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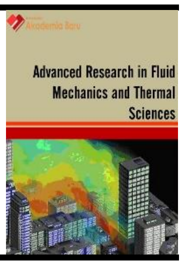

Simulation of Heat Transfer on Blood Flow through a Stenosed Bifurcated Artery

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Muhammad Sabaruddin Ahmad Jamali[1] , Zuhaila Ismail[1,*]

[1] Department of Mathematical Sciences, Faculty of Science, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia

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ABSTRACT

Atherosclerotic with high occurrence of plaque happened due to stenosis that caused narrowing of the vessel wall causing an alternation in the flow structure. Previous researchers have proved that the formation of stenosis with high probability of rupture can be characterized by the changing of the temperature distribution in the bifurcated artery. The aim of the study is to investigate the dynamic response of heat transfer in blood flow through bifurcated artery under stenotic condition. The blood vessel is modelled as a two-dimensional (2D) rigid wall and the blood flow is assumed to be Newtonian fluid, incompressible, laminar, and steady. Simulation result is obtained by using COMSOL Multiphysics 5.2, a software based on the FEM. The investigation is focused on the blood flow characteristics such as the velocity profile, temperature profile and streamline pattern of which has been discussed and fundamentally agreed well with the available literature. The outcome shows that the presence of stenosis with slightly change of the stenosis shape and value of Reynold number give appreciable influences to the velocity, temperature distribution and reverse flow recirculation as indicated by negative flow near the arterial wall.

Keywords:
Stenosis; Newtonian; COMSOL Multiphysics 5.2; Bifurcated artery; Heat transfer

1. Introduction

The study of the behaviour of blood flow in the blood vessels provides an understanding of the connection between flow and the development of diseases such as atherosclerosis, aneurysms and thrombosis. Coronary artery disease is caused by atherosclerosis that occurred due to stenosis which formed by fatty substances, cholesterol, cellular waste products, and smooth muscle cells accumulation on the arterial wall [1]. Stenosis is a localize plaque that cause the narrowing on the vessel wall and causing an alternation in the flow structure which consequently reduced the fluid flow passing to the other organs and tissues [2]. As the plaque tend to rupture, an individual may suffered to the risk of cardiovascular disease such as heart attack and stroke. The study of blood flow through single channel artery present with stenosis have been conducted by Jahangiri *et al*., [3] and Sharma *et al*., [4]. While in some other investigations [5-7], they focussed on bifurcated artery with

* *Corresponding author.*
E-mail address: zuhaila@utm.my (Zuhaila Ismail)

stenosis which is present at the mother artery or daughter artery itself. They claimed that the arterial geometry in bifurcation and bend shape particularly, will be the initiation of plaque accumulation. The fruitful study has been classified the geometry of bifurcated artery previously is according to the angulation between mother and daughter artery and according to the location of plaque. T- shaped bifurcated artery is classified when the angulation is > 70^o and plagued shifting to the bifurcation branched is more difficult, but for Y- shaped bifurcated artery is more pronounced because the angulation of mother to daughter artery is < 70^o, [8]. As observed in previous study, the flow reversal and recirculation zones are formed at downstream of stenosis and along the edge the daughter artery [5]. It is believed that the existence of flow recirculation in cardiovascular system can cause danger to the health of a person especially artherosclerosis patient since the blood is moving very slowly in this zone. In the present study, the bifucated artery consist of stenosis in the mother artery elongate into the bifurcation (daughter artery) in order to analyse blood flow characteristic in such unhealthy bifurcated artery.

The bioheat transport phenomena in hemodynamics influence more on the growth of atherogenetic processes however offer a significant insight in fruitful experimental and theoretical investigation. The understanding of the perturbation of the temperature distribution as a function of the vessel diameter is critically important to the development of appropriate models of bioheat transport. In physiological situations, the temperature distributions perturbed when the diameter of the blood vessel is large [9]. According to previous study, it is interesting to note that the localized cooling regions are present within heated tissues during hyperthermia treatment when the vessel blood is large in size [10, 11]. The normal temperature of the human blood is about 37°C. Thus, irreversible ill effects will occur in the proteins of blood which is can cause of death after such high fever [12]. Moreover, hypothermia or hyperthermia is widely used for many purposes such as open heart surgeries and cancer treatment, the temperature is substantially important. Temperature magnitude in hyperthermia treatment are important by raising the temperature of cancerous tissue above a therapeutic value 42°C, while maintaining the surrounding normal tissue at sub lethal temperature value. In the past, there has been a number of studies to examine heat transfer in blood vessels. Zaman *et al*., [13] investigate the influence heating protocol on temperature distribution in a single channel vessel and tumor tissue considering hyperthermia treatment. They concluded that large vessel has effect on the heat transfer characteristics in tissues receiving hyperthermia treatment. The effect of heat transfer considering stenosed artery under assumption of the optically thin fluid has been presented by Ogulu and Tamunoimi [14].

The heat transfer coefficient considerably effected when the channel size, shape and cross section of channel, fluid properties, and fluid flow arrangement are varying [15]. The influence of Reynold number on heat transfer in catheterize multiple stenosis artery and in nanofluid minichannel has been investigated by Jehhef and Kadhum Audaa [16] and Muhammad *et al*., [17] respectively. They concluded that there would be a significant influence of Reynolds number on heat transfer enhancement along the geometry and fluid properties. Santabrata and Subir [9] studied mathematical model of the heat and mass transfer through bifurcated arteries with stenosis in mother and daughter artery. They reported that at the throat of the constricted daughter artery, in particular, give appreciable influences on temperature profile.

