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ORIGINAL ARTICLE

Employing Sisko non-Newtonian model to investigate the thermal behavior of blood flow in a stenosis artery: Effects of heat flux, different severities of stenosis, and different radii of the artery

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KEYWORDS

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Different stenosis severity;
Different Artery radii

Abstract In this paper, a numerical investigation is carried out to study the blood flow behavior within the stenosis artery. An artery is under applying a constant heat flux on the boundary walls in this simulation. Lumen model is employed for simulation of the artery and the Sisko model is used to indicate properties of blood as non-Newtonian fluid. Also, the cone geometry of stenosis with different severities and radii are simulated. Then, effects of heat flux, different severities of stenosis, and different radii of the artery are studied on the blood flow behavior. It is reported that before stenosis, velocity is increasing and heat transfer rate is also increasing which cause temperature to be decreased in stenosis position. But after stenosis, velocity is decreased. Consequently, heat transfer rate is decreased which leads to reduction in blood temperature. Also, since the blood particles adhere to the arterial wall, with increasing radial distance from the walls, velocity is increased, which causes maximum velocity to be found in the central region. Moreover, the thermal driving force is damped in the lateral region of the artery and does not affect velocity. On the other side, as the severity increases step by step, the temperature decreases, respectively. In fact, the cross-sectional area decreases with increasing severity of stenosis. Consequently, velocity increases and causes heat transfer enhancement, which leads to a reduction in blood temperature. Therefore, the highest temperatures are related to the artery with an intensity of 20%. Although the cross-section area of the artery can change blood temperature, but its role can be ignorable in temperature enhancement and body healthy in this regard.

1. Introduction

Blood circulation plays a very important role in interactions between living tissues [1,2]. Blood helps to balance the body through its plasma by maintaining body temperature. Blood plasma is able to transfer and absorb the heat, which is also coupled with blood flow velocity within veins. Also, the effects of stenosis on fluid flow and its heat transfer are very important. So, it is necessary to study changes in blood flow and heat transfer in vessels with regard to various parameters such as vessel dimensions, clogging rate, and blood characteristics. On the other side, investigation of artery from different aspects is extensively becoming prevalent in different references [3–5]. Also, researchers [6] worked on the methods for modeling of pandemic COVID-19 estimation and analyses of COVID-19 victims rate by employing new class of distributions. Singh et al. [7] studied an epidemiological model to present computer viruses behavior and reported the solution of the problem by employing an iterative method. Shafiq et al. [8] studied thermal behavior of microorganisms in magnetic field and reported velocity and temperature alteration by both magnetic parameter. Leman et al. [9] reviewed predicting factors on modeling health behavior. Also, the role of rheology and additives in thermal behaviors of fluid was studied extensively [10–18]. Hunter [19] was the pioneer in studying the blood flow within the vein numerically. He focused on the stress and strain behaviors of vessel walls with the Newtonian blood assumption. Mukhopadhay and Layek [20] simulated blood inside the artery with different geometries. They reported that blood behaves as a Newtonian fluid. Also, Chakravarty and Sen [21] studied blood as Newtonian fluid in their investigation. Tsubota et al. [22] studied blood as incompressible and Newtonian fluid in their research and presented a particle method for blood flow simulation. Horng et al. [23] modeled the arteries in a cylinder shape with solid walls. They considered blood properties and reported that differences between constant and fluctuated velocities in the blood do not strongly affect the heat transfer rate of blood flow within the vein. Zaman and khan [24] investigated the effects of thinning/thickening of blood incisions on nanofluid rheology in the developed curved channel. They presented numerical solutions for the equations of temperature, velocity and concentration formulations to analyze hemodynamic effects due to the curvature of the narrow channel. Zaman et al. [25] simulated unsteady flow in stenosis artery and compared influences of hybrid (silver/aluminum) nanoparticles with silver nanoparticles on blood behavior. They reported that silver/aluminum nanoparticles are more helpful in attenuating wall shear stress and impedance than silver. Ali et al. [26] used Carreau fluid model to study blood flow within narrowed stenosis artery under magnetic effects which was with catheterized overlapping. They presented and analyzed graphical results of wall shear stress on the basis of different parameters of blood and flow geometry. Zaman et al. [27] investigated the effects of nanoparticles within blood fluid flowing inside an artery. They reported that presence of nanoparticles reduces axial velocity of blood within artery. Also increasing nanoparticle concentrations weaken blood streamline which leads to deviation in streamline patterns. Shareghi and Toghraie [28] studied blood flow inside a healthy vein. In their work, the Sisko model was used to study the shear stress of blood fluid within the vessel. Their results show that the Sisko model is a valid model in written code to analyses shear stress of blood flow. Afterward, Toghraie et al. [29] studied the thermal behavior of blood inside the vessel. In this work, blood behavior was indicated on the basis of the Sisko model. This work shows that Sisko is a valid model to investigate the thermal charactristics of blood. Foong et al. [30] studied blood in an artery, which was energized by a thermal heat flux via the vessel walls. They used the Sisko model to determine blood properties. In this research, the artery was healthy in cylindrical shape using the Lumen model. They reported that heat transfer is enhanced with increasing thermal heat flux rate. Yan et al. [31,32] simulated gradual stenosis in a healthy artery with different constant angles. They also employed the Sisko pattern for blood characteristics in their simulations. They focused on the dynamic behavior of blood flow in the vein and reported that various angles of stenosis could change blood velocity and shear stress. Karimipour et al. [33] studied the role of stenosis on the blood velocity and reported that stenosis increases blood flow velocity, which increases shear stress on the walls of the vessel.

