeted drug delivery along a stenosed artery. The study aimed at understanding the flow pattern and nanoparticle aggregation in a diseased arterial segment having atherosclerosis [10] studied the biomagnetic blood flow in a stenosed bifurcated artery with elastic walls. The nonNewtonian character of blood was taken into account.

[11] investigated the effects of the severity of the stenosis on fluid flow in the diseased artery numerically with the help of a finite volume technique. Blood was assumed to follow the nonNewtonian character.

The evaluation of the attribute of blood flow together with the degree of obstruction generated in the arteries through different geometries was studied by [12]. The Flow of blood through the ill- afflicted artery was taken into account.

Other studies that investigated the flow of blood in stenosed artery are [13-19].

Mathematical formulation for blood flow and heat transfer during heat therapy is hardly studied as shown in the literature above. It is important to model and solve the formulation to understand the physics of blood and heat transfer during hyperthermia. In that regard therefore, the current investigation formulates and simulates the physics of arterial blood flow and temperature distribution during heat therapy along a large vessel.

2. Problem formulation

According to [11,12,20] blood can be considered to follow the Newtonian character when it flows in large arteries. Similarly, the current study assumes the blood to follow the Newtonian law of viscosity. It is further considered that the flow is unsteady, incompressible, axisymmetric rectilinear such that only the axial velocity component u_z is nonzero. The streamlines are also assumed to be straight lines. Besides, it is also considered that the flow is fully developed pressure-driven in cylindrical artery. The external heat source is assumed to be available to raise the body temperature. These considerations are applied to the well known continuity, momentum and energy equations, that is in the principles of mass, momentum and energy conservation. Besides, in this regard, the concentration equation in blood flow designates the transport of substances such as oxygen, nutrients, drugs, or waste products within the bloodstream. This equation accounts for both convective transport due to blood flow and diffusive transport due to concentration gradients.

Continuity equation: $$\frac{\partial \rho}{\partial t} + \nabla.\left(\rho V\right) = 0 \qquad (2.1)$$

Momentum equation: $$\rho \frac{\partial \boldsymbol{V}}{\partial t} = -\nabla p + \nabla.\sigma_{ij} + \boldsymbol{F}_b \qquad (2.2)$$

Energy equation: $$\rho c_p \frac{\partial T}{\partial t} = \nabla.\left(k \nabla T\right) + Q_h \qquad (2.3)$$

Mass Transfer: $$\frac{\partial C}{\partial t} = \nabla.\left(D \nabla C\right) + R_c \qquad (2.4)$$

Making use of the assumptions considered, the above equations become;

$$\frac{\partial uz}{\partial z} = 0 \qquad (2.5)$$

$$\rho \frac{\partial u}{\partial t} = -\frac{\partial P}{\partial z} + \mu \left(\frac{1}{r}\frac{\partial u_z}{\partial r} + \frac{\partial^2 u_z}{\partial r^2}\right) \qquad (2.6)$$

$$\rho cp \frac{\partial T}{\partial t} = k\left(\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2}\right) + \mu\left(\frac{\partial u_z}{\partial r}\right)^2 + q0\left(T - T_0\right) \qquad (2.7)$$

$$\frac{\partial C}{\partial t} = D\left(\frac{1}{r}\frac{\partial C}{\partial r} + \frac{\partial^2 C}{\partial r^2}\right) + K_R\left(C - C_0\right) \qquad (2.8)$$

Subject to the boundary and initial conditions

$$\frac{\partial u_z}{\partial r} = \frac{\partial T}{\partial r} = \frac{\partial C}{\partial r} = 0 \text{ at } r = 0 \qquad (2.9)$$

$$u_z\left(r,t\right) = 0,\ T\left(r,t\right) = T_W,\ C\left(r,t\right) = C_W \text{ at } r = R(z) \qquad (2.10)$$

$$u_z\left(r,0\right) = f\left(r\right),\ T\left(r,0\right) = T_0,\ C\left(r,0\right) = C_0 \qquad (2.11)$$

In this regard, the prescribed axial pressure gradient due to the pulsating nature of the blood flow in dimensionless form has been taken for human beings as:

$$-\frac{\partial P}{\partial z} = A_0 + A_1 \cos\left(nt\right) \qquad (2.12)$$

The arterial stenotic condition has the function as given here under

$$R\left(z\right) = a - \sigma\left(1 + \cos\frac{\pi z}{2z_0}\right) \text{for } -2z_o \le z \le 2z_o \qquad (2.13)$$

