MODEL OF TERAHERTZ PULSE-BLOOD FLOW INTERACTION FOR OVERCOMING CHOLESTEROL PLAQUE VENTURI EFFECT IN ARTERY

Usman Malik, Muhamad .Hamdi
Physics Department, Math and Science Faculty, University of Riau
Pekanbaru, Tel.+62 761 63273,

ABSTRACT

This model attempts to analyze involvement using THz radiation interaction with cholesterol deposits form plaque on the inner walls of an artery. It interacts with blood fluid by principle of THz radiation heat transfer mechanism for overcoming cholesterol plaque venture effect in artery. Athermanous plaque, a buildup of white blood cell wherein is sometimes termed fatty, despite absence of adiposities deposits within the wall of an artery. When cholesterol deposits form plaque on the inner walls of an artery, the velocity of blood flow increases when t increases and generates higher pressure according to the venture effect. Consequences of this effect can lead to collapse the artery, causing a myocardial infarction in a coronary artery. Analysis on the cholesterol plaque effect in blood flow through the forced convection of terahertz pulse heat release in artery causes the blood flow change after interacting with terahertz pulse. The results indicate that blood velocity and diffusivity for axial positions to higher with change of temperature rises along radial position caused by heat release of the absorbed terahertz pulse power in blood flow. Transient behavior of a 10 THz pulse-blood flow interaction in artery wherein the result chosen varies the blood kinematics viscosity to see how fast this final blood velocity profile is attained. Indeed, for very small blood kinematics viscosities, the response is slower. This result is to be expected since the blood kinematics viscosity unit is cm^2/s just like the diffusion coefficient and the thermal diffusivity.

Key words: Terahertz pulse, blood flow, cholesterol plaque, venturi effect, artery

INTRODUCTION

The new model for laminar blood flow in analysis for overcoming the cholesterol plaque effect using principle of the forced convection terahertz pulse heat release inside arteries can be derived by modified terahertz heat diffusion equation between terahertz power-blood flow interactions in model equation. Analysis focuses on the temperature distribution profile change versus radial position at different axial positions. Average blood flow velocity and diffusivity change can be determined before and after interacting with the 10 THz pulse. The governing equation and boundary conditions are chosen. Average flow velocity with different diffusivity before interacting. They change after interacting to certain velocity with diffusivity for axial positions. Results shows that change of temperature rises higher along radial position for axial position and then significant change occur with increase axial position. In fact, it is caused by heat release from the absorbed power from terahertz pulse. This model describes the velocity profile at constant time intervals with different profiles. The result chosen varies the blood kinematics viscosity to see how fast this final blood velocity profile is attained. Indeed, for very small blood kinematics viscosities, the response is slower. This result is to be expected since the blood kinematics viscosity unit is cm^2/s just like the diffusion coefficient and the thermal diffusivity [1]. Blood kinematics viscosity is the important factor for momentum transfer [2]. The velocity distribution before terahertz pulse propagates into blood flow computed numerically for a pulsatile pressure-driven blood flow in an artery. This model considerably simplifies the actual flow through veins and arteries for analyzing the cholesterol plaque effect in slow blood flow. When the blood kinematics viscosity is large and momentum diffusion is fast i.e. the Reynold number, Rw, is small can instantaneously adjust to changing pressure. The blood velocity is then in phase with the pressure gradient. On the other hand, when the blood kinematics viscosity is small and momentum diffusion is slow, then Rw is large wherein the blood velocity at the center of the artery, velocity lags the pressure gradient by 90°. One can see that when everything is in phase then the blood flow behaves locally as a quasi-steady Poisueille flow, in which results of the curves coincide, the curve being the parabolic solution and the curve taking inertial effects into account [3]. At a Reynold number from low to high value, inertial effects become significant and the velocity field is change locally parabolic in curves are a slight distinct.