Previous work are mostly focused on the employing models and also studies of blood in healthy artery. Therefore, the present paper develops previous researches with simultaneous investigations in effects of different severities, different radii of the artery, and heat flux on the flow behavior of blood flow within the stenosis artery. Thus, investigation the influences of stenosis intensity and artery dimension on the hydrodynamic and thermal behaviors can intrigue further researchers for complementary research especially by new methods. Hence, simultaneous employing of cone stenosis with different severities in presences of thermal flux has not covered yet.

2. Numerical simulation

In this paper, a numerical investigation is done to study the blood flow behavior within the stenosis artery by Finite Volume Method (FVM) which contains divergence and also it is in algebraic form for solving problems by converting volume integrals to surface integrals. UDF in Fluent is used to define blood properties. Also, simulation is carried out by Fluent software. In this simulation, a constant heat flux of q" = 4W/m^2 is applied on walls, as shown in Fig. 1.

Lumen model is employed for simulation of the artery. Also, the Sisko model is used to indicate blood properties. Also, the cone geometry of stenosis with severities of 20 %, 30 %, and 40 % is simulated. The severity of stenosis means the ratio of the height of stenosis to the radius of the artery. In next step, radii of 0.0020 m, 0.0025 m, 0.0030 m and 0.0035 m are simulated for the artery. Afterward, effects of heat flux, different severities of stenosis, and different radii of the artery are studied. First, an artery radius and severity of 0.002 m and 40 % are fixed to investigate the influences of heat flux on the flow velocity. Second, the influences of different stenosis severity are studied on the blood temperature while the artery radius remains constant. In the third step, stenosis severity is fixed, and the influences of radius are investigated on the blood temperature.

Vessel is simulated in the 3D cylindrical coordinate of r, θ and Z, as shown in Fig. 1. With supposing unique results in the angular direction of θ, the system coordinate becomes simple in 2D direction of r, Z with the following assumptions.

- Blood is homogenous, incompressible in laminar and steady-state with negligible gravity and uniform velocity.
- The artery wall is rigid.
- Taking above assumption, Fig. 2 shows schematic of simulation.
- Also, values of geometric parameters in Fig. 2 are indicated in Tables 1.

Below, the continuity and momentum equations are expressed for the incompressible fluid as following sequences [31]:

$$U = W(r, z) \tag{1}$$

$$\nabla . U = 0 \tag{2}$$

$$\rho \frac{DU}{Dt} = \nabla . \gamma \tag{3}$$

where, ρ is the fluid density and introduces Cauchy stress as below [29].