3. Scaling of model equations

The following variables are introduced to scale the variables

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$$\theta = \frac{T - T_0}{T_w - T_0}, C^* = \frac{C - C_0}{C_w - C_0}, \bar{z} = \frac{z}{z_0}, e = \frac{\sigma}{r}, w = \frac{u_z}{U_c}, \tau = \frac{tU_c}{a^2},$$

$$m = \frac{\rho a^2 n}{\mu}, H = \frac{R(z)}{a}, K_R^* = \frac{\rho K_R a^2}{\mu}, \left(A_0^*, A_1^*\right) = \left(A_0, A_1\right)\frac{\rho a^3}{\mu^2}, r^* = \frac{r}{a} \tag{3.1}$$

The non-dimensional model equations are written using Eq. 3.1, for convenience, we drop the drop the asterisks. This results to the following non-dimensional model equations;

$$\frac{\partial w}{\partial z} = 0 \tag{3.2}$$

$$\frac{\partial w}{\partial \tau} = A_0 + A_1 \cos m\tau \frac{1}{\mathbf{Re}}\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r}\right) \tag{3.3}$$

$$\frac{\partial \theta}{\partial \tau} = \frac{1}{\mathbf{Pr}}\left(\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r}\frac{\partial \theta}{\partial r}\right) + \frac{\mathbf{Ec}}{\mathbf{Re}^2}\left(\frac{\partial w}{\partial r}\right)^2 + Q\theta \tag{3.4}$$

$$\frac{\partial C}{\partial \tau} = \frac{1}{\mathbf{Sc\,Re}}\left(\frac{\partial^2 C}{\partial r^2} + \frac{1}{r}\frac{\partial C}{\partial r}\right) - \frac{1}{\mathbf{Re}} K_R C \tag{3.5}$$

Where

$$\mathbf{Re} = \frac{\rho a U_c}{\mu}, \mathbf{Ec} = \frac{U_c^2}{c_p\left(T_w - T_0\right)}, \mathbf{Pr} = \frac{c_p \mu}{k}, Q = \frac{q_0 a}{\rho c_p U_c} \text{ and } \mathbf{Sc} = \frac{\mu}{\rho D}$$

are respectively Reynolds number, Eckert number, Prandtl number, Heat source parameter and Schmidt number. The dimensionless form of the stenosis geometry is given as

$$H\left(z\right) = \begin{cases} 1 - e\left[1 + \cos\left(\frac{\pi z}{2}\right)\right] & \text{if } -2 \le z \le 2 \\ 1 & \text{Otherwise} \end{cases}$$

Besides, the dimensionless form of the boundary and initial conditions become;

$$w(r,0) = w_0,\ T(r,0) = T_0,\ C(r,0) = C_0 \tag{3.6}$$

$$w(r,t) = T(r,t) = T_w,\ C(r,t) = C_w \text{ on } r = H(z) \tag{3.7}$$

$$\frac{\partial w(r,t)}{\partial r} = \frac{\partial T(r,t)}{\partial r} = \frac{\partial C(r,t)}{\partial r} = 0, \text{ on } r = 0 \tag{3.8}$$

4. Method of solution

A radial coordinate transformation is now introduced. The variable η such that $\eta = \frac{r}{R\left(z\right)}$. This has an effect of immobilizing the arterial wall in the transformed coordinate η. Incorporating this transformation we get the following governing flow equations.

$$\frac{\partial w}{\partial \tau} = A_0 + A_1 \cos m\tau + \frac{1}{\mathrm{Re}H^2}\left(\frac{\partial^2 w}{\partial \eta^2} + \frac{1}{\eta}\frac{\partial w}{\partial \eta}\right) \tag{4.1}$$

$$\frac{\partial \theta}{\partial \tau} = \frac{1}{\mathrm{Pr}H^2}\left(\frac{\partial^2 \theta}{\partial \eta^2} + \frac{1}{\eta}\frac{\partial \theta}{\partial \eta}\right) + \frac{\mathrm{Ec}}{\mathrm{Re}^2}\left(\frac{\partial w}{\partial \eta}\right)^2 + Q\theta \tag{4.2}$$

$$\frac{\partial C}{\partial \tau} = \frac{1}{\mathrm{Sc\,Re}H^2}\left(\frac{\partial^2 C}{\partial \eta^2} + \frac{1}{\eta}\frac{\partial C}{\partial \eta}\right) - \frac{1}{\mathbf{Re}} K_R C \tag{4.3}$$