So far, the existing literature investigated the flow structure and characteristic of heat transfer on Newtonian and non-Newtonian fluid models. The fluid behaves as a strong non-Newtonian characteristic in the small artery at low shear rate. However, it has been confirmed that the Newtonian model is considered as a good approximation when the shear rates is more than 100 s^{-1} (reciprocal seconds), which have a tendency to occur in large artery [18,19]. Motivated by all those studies mentioned, we propose to examine the steady laminar flow through stenosed bifurcated artery with presence of heat transfer. As the anatomical considerations, the geometry model has been constructed in present study regarding to [8,20-22]. The streaming blood is characterised by the Newtonian fluid model. The simulation result is obtained by using COMSOL Multiphysics 5.2, a software based on the FEM. In present study, a detailed evaluation on the biomechanical factors that may be responsible for this disease progression which are flow velocity and flow temperature as well as streamline pattern will be performed and discussed in details. This type of study will be advantages and aids the medical expertise with better insight to predict and analyzing the blood flow's behavior in term of velocity and temperature distribution inside artery during hyperthermia and cryosurgery.

2. Problem formulation

In order to formulate the computational domain for the stenosed bifurcated artery, these following assumptions are imposed:

1. The artery forming bifurcation is of finite length.
2. The artery consists of stenosis located in the parent vessel, proximal and ostium of bifurcation.
3. Curvatures are introduced at the lateral junctions and the flow divider of the arterial bifurcation to ensure that one can rule out the presence of any discontinuity causing non-existent of separation zones.

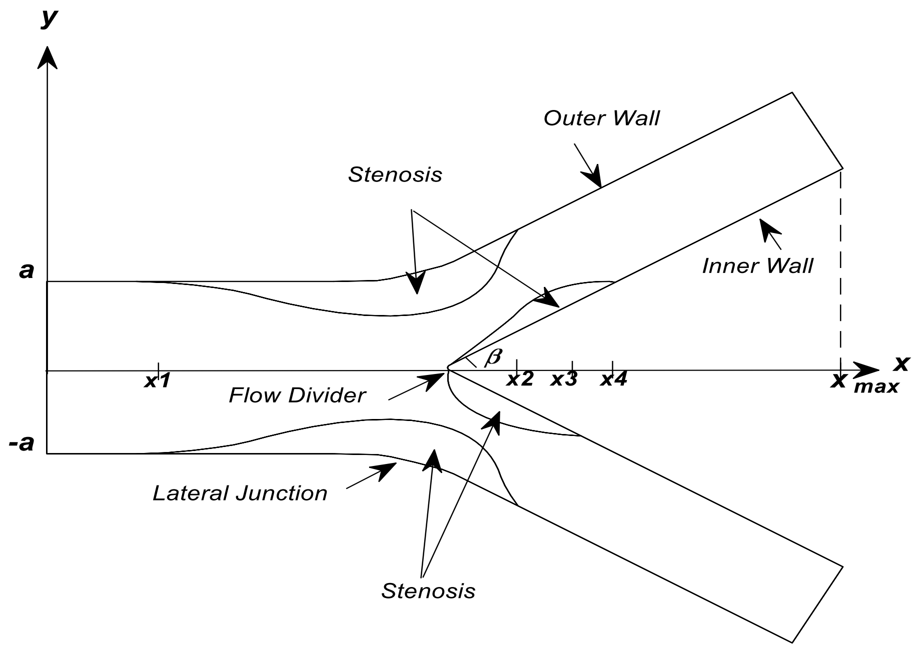


Fig. 1. Geometry of the stenosed arterial bifurcation model [8,17-19]

Note that, a is the radii of the mother artery. x_1 to x_2 is the distance of the stenosis at outer wall. x_3 and x_4 is distance of stenosis at inner wall from the flow divider. The simulation result will be performed in order to estimate the velocity profiles, temperature profile and streamline pattern.

2.1 Governing equations

The blood flow in the arterial bifurcation is considered to be in dimensionless, steady, laminar, and incompressible.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{\partial p}{\partial x}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{\partial p}{\partial x}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{1}{\mathrm{Re}\,\mathrm{Pr}}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

The Prandtl number, Pr and Reynolds number, Re :

$$\mathrm{Pr}=\frac{C_p\mu}{k}\ ,\ \mathrm{Re}=\frac{\rho u_\infty L}{\mu} \tag{5}$$

where u and v represents the velocity of blood in x and y directions, respectively. (4) shows the energy equation where C_p denotes the specific heat of blood, k is the thermal conductivity of blood, T is temperature, ρ is the density of blood and p is the pressure distribution acting on the surface.

2.2 Boundary Conditions

At the inlet, a parabolic velocity profile is imposed as

$$u(x,y)=u_{\max}\left(1-\frac{y^2}{a^2}\right) \text{ and } v(x,y)=0 \text{ at } x=0, \text{ and } -a<y<a\,. \tag{6}$$

Moreover, an uniform temperature is assumed at wall of artery, and a constant temperature $T_0=37^0C\,(310.15\mathrm{K}),$ is set at the inlet of the artery, which given by

$$T(x,y)=T_0\,,\ \text{at } x=0. \tag{7}$$

No-slip conditions along all the arterial walls: $u(x,y)=0,\ v(x,y)=0.$ A traction-free condition is applied at the outlet which can be stated as

$$\left(-p\mathbf{I}+\tau\right)\cdot\mathbf{n}=0, \tag{8}$$

where $\mathbf{n}$ represents a unit outward normal vector with the pressure point constraint, $p=0$ being implemented at $x=0$ and $y=-0.5$.