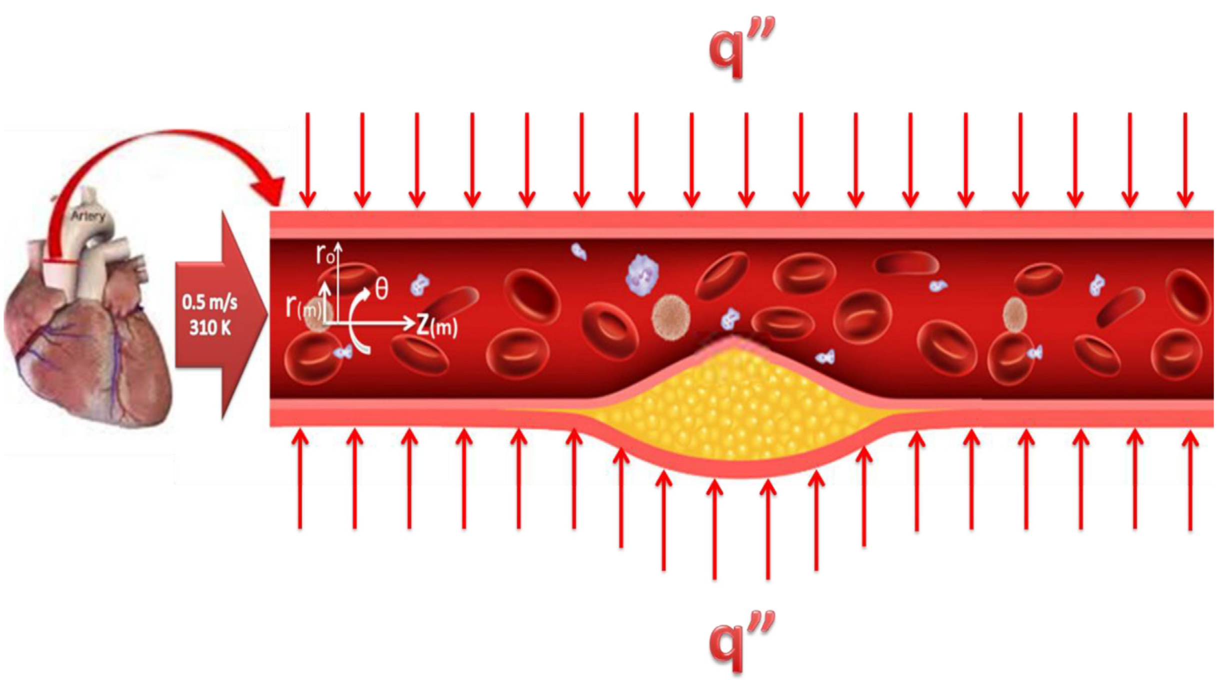

Fig. 1 Blood flow inside an artery.

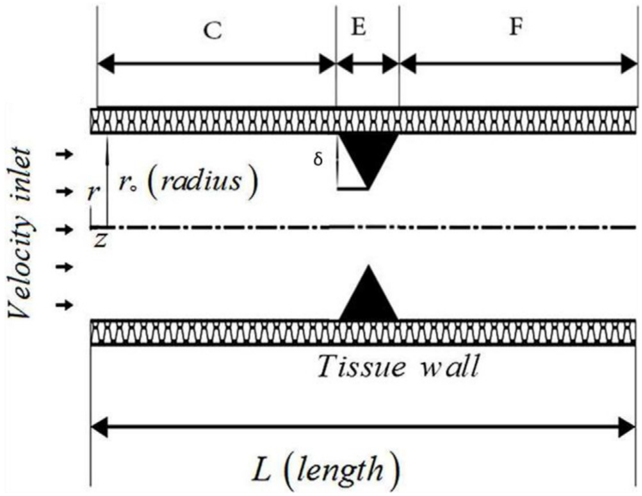

Fig. 2 Schematic of an artery taking mentioned assumptions [33].