THEORETICAL CONSIDERATION

The intensity is attenuated exponentially due to absorption and scattering given by the Beer-Lambert law

$$\Phi(r,z) = \Phi_o e^{-\mu d(r,z)} \qquad (1)$$

The propagation of scattered terahertz pulse is described by the light transport equation [3]

$$\begin{aligned}(s\,.\,\nabla)L(\bar{r}\,.\,\hat{s}) &= \frac{dL(\bar{r}\,.\,\hat{s})}{ds} \\ &= -\mu_t L(\bar{r}.\hat{s}) + \mu_s \int_{4\pi} p(\hat{s}\,.\,\hat{s}')L(\hat{r}.\hat{s}')\,d\omega\end{aligned} \qquad (2)$$

where is $\mu_t = \mu_s + \mu_a$ is the attenuation coefficient, [cm^{-1}] is the absorption coefficient and [cm^{-1}] is the scattering coefficient. The left-hand side of the transport equation describes the rate of change of radiance $L(\bar{r},\hat{s})$ [$W/cm^2.sr$] at a point indicated by $\bar{r}(x,y,z)$ in the direction. The first term on the right-hand side is energy attenuated due to absorption and scattering. The minus sign in this term is due to the radiance decrease. The second term is the energy increase due to radiance from all other directions scattered into direction about a solid angle. The most important parameter in the interaction is power density, $\Phi(r,z)$ (W/cm^2) which is a function of power delivered and terahertz radiation source spot size on the blood flow,

$$\Phi_o(r,z) = \frac{P}{A} \qquad (3)$$

where *P* (W) is terahertz radiation input power and A is diameter area artery or πr^2 with r (cm) is the radius of the spot, called spot size. The product of fluence and the absorption coefficient equals the heat or energy source : the amount of energy rate deposited in a unit volume of blood. The rate of heat generation per unit volume S(r, z) (W/cm^3) (Haim Azhari,2010) is

$$S(r,z) = \dot{q}(r,z) = \mu_a \varphi(r,z) = \frac{P}{4\pi\pi^2 r} e^{-\frac{d(r,z)}{\delta}} \qquad (4)$$

where φ(r,z) is the steady-state fluence rate or power density (W/cm^2) , P is terahertz radiation power (W),
δ is the optical penetration depth and r is the position from the axis of terahertz radiation . Generation of heat is due to deposition of photons and by excitation and deexcitation of molecules increasing the internal energy. In blood the terahertz radiation absorbers are water, cholesterol, glucose, insulin and hemoglobin, etc. Local absorption of photons creates local volumetric heat production, S(r,z) (W/cm^3) which is equal to the product of the local absorption coefficient and local fluence rate φ(r,z) ($W/cm^{2)}$), $S(r, z) = \mu_a\varphi(r, z)$. The steady-state and transient absorbed optical power density from a localized optical source can be expressed by equation.

The increase in temperature (ΔT) of a blood flow due to absorption of terahertz radiation into blood flow in artery can be determined. If the artery wall membrane temperature is T_w , use the incompressible-flow energy equations to solve for the temperature distribution T (y) between the walls for some blood flow conditions. If a artery of *l* length and r radius with diffusivity κ has temperature T interacting with powered terahertz pulse *P* with its rate of energy per blood volume, Q_{THz} , then its heat conduction of the final condition u (r,z) at any point of artery . It is evident from symmetry, the heat conduction equation system is

$$\frac{\partial u}{\partial t} = \kappa\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial z^2}\right) + Q_{THz} \qquad (5)$$