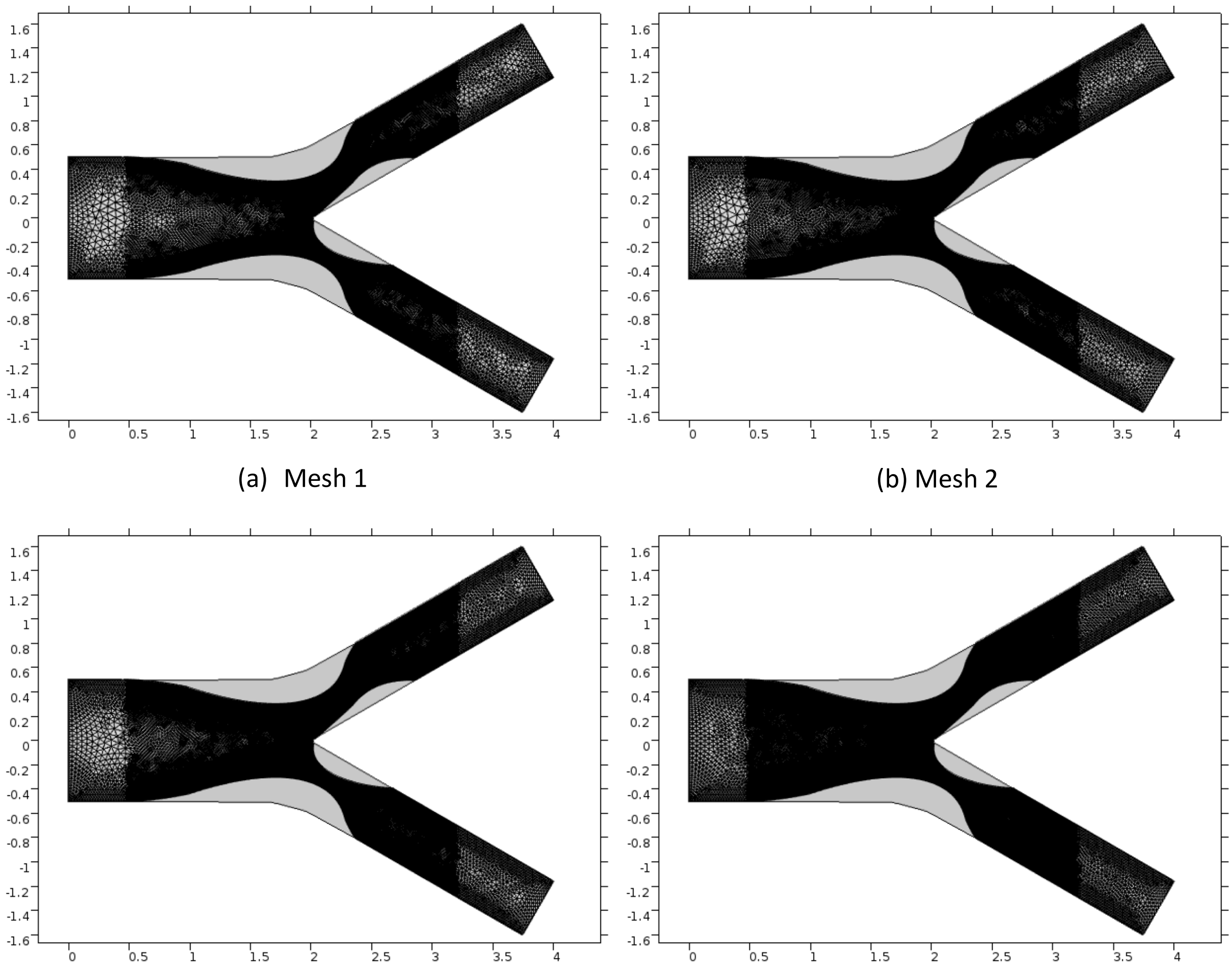
2.3 Computational mesh and Validation

The governing equations (1)-(4) subjected to the boundary conditions (6)-(8) mentioned above are solved by using the commercial software package, COMSOL Multiphysics 5.2. All computations are performed on a personal computer running 64 bit Windows 8 with speed of

1.70GHz and a RAM of 9.89GB. Mesh dependency test is performed to ensure the results obtained are not depended on the mesh parameters. Several attempt of mesh are performed, see Figure 2. The number of domain elements and maximum velocity computed using COMSOL Multiphysics in present study are summarized in Table 1.

Table 1
Mesh parameters computed using COMSOL Multiphysics

Software	Parameter	Domain elements	Maximum velocity (m/s), (Coordinate)
	Mesh 1	16947	3.7568, (2.39680, 0.46592)
Present study, COMSOL	Mesh 2	18400	3.7569, (2.39680, 0.46592)
	Mesh 3	19531	3.7562, (2.39602, 0.45583)
	Mesh 4	20593	3.72720, (2.39150, 0.47900)



(a) Mesh 1
(b) Mesh 2
(c) Mesh 3
(d) Mesh 4

Fig. 2. Different unstructured triangular mesh elements

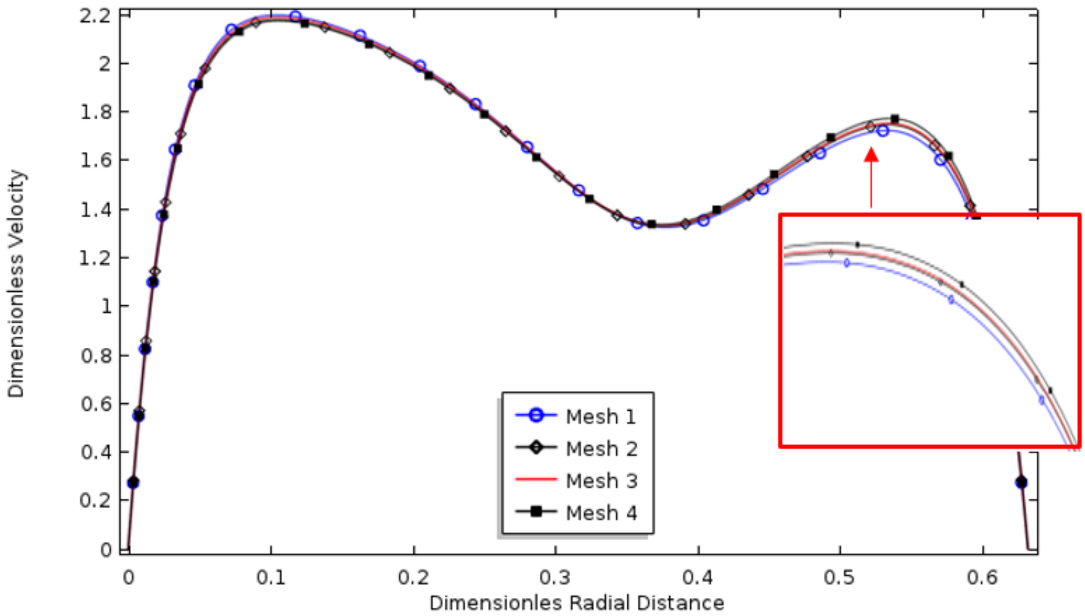


Fig. 3. Velocity profiles for different number of domain elements at constricted region

Based on the mesh dependency test demonstrated from Table 1, Figure 2 and Figure 3, maximum velocity in range between Mesh 2 and Mesh 3 are nearly identical with domain element 18400 and 19531 respectively. In order to reduce computational time, mesh 2 is selected in order to provide a satisfactory solution to our problem.