Table 1 Geometric Parameters.

C	E	F	L
0.002 *m*	0.016 *m*	0.014 *m*	0.05 *m*

where, ρ is the fluid density and γ introduces Cauchy stress as below [29].

$$\gamma = -PI + S \tag{4}$$

Sisko model [29] is also used below equations,

$$S = \left[a + b\left(\left|\sqrt{\Pi}\right|\right)^{n-1}\right]A \tag{5}$$

$$A = L + L^T \tag{6}$$

$$L = \nabla U \tag{7}$$

$$\Pi = \frac{1}{2}tr\left(A^2\right) \tag{8}$$

where A and L are deformation rate and n = 0.639 and b = 0.1735 are non-Newtonian constants of blood [28]. Table 2 presents the blood properties at temperature of 310 K.

Also, detail of energy equation is introduced as following [29]. Energy equation is coupled with velocity components. In equation (9), β and Φ present compressibility and dissipation respectively. Also, ρ is density, T is temperature and k

Table 2 Blood properties [28].

Density	1060 $\frac{kg}{m^3}$
Viscosity	0.0035 $\frac{kg}{m.s}$
Specific heat	3770 $\frac{W.s}{kg.K}$
Thermal conductivity	0.5 $\frac{W}{m.K}$

and C_p are thermal conductivity and specific heat at constant pressure. Dissipation is function of velocity components of u and w orderly in r and z directions of cylindrical coordinate system.

$$\rho C_p\left[u\frac{\partial T}{\partial r} + w\frac{\partial T}{\partial z}\right] = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \Phi + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \beta T\left(u\frac{\partial P}{\partial r} + w\frac{\partial P}{\partial z}\right) \tag{9}$$

$$\frac{\Phi}{\mu} = 2\left[\left(\frac{\partial u}{\partial r}\right)^2 + \left[\frac{u}{r}\right]^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial r}\right) - \frac{2}{3}\left(div\vec{U}\right)^2$$

For the temperature gradient, following equation is also derivated [31].

$$\frac{dT}{dz} = \frac{2q''}{\rho W_c C_p r} \tag{10}$$

which q'' is constant heat flux and T_w and T_m are wall and bulk temperatures, respectively. Also, we have [32].

$$\frac{11\rho W_c C_p r^2}{96k}\frac{dT}{dz} = T_W - T_m \tag{11}$$

At artery walls, velocity is zero and constant heat flux is applied as much as $q'' = 4$ W/m^2.

$$q'' = -k\frac{dT}{dz} \tag{12}$$

Then Nusselt number is defined as known following equation,

$$Nu = hd/k \tag{13}$$

Fig. 3 presents meshing structures and Table 3 presents details of 5 types of mesh which are employed for independency test of simulation.

Then, grid dependency test demonstrated that meshing size is suitable and converged. After comparison of mesh types, C type is employed. Also, this work is valid due to published previous part of this research as reference [28].

3. Result and discussion

In this work, blood flow was simulated inside the stenosis arteries with different severity of the cone shape of stenosis. The Sisko model was used to indicate the blood properties. In this section, at first, the severity and the cross-section area are fixed to investigate the effects of heat flux on the blood velocity. Secondly, the radius of the artery is fixed, and the effects of different stenosis are studied on the blood temperature. Thirdly, influences of the cross-section area of the artery are investigated on the blood temperature. Results and discussion are as follows.

Figs. 4 and 5 present the blood velocity within an artery. The vertical axe shows velocity values in m/s unit, and horizontal axe shows axial and radial distances orderly from references of the entry section and center of vein. Each figure contains two profiles that are related to two different conditions of with and without applying heat flux. The radius of the artery is 0.002 m, and the severity of stenosis is equal, with 40 % of the cross-section area of the artery. Also Sisko blood model is unique for all the above results. As can be seen from