The above equations are subject to boundary and initial conditions

$$w(\eta,0) = w_0,\ \theta(\eta,0) = \theta_0,\ C(\eta,0) = C_0 \tag{4.4}$$

$$w(\eta,\tau) = 0,\ \theta(\eta,\tau) = \theta_w,\ C(\eta,\tau) = C_w \text{ on } \eta = 1 \tag{4.5}$$

$$\frac{\partial w(\eta,\tau)}{\partial \eta} = \frac{\partial \theta(\eta,\tau)}{\partial \eta} = \frac{\partial C(\eta,\tau)}{\partial \eta} = 0 \text{ on } \eta = 0 \tag{4.6}$$

Now with the help of the axial velocity and the temperature of the streaming blood we easily determine the the skin friction C_f and the Nusselt number Nu as follows

$$C_f = \frac{1}{H}\frac{\partial w}{\partial \eta}\Big|_{\eta=1} \tag{4.7}$$

$$N_u = -\frac{1}{H}\frac{\partial \theta}{\partial \eta}\Big|_{\eta=1} \tag{4.8}$$

4.1 Finite difference scheme

The three equations 4.1-4.3 are solved using the finite difference method. According to [21] and [22] pointed out that the finite difference scheme is easier, cheaper and more efficient to employ in solving partial differential equations. The Central difference formula is used to express the spatial derivatives and the forward difference formula is applied to the time derivatives. This is as shown hereunder;

$$\frac{\partial w}{\partial \eta} = \frac{w_{i+1,j} - w_{i-1,j}}{2\Delta\eta}, \quad \frac{\partial^2 w}{\partial \eta^2} = \frac{w_{i+1,j} + 2w_{i,j} - w_{i-1,j}}{(\Delta\eta)^2} \tag{4.9}$$

Similarly;

$$\frac{\partial \theta}{\partial \eta} = \frac{\theta_{i+1,j} - \theta_{i-1,j}}{2\Delta\eta}, \quad \frac{\partial^2 \theta}{\partial \eta^2} = \frac{\theta_{i+1,j} + 2\theta_{i,j} - \theta_{i-1,j}}{(\Delta\eta)^2} \tag{4.10}$$

And

$$\frac{\partial C}{\partial \eta} = \frac{C_{i+1,j} - C_{i-1,j}}{2\Delta\eta}, \quad \frac{\partial^2 C}{\partial \eta^2} = \frac{C_{i+1,j} + 2C_{i,j} - C_{i-1,j}}{(\Delta\eta)^2} \tag{4.11}$$

For time derivative we have;

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$$\frac{\partial w}{\partial \tau}=\frac{w_{i,j+1}-w_{i,j}}{k},\quad \frac{\partial w}{\partial \tau}=\frac{\theta_{i,j+1}-w_{i,j}}{k},\quad \frac{\partial C}{\partial \tau}=\frac{w_{i,j+1}-w_{i,j}}{k} \tag{4.12}$$

We also define $\eta(i) = (i - i)\Delta\eta$ *and* $\tau_j = (j - 1)\Delta\tau = (j - 1)k$. Incorporating equations 4.9 – 4.12 into equations 5.1 – 5.3 we have;

$$w_{i+1,j}=w_{i,j}+k(A_0+A_1\cos(m\tau_j))+\frac{k}{\mathbf{Re}H_i^2}\left(\frac{w_{i+1,j}+2w_{i,j}-w_{i-1,j}}{(\Delta\eta)^2}\right)+\frac{k}{\mathbf{Re}H_i^2\eta_i}\left(\frac{w_{i+1,j}-w_{i-1,j}}{2\Delta\eta}\right) \tag{4.13}$$

$$\theta_{i+1,j}=\theta_{i,j}+\frac{k}{\mathbf{Pr}H_i^2}\left(\frac{\theta_{i+1,j}+2\theta_{i,j}-\theta_{i-1,j}}{(\Delta\eta)^2}\right)+\frac{k}{\mathbf{Pr}H_i^2\eta_i}\left(\frac{\theta_{i+1,j}-\theta_{i-1,j}}{2\Delta\eta}\right)+\frac{kEc}{(\mathbf{Re})^2H^2}\left(\frac{w_{i+1,j}-w_{i-1,j}}{2\Delta\eta}\right)+Q\theta_{i,j} \tag{4.14}$$

$$C_{i+1,j}=C_{i,j}+\frac{k}{(ScRe)^2H^2}\left(\frac{C_{i+1,j}+2C_{i,j}-C_{i-1,j}}{(\Delta\eta)^2}\right)+\frac{k}{ScReH_i^2\eta_i}\left(\frac{C_{i+1,j}-C_{i-1,j}}{2\Delta\eta}\right)+\frac{k\mathbf{Re}}{K_R}C_{i,j} \tag{4.15}$$

Results and discussion

In this section, a graphical results of the study are presented to portray various effects of different fluid flow parameters.The stability was maintained be ensuring that $0<\frac{\Delta\tau}{(\Delta\xi)^2}\le 0.5$.