For the purpose of validation, geometry is constructed based on model proposed by [5,23]. Let (x, y) be the coordinates of a material point, then

$$R_1(x)=\begin{cases} a, 0\le x\le d,\ d+l_0\le x\le x_1 \\ a-\frac{4\tau_m}{l_0^2}\left(l_0(x-d)-(x-d)^2\right), d\le x\le d+l_0 \\ a+r_0-\sqrt{r_0^2-(x-x_1)^2},\ x_1\le x\le x_2 \\ 2r_1\sec\beta+(x-x_2)\tan\beta,\ x_2\le x\le x_{\max}-s \end{cases}\quad R_2(x)=\left\{\begin{matrix} 0, & 0\le x\le x_3, \\ \sqrt{r_0^{'}-\left(x-\left(x_3+r_0^{'}\right)\right)^2}, & x_3\le x\le x_4, \\ r_0^{'}\cos\beta+(x-x_4)\tan\beta, x_4\le x\le x_{\max}, \end{matrix}\right\}, \tag{9}$$

where $R_1(x)$ and $R_2(x)$ represent the radii of the outer and inner wall, respectively. Meanwhile, a and r_1 are the respective radii of the mother and daughter artery. r_0 and $r_0^{'}$ are the radii of curvature for the lateral junction and the flow divider, respectively. Whereas, l_0 is the length of the stenosis at a distance d from the origin. Location of the onset and offset of the lateral junction are denoted by x_1 and x_2, respectively. x_3 indicated as the apex, τ_m represents the maximum height of stenosis occur at $d+l_0/6$ and $d+5l_0/6$ while β denote half of the bifurcation angle. Parameters involved in the above expressions may be given as

$$x_2=x_1+r_0\sin\beta,\ r_0=(a-2r_1\sec\beta)/(\cos\beta-1),\ r_0^{'}=(x_3-x_2)\sin\beta/1-\sin\beta. \tag{10}$$

$$x_3=x_2+q,\ s=2r_1\sin\beta,\ \ x_4=x_3+r_0^{'}(1-\sin\beta). \tag{11}$$

The dimensional data for validation purpose have been made use from [5] and [20]:
$a = 0.0075\text{m}$, $l_0 = 0.015\text{m}$, $d = 0.005\text{m}$, $x_{\max} = 0.06\text{m}$, $x_1 = 0.025\text{m}$, $\rho = 1050\text{kgm}^{-3}$, $\mu = 0.0035\text{Pas}^{-1}$, $\beta = 30^{\circ}$, $q = 0.002\text{m}$, $r_1 = 0.51a$, $l_0 = 0.015\text{m}$, $d = 0.005\text{m}$, $x_{\max} = 0.06\text{m}$, $x_1 = 0.025\text{m}$.

Figure 4 shows result in dimensionless velocity profile obtained from COMSOL Multiphysic 5.2 at $x = 12.5$, which at the maximum constriction. For the purpose of validation, Figure 4 have been brought to the same platform as [23] and the result reveals that they are in good agreement. The outcome by COMSOL is achieved when the Reynolds number was set to 155. Parabolic curves were produced from both results at the *x*–axis with the highest value approximately 0.07. Note that, at $a = 0.4$, the dimensionless velocity value for current study and [6] are 0.069 0.069 and 0.065 respectively and give different value of 0.004.