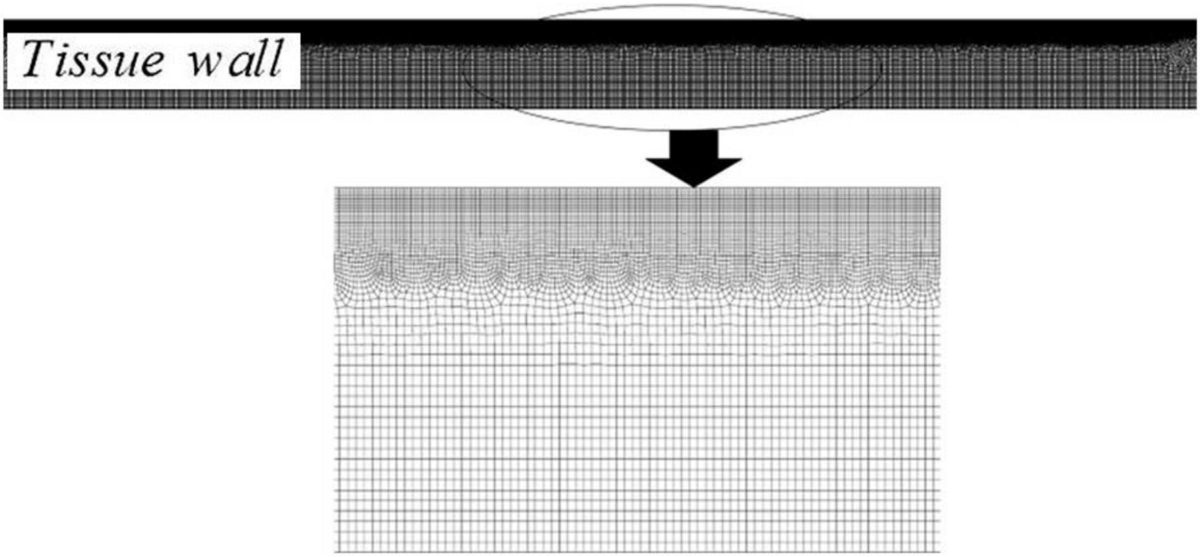

Fig. 3 Meshing structures.

Table 3 Data of 5 mesh.

Mash	Element in Z*r directions
A	850*10
B	1250*15
C	1670*20
D	2100*25
E	2520*30

Fig. 4, the velocity values at the beginning of the artery are as much as 0.05 m/s for both conditions of with and without heat flux. Afterward, velocity profiles are increasing with increasing length from the inlet, so that at Z(m) = 0.002 m, the velocities reach to 0.1 m/s roundabout. Next, with increasing axial distance, velocity profiles reach to 0.09 m/s with small fluctuations. But as soon as the blood flow reaches the length of 0.02 m from the inlet reference, the velocity increases rapidly to reach its maximum value of 0.235 m/s at Z(m) = 0.028 m. After this point, blood velocity decreases rapidly with a previous similar slope that reaches a stable value of 0.09 m/s again. The reason for these increases and decreases behaviors is due to exposure to stenosis and passing blood flow through it and its consequences. Because by reaching the location of the blockage, the arterial duct becomes narrowed, this causes narrower blood flow which means a reduction of the cross-sectional area of the vessel. Therefore, this phenomenon leads to an increase in the flow velocity and its influences on the thermal behaviors. Nevertheless, as shown in Fig. 4, the profiles overlap, and the heat flux has no effect on increasing or decreasing the velocity. Because the heat flux direction is perpendicular to the blood flow direction, so, the heat force cannot affect the velocity of blood flow in the axial direction. On the other hand, the magnitude of the hydrodynamic driving force in the direction of the arterial axis is much stronger than the thermal driving force perpendicular to the flow axis. Therefore, as a specific result from Figs. 4 and 5, it is concluded that influence of heat flux is ignorable throughout the artery. Fig. 5 also shows that the radial velocity is decreasing gradually with increasing radial distance from the vessel wall. The maximum velocity is as much as 0.25 m/s in the center of blood flow while the minimum is seen at the wall of the artery. Because the blood particles adhere to the arterial wall due to the non-slip condition. Therefore, with increasing radial distance from the walls, effects of viscosity and friction are reduced on the velocity which causes maximum velocity to be found in the center of the artery.