The boundary conditions are given by , $0 < r < R$, $0 < z < l$ and $t > 0$, $| u (r,z,t) < M |$. Equations of blood flow in blood vessel that relate with temperature, velocity and time given as follows

$$\rho_b C_b \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial y^2} + \mu\left(\frac{\partial u}{\partial y}\right)^2 + Q_{THz} \qquad (6)$$

$$u(r)\frac{\partial T}{\partial x} = K\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right] + Q_{THz} \qquad (7)$$

where C_b is the specific heat of the blood in J kg^{-1} $^oC^{-1}$, ρ_b is the density of the blood in kg/m^3. The blood can also absorb energy of radiation particle from the incoming terahertz intensity. The power absorbed is

$$Q_{THz} = \frac{1}{2}\omega \int_V dr\, \varepsilon''(r) | E_{int} |^2 = \frac{1}{2}\omega\varepsilon''_d V_o | E_{in} |^2 \qquad (8)$$

where Vo volume of radiation particle , E is the electric field intensity in V/m, ω is the angular frequency in terahertz range.

DESIGN OF MODELING

Modeling parameters and assumptions

In the professional literature for the modeling of terahertz pulse-blood flow interaction and thermal comfort, there is a large variety of mathematical models on the heat transfer in blood tissue of the human body, including the influence of the blood flow in the vascular network. This model is developed in some assumptions that are:

- The blood tissue is isotropic
- The physical properties of the blood tissue are independent of the tissue temperature
- Arterial blood temperature is constant at 37 ^oC
- The metabolic heat generation rate is constant per unit volume and unit time
- The blood perfusion rate is uniformly spatially and temporally independent of tissue temperature

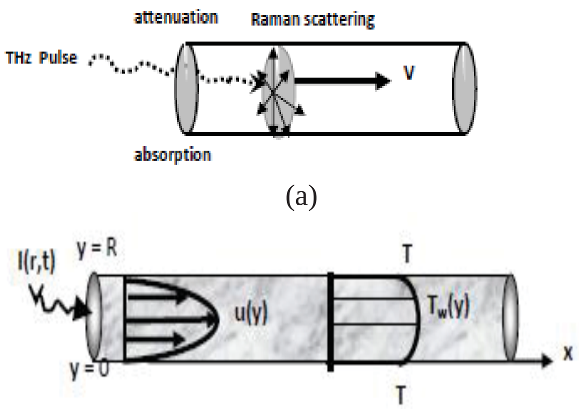
Physics parameters given in Table 1, they are used in calculation of model.

Terahertz pulse with their wavelength ranges interacting into blood flow is basically occurred a process of light absorption strongly and low scattering in blood flow as can be seen in Fig.1.a. frequencies is discovered by opto-electronic technique and then developed by optical technique.

Table 1: Thermal optic properties of blood fluid

Parameters	Value
blood thermal conductivity	0. 642 W/m ^oC
blood heat convection coefficient	10 W/m^2 ^oC
specific heat capacity of blood fluid	4180 J/kg ^oC
density of blood fluid	1000 kg / m3
blood perfusion rate	40 kg/m^3 s
blood fluid average velocity	0. 45 m /s
absorption coefficient	9.75 Np/m
propagation coefficient	12.16 rad/m
radiation group velocity	5.2 x 10^8 m /s
specific heat of blood	4200 J/kg.^oC

The wavelength from millimeters scale can absorb and penetrate in millimeter in depth through the blood fluid. As in Fig 1b the terahertz pulse beam propagates through the blood flow in Δt the time duration in seconds, and ΔT is the temperature rise in the blood in ^oC. It is clear in Fig.1.b indicates that the rise blood temperature in



(a)

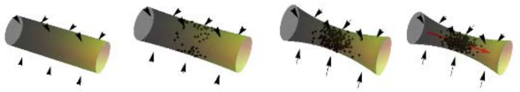
(b)