MATLAB software was used to produce the graphical results. The following values were used, Re = 3, e = 0.1, A_0 = 1, A_1 = 0.5, Pr = 1, Ec = 0.1, Q = 1, Sc = 0.1.These parameters were varied to see their impact on the fluid flow properties.

Figure 1 shows the transient effect of velocity profiles. The figure is plotted in three dimensions where radial distance, time and velocity are shown. Besides, it is found in Figure 2 velocity profile increases with increase in Reynolds number. Increase of Reynolds number implies the increase in inertia force than the viscous force. This increase in inertia forces, raises the fluid's velocity profile.

The effect of stenotic condition on the arterial wall to the velocity of blood is shown on Figure 3.

The velocity profile decline as stenotic height increases. Increase in stenotic height reduces the arterial radius which leads to the increase in resistance of the fluid to flow.

Figure 4 is established to observe the effect of the driving force for the blood's flow, this is the steady state part of pressure gradient on the axial velocity of blood. The velocity is observed to enhance as the steady state part of pressure increases. This

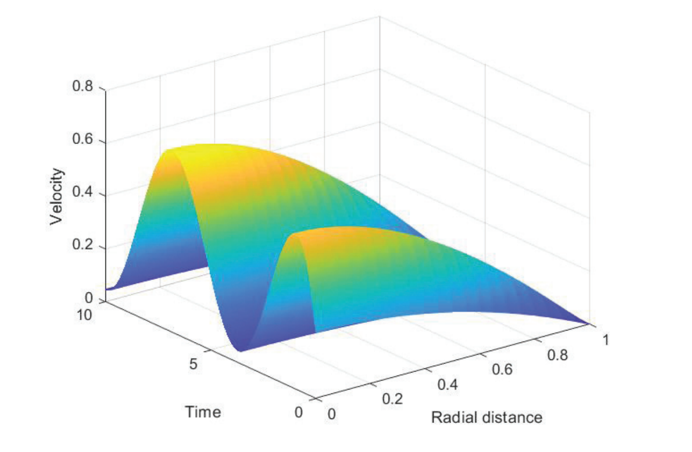

Figure 1: The transient effects of velocity profiles.

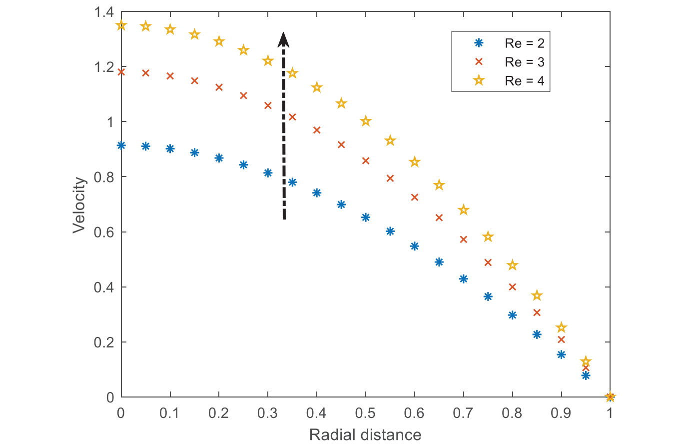

Figure 2: The effect of Reynolds number on velocity.

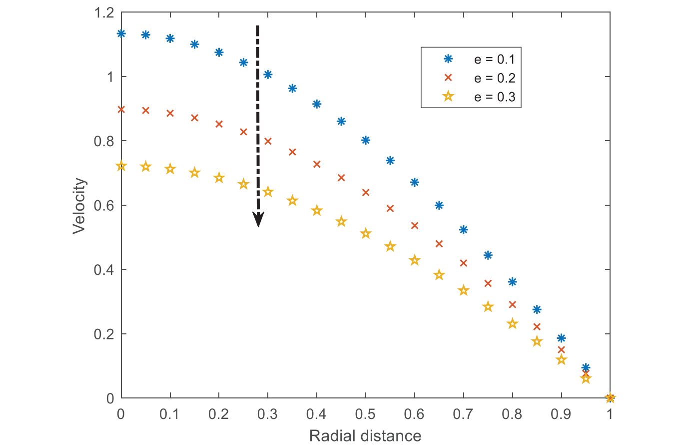

Figure 3: The effect of Stenosis on velocity.

increases more flow of blood because its increase drives more fluid to flow.