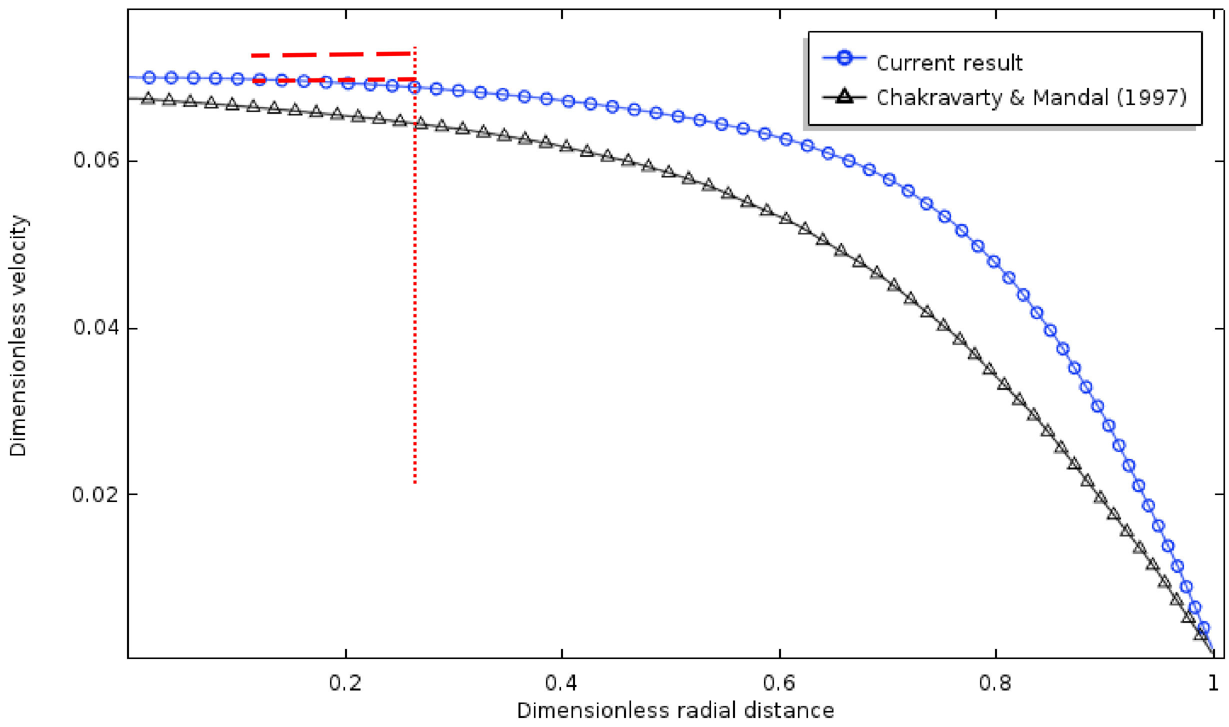
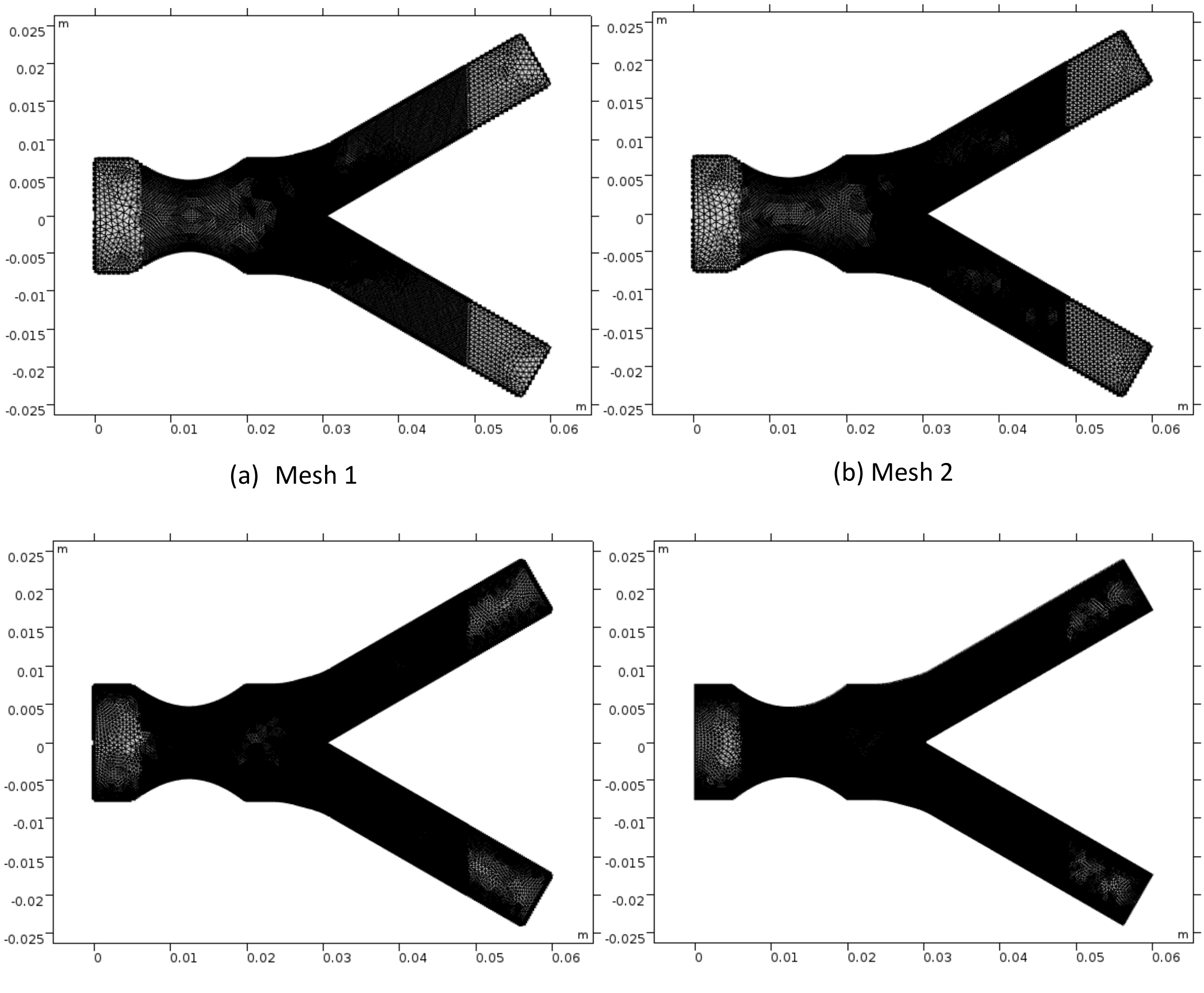


Fig. 4. Dimensionless velocity profiles, (Re = 155)

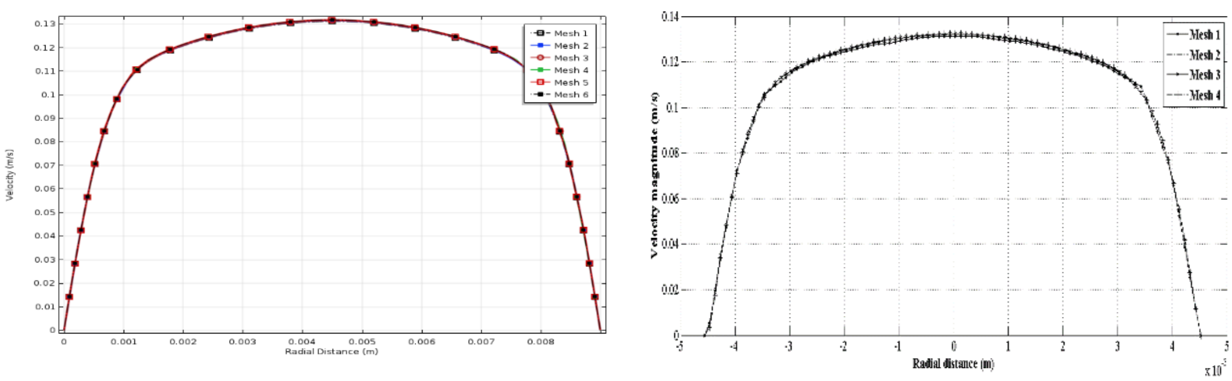
Several attempt of mesh are performed in COMSOL Multiphysics to ensure the results obtained were not depended on the mesh parameters, see Figure 5. Figure 6 shows the dimensional velocity profile obtained from COMSOL Multiphysic and Matlab. Both results obtained agreed well with each other with a very small difference recorded approximately 0.0003 m/s for the maximum velocity. Table 2 consists of the respective maximum velocity obtained from COMSOL Multiphysics and Matlab from [5] together with its coordinate.