Figure.1. Propagation of terahertz intensity-blood flow interaction (a). Analysis on scattering between blood flow and terahertz pulse (b). The velocity profile for laminar blood flow between both walls of artery

artery is proportional to the blood flow's dielectric loss factor, in addition to electric field intensity squared, frequency, and treatment time. When cholesterol deposits form plaque on the inner walls of an artery, the velocity of blood flow increases red arrow when time increases and generates higher pressure according to the venturi effect black arrows. This can lead to collapse the artery, causing a myocardial infarction in a coronary artery, for example. It uses calculation in random with seed random, *N* and random real , r = (ΔN) t, change of effect on pressure respect to polar coordinate :

$$p_x = rG_o \cos\theta \quad \text{and} \quad p_y = r\,G_o \sin\theta + 1 \qquad (9)$$

Where G_o is a constant relation to force per blood volume in artery membrane. Integer part of Nt, θ random real in interval from 0 to 2θ and normal distribution from 0.05 to 1 see in Fig.2. Existence of cholesterol in blood vessel shows the phenomenon of sediment or gravel accumulating form plaque on the inner walls of an artery. It causes the velocity of blood flow to rise as indicated in red arrow. In Figure 2 (a),(b),(c) and (d) depicts when t > 0.4 second and generates higher pressure according to the venturi effect in black arrows. This can lead to collapse the artery, causing a myocardial infarction in a coronary artery.



(a) (b) (c) (d)

Figure 2 . (a) t = 0 with random seed, N = 0, (b) t=0.1 with random seed, N = 10^6 (c) t=0.4 with random seed, N = 10^6 , (d) t= 0.45 with random seed, N = 10^6

Blood pulsatile flow in a artery

The blood velocity distribution, u(r,t), is computed numerically for a pulsatile pressure-driven blood flow in a artery. This model considerably simplifies the actual blood flow through veins and arteries. When the kinematic viscosity is large and momentum diffusion is fast (i.e. the Strouhal number, R_w, is small, the velocity at the center of the tube, u(r,t) can instantaneously adjust to changing pressure, -∂p/∂z. The velocity is then in phase with the pressure gradient. On the other hand, when the kinematic viscosity is small due to cholesterol plaque effect in blood and momentum diffusion is slow, then R_w is large and the velocity at the center of the artery , u(r,t) , lags the pressure gradient by 90°. The long-time analytical solution for R_w , matches the numerical solution very well, after a short transient period.

This derivation can be found and one can see that when everything is in phase then the flow behaves locally as a quasi-steady Poisueille flow. At a high Strouhal number, inertial effects become more significant and the velocity field is no longer locally parabolic curve. Equations for blood flow in artery due to the oscillating pressure-driven blood flow in a artery obeys the following equations:

$$\frac{\partial p}{\partial z} = G_o(1 + \varepsilon \sin(\omega t)) \qquad (10)$$

$$\rho \frac{\partial u}{\partial t} = G_o(1 + \varepsilon\ \sin(\omega\omega t)) + \frac{\mu}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right) \qquad (11)$$

$$u = \frac{1}{4}(1-r^2) - \varepsilon\{\frac{e^{iRw\,\hat{t}}}{R_w}[1 - J_o\{\sqrt{\frac{R_w}{i}}\hat{r}\}/J_o\{\sqrt{\frac{R_w}{i}}\}]\} \qquad (12)$$

$$\bar{u} = \frac{u}{G_o R^2/\mu} \qquad (13)$$

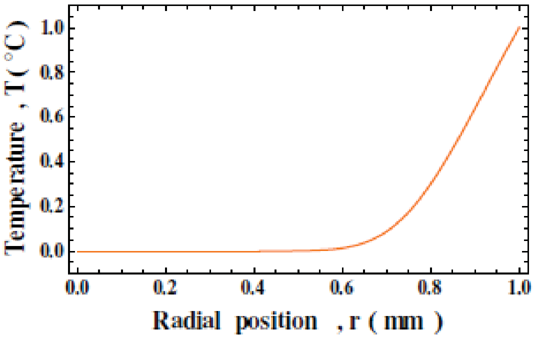
$$R_w = \frac{\omega R^2}{v} \qquad (14)$$

where $\bar{u}$, $\hat{r}$, v and $\hat{t}$ are the dimensionless velocity, radial position, kinetic viscosity and time. The variable R_w can be considered as a Reynolds number, since it appears as the ratio of inertial forces to viscous forces. There are two characteristic times for this problem: 1/ ω, the period of the imposed pressure gradient, and R^2/v , the time for diffusion of momentum across the artery.