Here below are the graphical results of the temperature profiles. Figure 5 shows the transient effect of fluid's temperature in three dimensions. However, in Figure 6, fluid's temperature increases as the radius of the artery decreases due to plaques. Increase in stenotic height increases the resistance. As stenosis increases, the pressure increases which

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in turn affect the metabolic activities. The change in metabolic activities enhances the fluids temperature.

The variation of temperature due to Prandtl number is elucidated in Figure 7. The graph reveals that increase of Prandtl number enhances the temperature. The enhancement of temperature is a result of increase in viscosity. This is because, increasing Prandtl number implies that viscosity is becoming dominant than the thermal conductivity. As viscosity increases, the resistance to flow increasing due to friction which eventually raises the temperature. Figure 8 shows the variation of temperature due to the increasing in Eckert number. The result reveals the increase in temperature due to increase in Eckert number. As an Eckert number gets higher in values, the kinetic energy or velocity increases than temperature differences. This kinetic energy get converted to the heat energy which causes rise in temperature.

The variation of temperature profile for different values of heat source parameter is depicted in Figure 9. The figure shows that, the temperature increases as the heat source parameter increases. The enhancement of the temperature as heat source rises was expected because heat therapy involves raising the body temperature or the affected part of the body to the higher temperature. The higher temperature in this regard, kills the abnormal mass of tissue that forms when cells grow and divide more than they should or do not die when they should. Medically, such tissues, their sizes decrease as a result of a decrease in the number of malignant cells brought

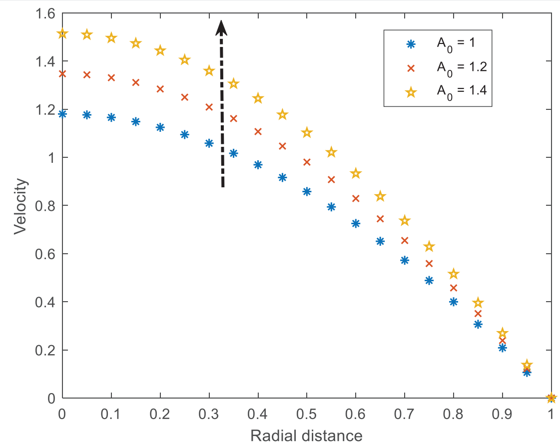

Figure 4: The effect of Steady state part of pressure gradient on velocity.

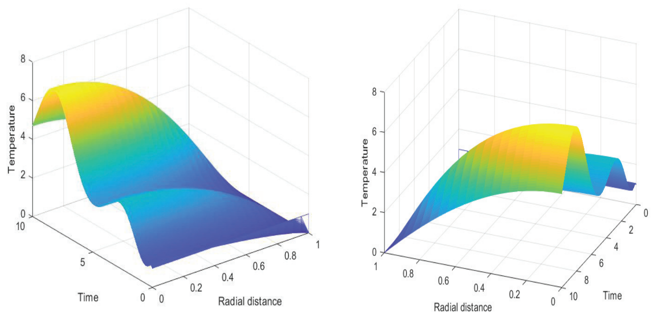

Figure 5: The transient effects of temperature profiles.

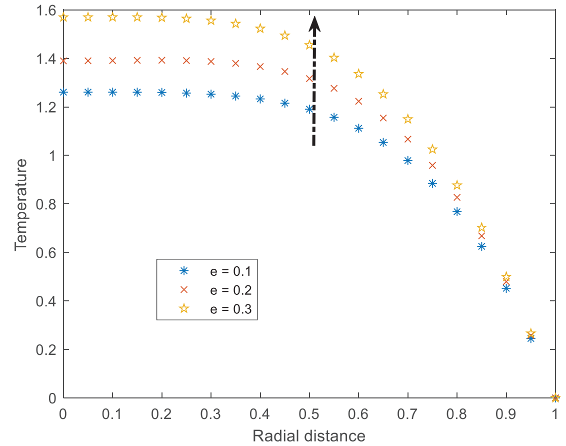

Figure 6: The effect of Stenotic height on temperature profiles.