(a) Mesh 1 (b) Mesh 2

(c) Mesh 3 (d) Mesh 4

Fig. 5. Different unstructured triangular mesh elements



(a) (b)

Fig. 6. Dimensional velocity profiles, (Re = 300) from a) COMSOL Multiphysics, and b) Matlab [5]

Table 2
Comparison of maximum velocity and their coordinate

Software	Maximum velocity (m/s)	Coordinate (x, y)
COMSOL Multiphysics	0.134902	$(0.015154, 3.4239\times10^{-5})$
Matlab, [5]	0.134610	$(0.015, 2.6418\times10^{-5})$

3. Simulations and results

Figure 7 shows the location for evaluation of the problem variables to analyse the blood flow characteristic such as the velocity profile, temperature profile and streamline pattern which is influenced by difference of Reynold number to the blood temperature with Pr=21.

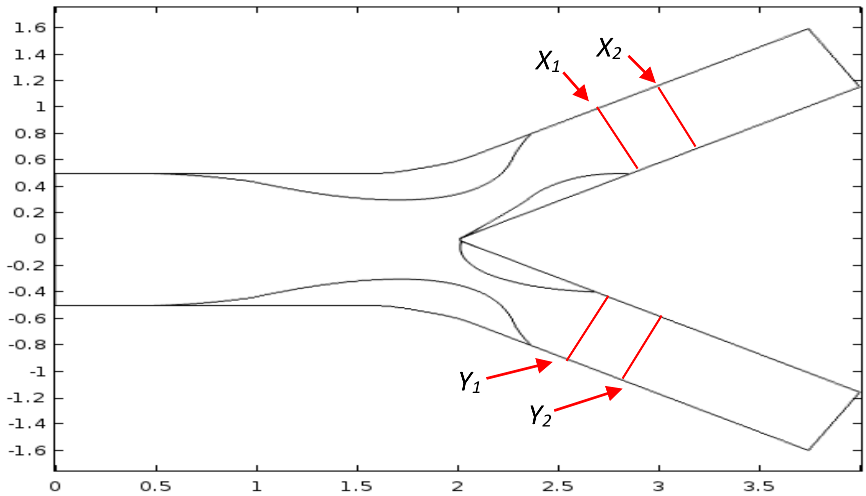


Fig. 7. Location for evaluation of problem variables

3.1 Velocity Profile

Figure 8 illustrates the axial velocity, plotted against dimensionless radial distance for selected Re= 250 and Re=550 at location *X1* and *Y1*. In all cases, velocity is zero at both sides of the wall due to the no-slip condition and the assumption that the vessel behaves like a rigid tube. The velocity for upper and lower branch is skewed to the left and right respectively, which in case means to the outer wall of daughter artery. The shape of stenosis for upper and lower branch are slightly different and give considered effect on the pattern of velocity in the blood flow. Notice that, the velocity is decreasing to negative value and increasing to the peak, then decreasing back to negative value. Note that, as the Re increase, the recirculation areas formed and increases significantly which is indicated by a negative flow near the arterial wall.