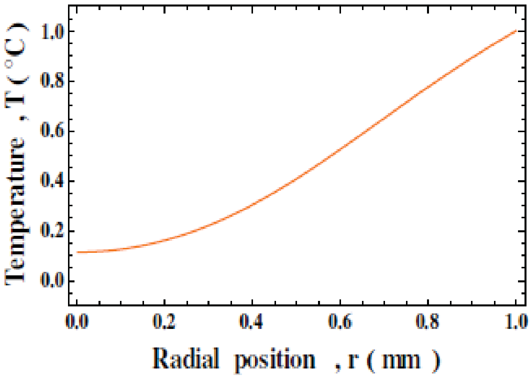
RESULTS AND DISCUSSION

Forced convection of terahertz pulse heat release in artery

The new model for laminar blood flow in analysis for overcoming the cholesterol plaque effect using principle of the forced convection terahertz pulse heat release inside arteries can be derived by modified terahertz heat diffusion equation between terahertz power-blood flow interactions in Eq.7.



(a)



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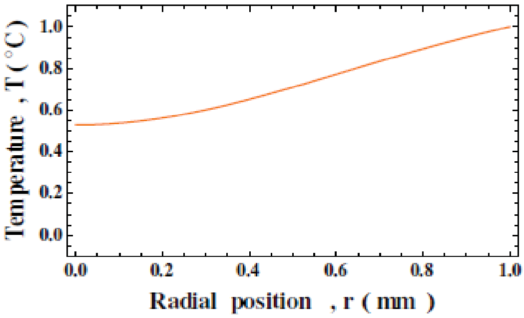


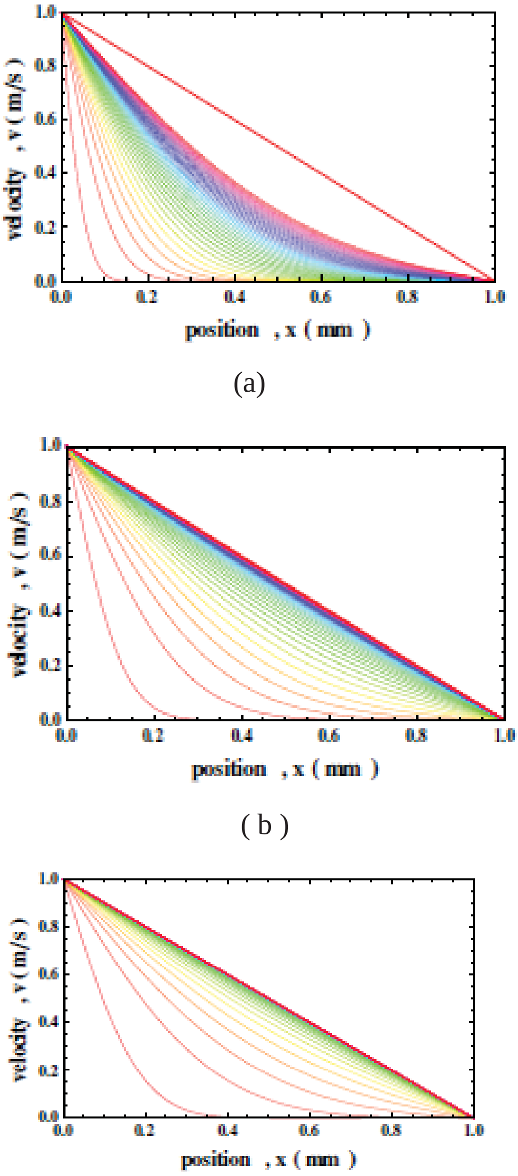
(c)