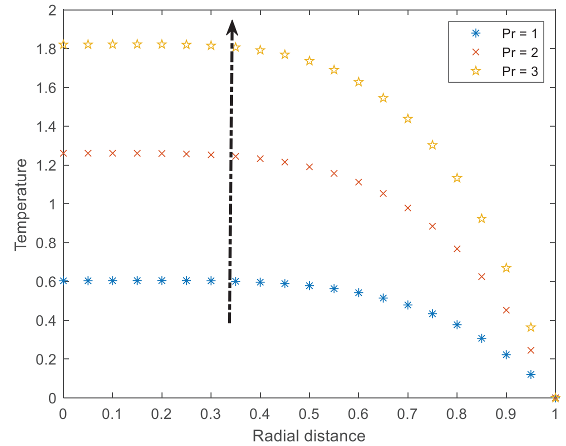

Figure 7: The effect of Prandtl number on temperature profiles.

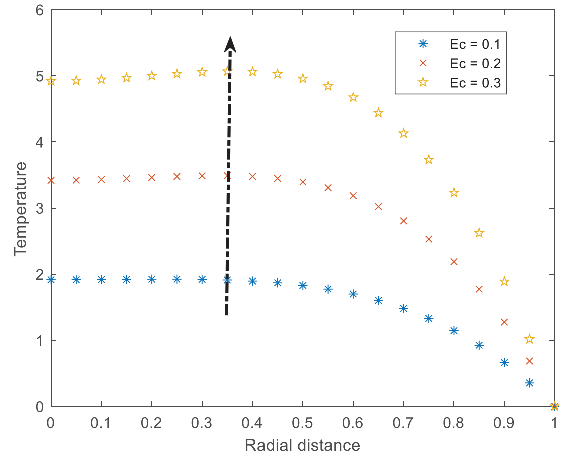

Figure 8: The effect of Eckert number on temperature profiles.

on by treatment or hyperthermia-induced cell death. Elevated temperatures have the potential to denature and agglomerate proteins in cancer cells, ultimately resulting in cell death. Similar result was obtained by [23].

In Figure 10, temperature is enhanced as a steady state part of pressure gradient increases. The increase in temperature is a result of increase velocity by A_0. It should be noted that blood

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flows from the region with high pressure to the region with low pressure. Now, higher pressure differences between two points in the circulatory system, enhances blood flow which in turn raises temperature.

In Figure 11, it is observed that the arterial skin friction increases with the increase in the Reynolds number. Physically, as the Reynolds number increases, the inertial force becomes more dominant that the viscous force. This implies that the velocity of the fluid is increasing. Such increase in velocity, eventually raises the arterial skin friction. Besides, getting aware of the high skin friction in arterial walls is crucial for preventing and managing cardiovascular diseases. The effect of stenotic height on skin friction is shown in Figure 12. Unlike in Reynolds number, the increase in stenotic height declines the skin friction. This is due to the fact that as stenosis increases, the velocity declines. The decrease in velocity therefore, leads to the decrease in the arterial skin friction.

Skin friction and Nusselt number plots

The variations of skin friction and Nusselt number are plotted below.

The Nusselt number which is the ratio of convective heat transfer to conductive heat transfer is defined as a non-

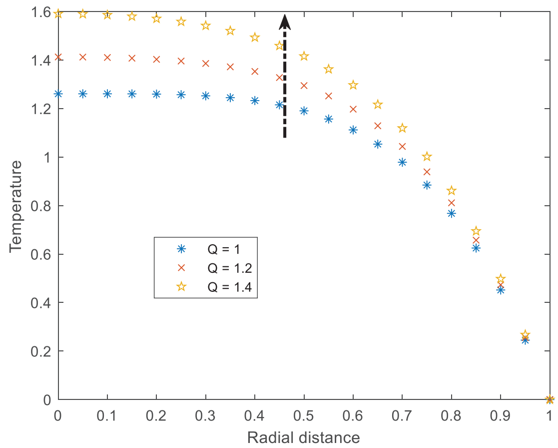

Figure 9: The effect of Heat source parameter number on temperature profiles.