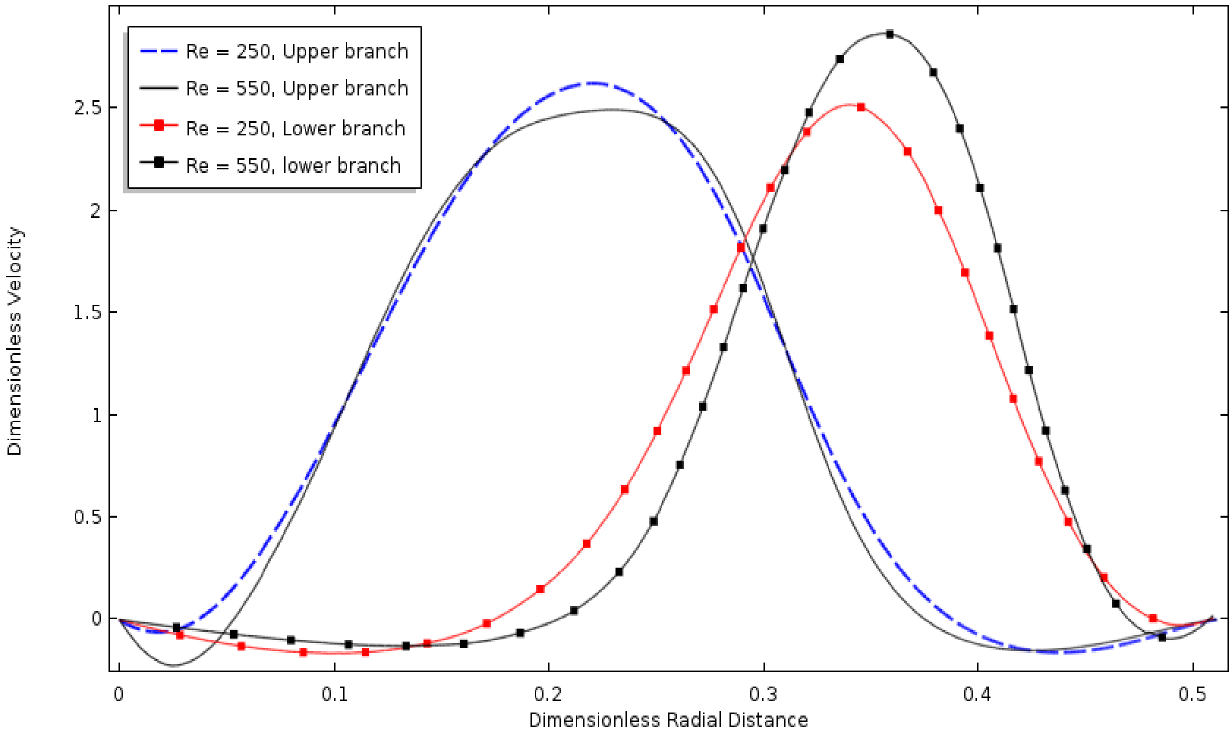


Fig. 8. Velocity profile for different Re at *X1* and *Y1*

3.2 Temperature Distribution and Temperature Profile

Figure 9 shows the heating artery with fixed temperature 43^{0}C (316.15 K) at the wall of artery, greater than the normal temperature, 37^{0}C (310.15 K). Clearly, the temperature distributes as pass through stenotic region and moves along the axis into the bifurcated arterial. Notice that the sudden jolt of temperature contour is evident in bifurcated artery due to the position and shape of stenosis. Figure 10 shows the temperature profiles with heating artery at locations *X1, X2* and *Y1, Y2* for different value of Re. For all cases, temperature is highest at both sides of the wall due to the no-slip condition and the assumption that the vessel behaves like a rigid tube. The temperature profiles get deviated downstream of the stenosis, that is, in the diverging segment of the stenosed artery where backflow occurs and recirculation zones are formed. Clearly, the pattern of temperature profiles for each case upper and lower branch are same. However, the temperature profiles both Figure 10 (a) and Figure 10 (b) seem to have point of inflexion (red box). Furthermore, the temperature for upper and lower branch is skewed to the left and right respectively, which means to the outer wall of daughter artery. For Re=300, the temperature profile near arterial wall is decreasing in value as move from distance *X1* to *X2* and *Y1* to *Y2*. However, at the same location (*X2*), the temperature profile increases as the Re increase.

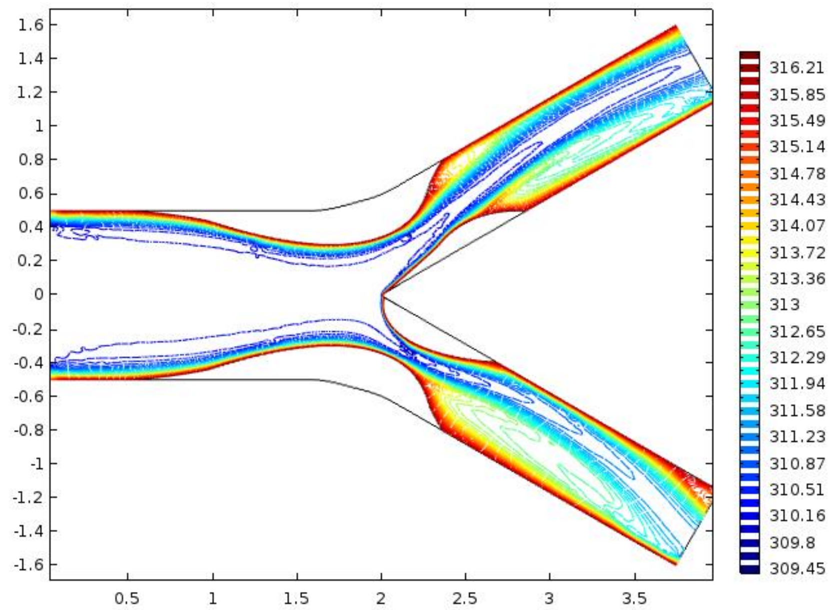
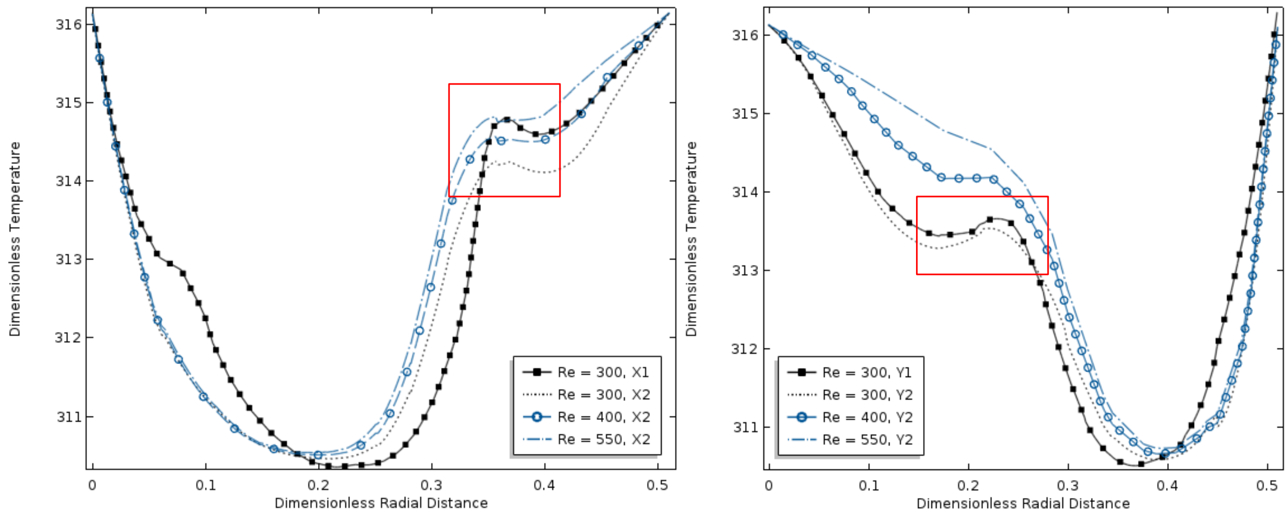