Figure 3. Forced terahertz heat convection in a artery internal laminar blood flow with change for axial positions , x from 0.2 mm in (a) to 0.6 mm in (c) before interacting and (d) after interacting with terahertz pulsa

In Figure 3, analysis focuses on the temperature distribution profile change versus radial position at different axial positions. Average blood flow velocity and diffusivity change can be determined before and after interacting with the 10 THz pulse. The governing equation and boundary conditions are chosen. Average flow velocity is 2 m/s with diffuses 0.01 before interacting. They change after interacting to 3 m/s with diffuses 0.21 for axial positions from x = 0.2 mm to 0.6 mm. As can be seen in Figure 3 a and b show that change of temperature rises higher along radial position for axial position 0.2 mm, and then significant change occur with increase axial position at 0.6 mm in Fig 3 c, and d. In fact, it is caused by heat release from the absorbed power from terahertz pulse.

Transient behavior of a 10 THz pulse-blood flow interaction in artery

This model condition in Figure 4.a,b and c show how analysis in cholesterol plaque effect of the blood flow in the slot develops in arteries. Initially the blood flow and both artery membrane walls are stationary. To start the blood flow the lower wall is brought to a constant velocity. Momentum equation



(a)

(b)

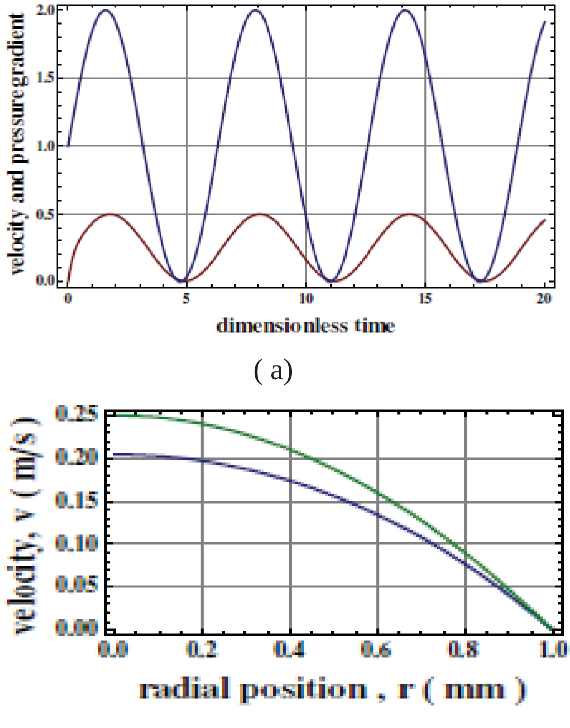
(c)

Figure 4. Transient behavior profile of a blood flow in arteries for the blood kinematics viscosity, μ is (a) 0.05, (b) 0.5 and (c) 1 .

and the no-slip boundary condition in eq. (7a) for K = 0, where μ is the kinematic viscosity and certain boundary and initial condition. The steady-state solution is the linear velocity profile. This model plots the velocity profile at constant time intervals from 0.01 to 1 s with different colors. The result chosen varies the blood kinematic viscosity to see how fast this final blood velocity profile (shown in red) is attained. Indeed, for very small blood kinematic viscosities, the response is slower. This result is to be expected since the blood kinematic viscosity unit is cm^2/s just like the diffusion coefficient and the thermal diffusivity [1]. Blood kinematic viscosity is the important factor for momentum transfer [2].

Blood pulsatile flow behavior of the 10 THz pulse-blood flow interaction in artery

The velocity distribution, u(r,t) before terahertz pulse propagates into blood flow computed numerically for a pulsatile pressure-driven blood flow in a artery . This model considerably simplifies the actual flow through veins and arteries for analyzing the cholesterol plaque effect in slow blood flow. When the blood kinematic viscosity is large and momentum diffusion is fast i.e. the Reynold number, R_w , is small about 1 , as shown in Fig. 5(a), wherein the blood velocity at the center of the artery, u (r,t) in red color, can instantaneously adjust to changing pressure, -$\partial p(t)/\partial z$ in blue color.