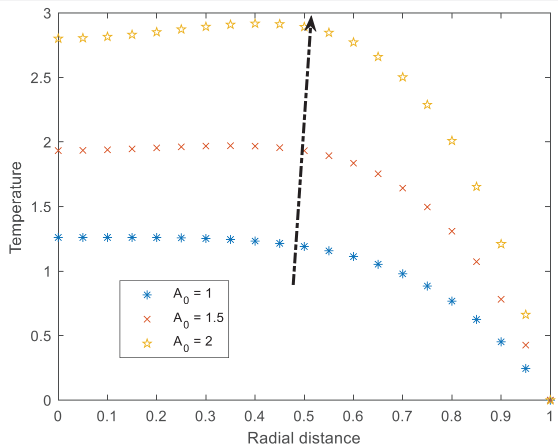

Figure 10: The effect of Steady state part of pressure gradient on temperature profiles.

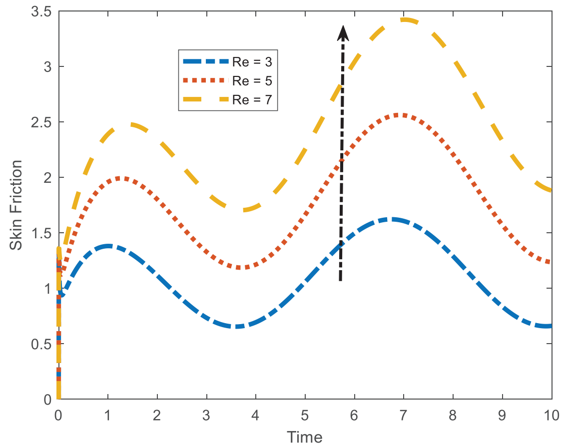

Figure 11: The effect of Reynolds number on arterial skin friction.

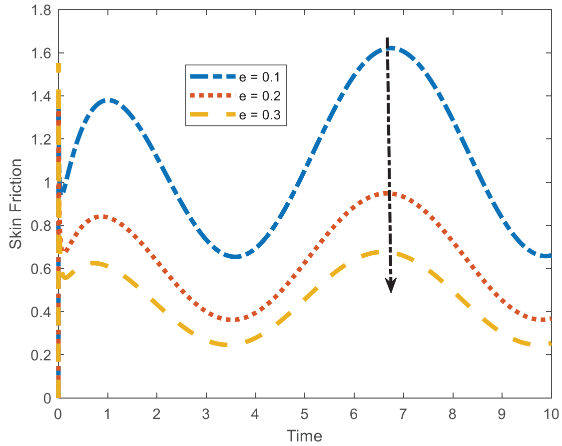

Figure 12: The effect of stenotic height on arterial skin friction.

dimensional number that quantifies convective heat transfer from a surface. Figures 13-16 shows that Nusselt number decreases with stenotic height and Reynolds number and increases with Prandtl number and heat source. In Figure 13 it is revealed that the Nusselt number declines with increase in the stenotic height. As stenotic height increases, more blood becomes to the wall that easily facilitate conduction of heat. Increasing conductive heat transfer leads to the decrease of the Nusselt number. The same is observed when the Reynolds number is increased. See Figures 14,15 the Nusselt number is observed to be enhanced by the Prandtl number which is the ration of momentum diffusivity to heat diffusivity. Physically, increasing the Prandtl number implies raising the conductivity which diminishes the Nusselt number. As expected, the heat source parameter is observed to increase the Nusselt number. This is as shown in Figures 16,17 exhibits the variation of the Nusselt number due to increase in the Eckert number. From the figure, we see that the Nusselt number increases with increase in Eckert number. It is important to note that increasing the Eckert number implies that convective heat transfer is dominant and kinetic energy gets converted into heat energy.

Conclusion

The investigation on the dynamics of blood flow, heat and mass transfer during hyperthermia treatment has

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been conducted for a chemically reacting blood. Blood has been assumed to follow the Newtonian law of viscosity. The formulated model has been solved numerically using Finite difference method. The effect of flow parameters were varied to see their impact. The profiles for arterial skin friction and the Nusselt number were also put in place. Hereunder are some of the most outstanding observations and findings, plaques in arteries diminishes the velocity profile, the Reynolds number

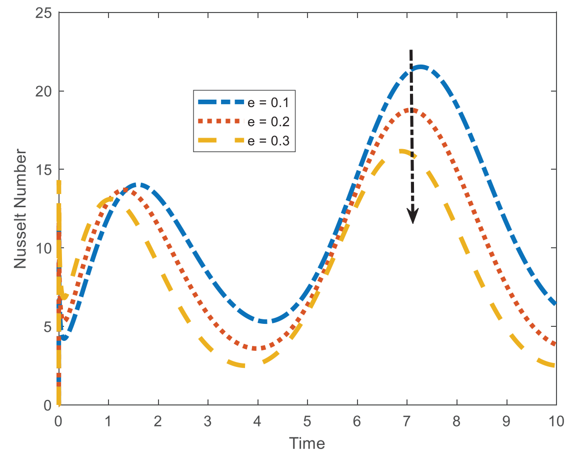

Figure 13: Effect of e on Nu.