Fig. 9. Temperature contour for heating artery, (Re=300, Pr= 21)



(a) (b)

Fig. 10. Temperature profile for different Re at (a) upper branch, (b) lower branch

3.3 Streamline pattern for different Re

The influence of Re on the flow recirculation zones are illustrated on Figure 11 for Re= 100, 250, 400 and 550. Obviously, the recirculation zones are found at the offset of the stenosis and increase in sizes as the Re increase. In fact, as the Re increases, the recirculation area grows even larger and move along the bifurcated arterial wall. Hence, *Re* discovered to enhance the vortex formation and may lead to a serious complication on the flow characteristics and may also trigger plaque rupture.

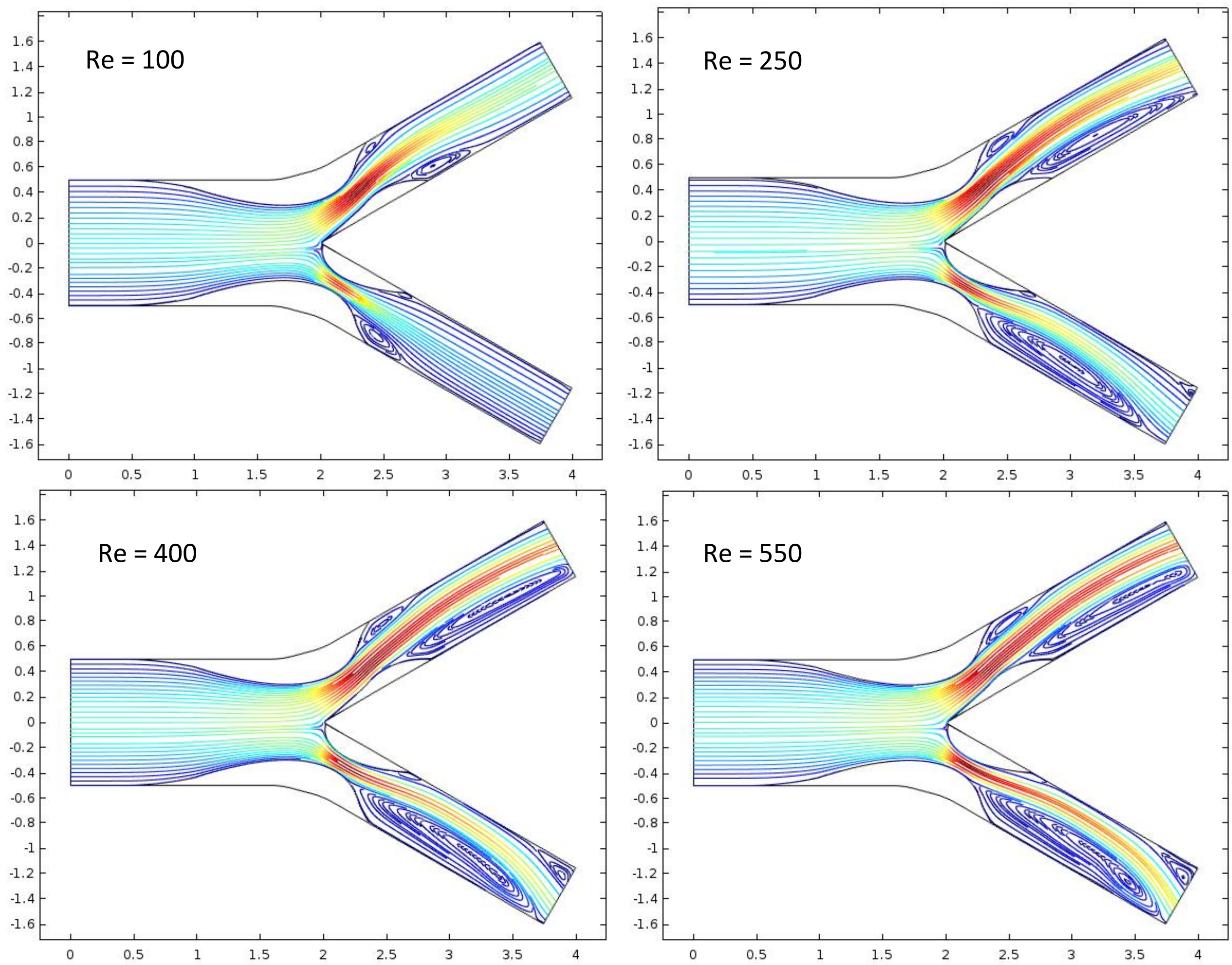


Fig. 11. Streamline pattern for different Re

4. Conclusions

A mathematical model of a steady, laminar, and incompressible blood flow in bifurcated stenosed artery has been developed. The analysis has been carried out on the heat transfer to investigate the velocity profile, temperature profile and streamline pattern at various locations considering effect of Reynold numbers to the blood flow. From the outcome, the shape of the stenosis in bifurcated artery (upper and lower branch) is one of the significant factors affecting temperature distribution because different stenosis shape establishes the different blood flow profiles and the occurrence of flow instabilities resulting in the variation of heat transfer at the plaque especially at the diverging part of stenosis. Furthermore, different Re give considerable effect to temperature variation, velocity profile and streamline pattern where backflow occurs and recirculation zones are formed at the downstream of stenosis region. This region corresponded to a region dominated by arterial wall temperature where the flow reversal and recirculation zones are formed that might have exposed an individual to a worsening effects of cardiovascular diseases. This study is beneficial for analyzing the behavior of temperature distribution inside artery during hyperthermia and cryosurgery. For future work, a generalized power law blood rheology should also be taken into account. Study can also incorporate a time and others haemodynamic effects to be discussed in details.

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