(a)

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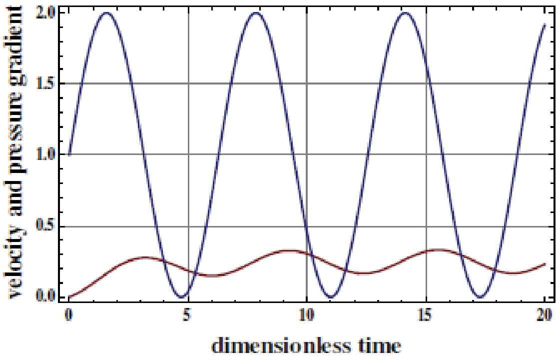

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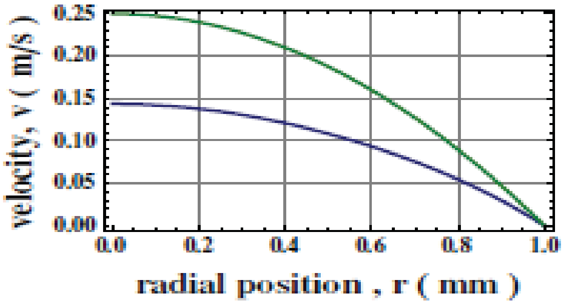
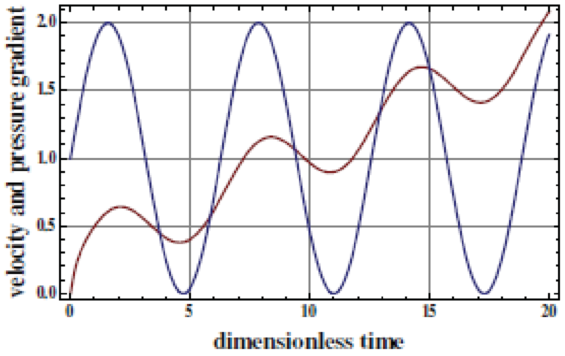
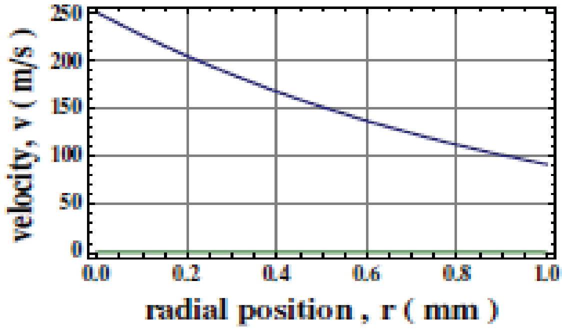


(d)

Figure. 5. Profile of pulsatile blood flow in a artery before interacting with terahertz pulse for Reynolds number , R_w =1 in (a), (b), and R_w =15 in (c), (d).



(a)



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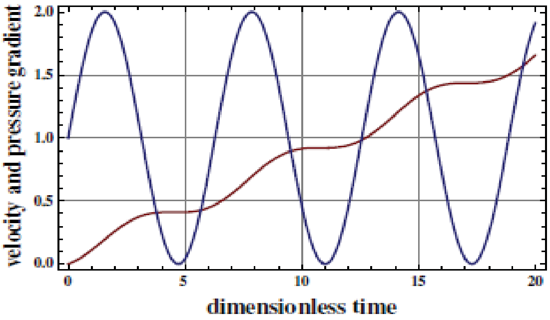