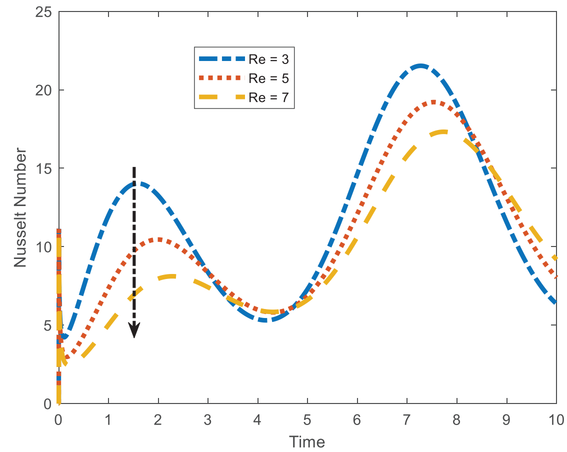

Figure 14: Effect of Re on Nu.

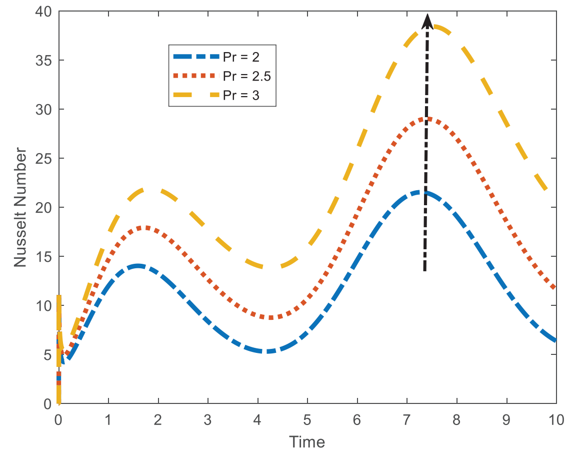

Figure 15: Effect of Pr on Nu.

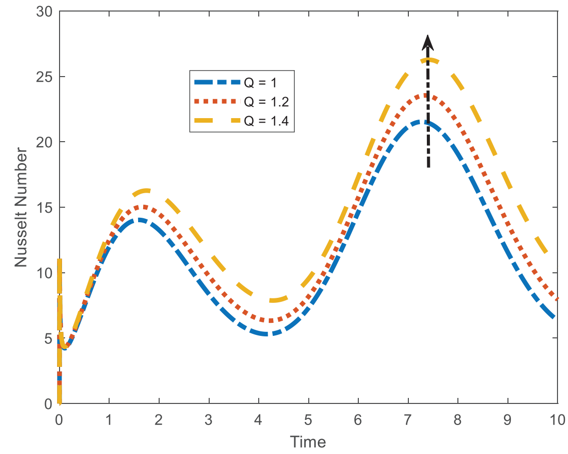

Figure 16: Effect of Q on Nu.

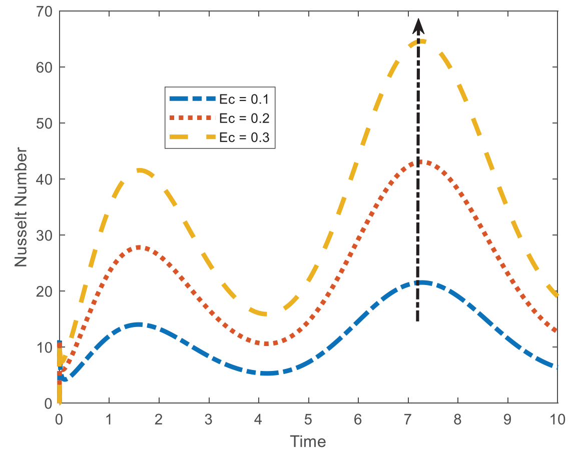

Figure 17: The effect of Eckert number Nusselt number.

enhances the flow fluid velocity. The Prandtl number, Eckert number, stenotic height, and External heat source significantly raise fluid temperature. Chemical reaction parameter, Reynolds number and Schmidt number decrease the fluid's concentration. Besides, concentration is enhanced by the increase in stenotic height.

The similar recommended future work include the considering blood to suit the non-Newtonian character and the blood's viscosity to be a variable and not a constant

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