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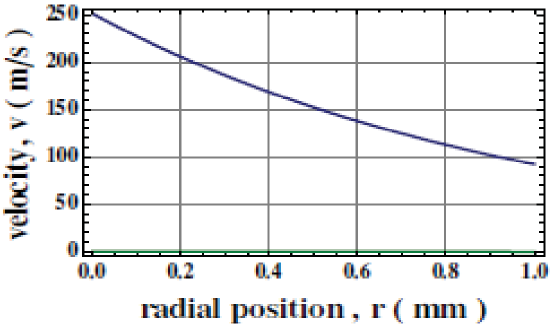

(d)

Figure. 6. Profile of pulsatile blood flow in a artery after interacting with terahertz pulse for Reynolds number , R_w =1 in (a), (b), and R_w =15 in (c), (d).

The blood velocity is then in phase with the pressure gradient. On the other hand, when the blood kinematic viscosity is small and momentum diffusion is slow, then R_w is large about 15 in Fig.5.(c) wherein the blood velocity at the center of the artery , u(r,t) lags the pressure gradient by 90°. One can see in Fig.5.(b),(d) that when everything is in phase then the blood flow behaves locally as a quasi-steady Poisueille flow, in which the green and blue curves coincide, the green curve being the parabolic solution and the blue curve taking inertial effects into account [3] . At a Reynold number from low to high value, inertial effects become significant and the velocity field is change locally parabolic in green and blue curves are a slight distinct. The velocity distribution profile, u(r,t), after interacting with terahertz pulse for a pulsatile pressure-driven blood flow in a artery shows that the significant change of model wherein the final blood flow tends to go linearly in artery. For the blood kinematic viscosity is large enough and momentum diffusion is very fast i.e. the Reynold number, R_w , is small about 1 , as shown in Fig. 6a .The blood velocity at the center of the artery ,u (r,t) in red color the small fluctuation increases to go straight line with additional time due to momentum mass transport transfer from terahertz pulse. Therefore, this change can instantaneously adjust to changing pressure, -∂p(t)/∂z in blue color. The blood velocity is then in different phase with the pressure gradient. On the contrary, when the blood kinematic viscosity is quite small and momentum diffusion is slower, then R_w is large about 15 in Fig.6.(c) and the blood velocity at the center of the artery , u(r,t) lags the pressure gradient by 180°. One can see in Fig.6.(c),(d) that when everything is in different phase then the blood flow behaves locally as a quasi-unsteady Poisueille flow [4] in which the green and blue lines coincide but decrease condition with increasing radial position, the green line being the linier solution and the blue line taking inertial effects into account. At a high Reynold number, inertial effects become significant and the reduced velocity field [2] is no longer locally linier in green and blue lines are a bigger distinct.

CONCLUSION

Analysis through the forced convection of terahertz pulse heat release in artery causes the blood flow change after interacting with terahertz pulse. Blood velocity and diffusivity for axial positions to higher with change of temperature rises along radial position caused by heat release of the absorbed terahertz pulse power in blood flow. Transient behavior of a 10 terahertz pulse-blood flow interaction in artery wherein the result chosen varies the blood kinematic viscosity to see how fast this final blood velocity profile is attained. Indeed, for very small blood kinematic viscosities, the response is slower. This result is to be expected since the blood kinematic viscosity unit is cm^2/s just like the diffusion coefficient and the thermal diffusivity. Blood kinematic viscosity is the important factor for momentum transfer. Blood pulsatile flow behavior of the 10 thz pulse-blood flow interaction in artery when the blood kinematic viscosity is large and momentum diffusion is fast i.e. the Reynold number, R_w , is small about 1 , wherein the blood velocity at the center of the artery can instantaneously adjust to changing pressure. One can see that when everything is in different phase then the blood flow behaves locally as a quasi-unsteady Poisueille flow, in which decrease condition with increasing radial position, being the linier solution and taking inertial effects into account. At a high Reynold number, inertial effects become significant and the reduced velocity field is no longer locally linier in green and blue lines are a bigger distinct.

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