Figs. 6 and 7 present the effects of stenosis on the temperature profiles of blood flow inside the arteries with cone geometry of stenosis. The vertical axe of these figures is graded to indicate temperature values in the Kelvin unit, and horizontal axis show axial and radial distances orderly from references of the inlet of vessel and center of vein. Each figure contains three profiles that are related to three different stenosis severities of 20 %, 30 %, and 40 %, respectively. The radius of the artery is 0.002 m. Also Sisko blood model is unique to get temperature results. It can be seen from Fig. 6 that blood temperature profiles of different stenosis are matched from the beginning of the artery at Z(m) = 0.1 m to the stenosis location at Z(m) = 0.028 m. Therefore, severity does not affect blood temperature in this region because the cross-sectional area is constant, and there is no change in velocity profiles. Therefore, the heat transfer rate is the same in all profiles. However, in the event of stenosis, the temperature profiles are spaced apart, and the temperature decreases with increasing severity of the stenosis. Hence, it is seen that the highest temperatures are related to the artery with an intensity of 20 % and lowest temperature is belonged to artery with intensity of 40 %. Thus, as the severity increases step by step, the temperature decreases, respectively. In fact, the cross-sectional area and blood flow diameter decreases step by step with increasing severity of stenosis, while oxygenation process is kept and mass flow rate of heart pumping power. Consequently, velocity increases and causes heat transfer enhancement, which leads to a reduction in blood temperature. Fig. 7 also shows that at radial distances from r = 0 to r = 0.0008 m, the temperature profiles are fixed together with a constant value of 310 K, roundly. Therefore, the penetration power of the heat flux is limited to the blood layers are

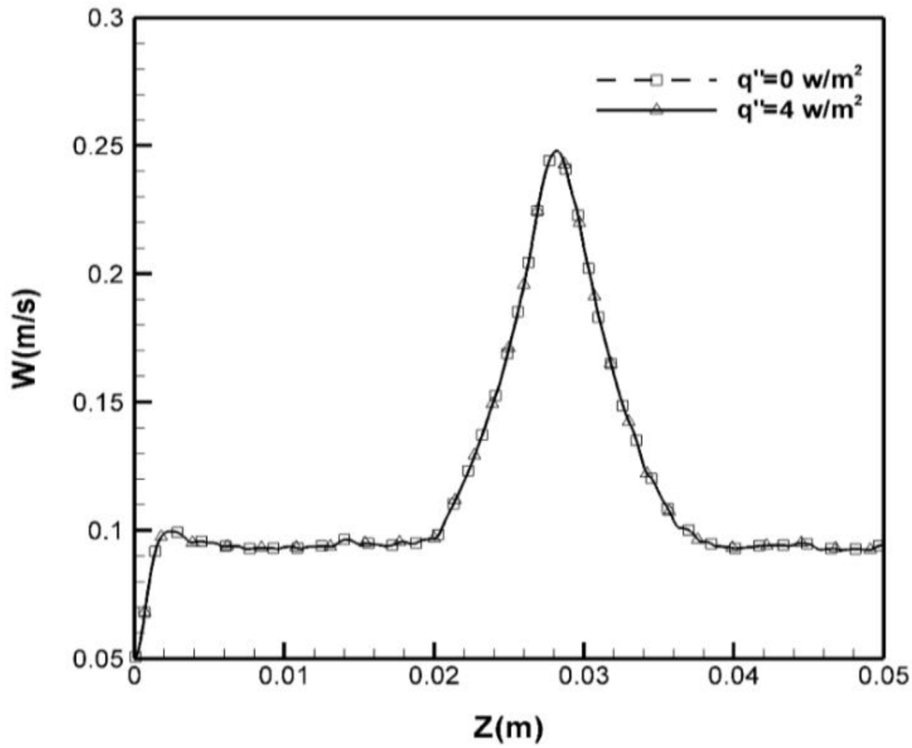

Fig. 4 The axial velocity of blood in the stenosis artery.

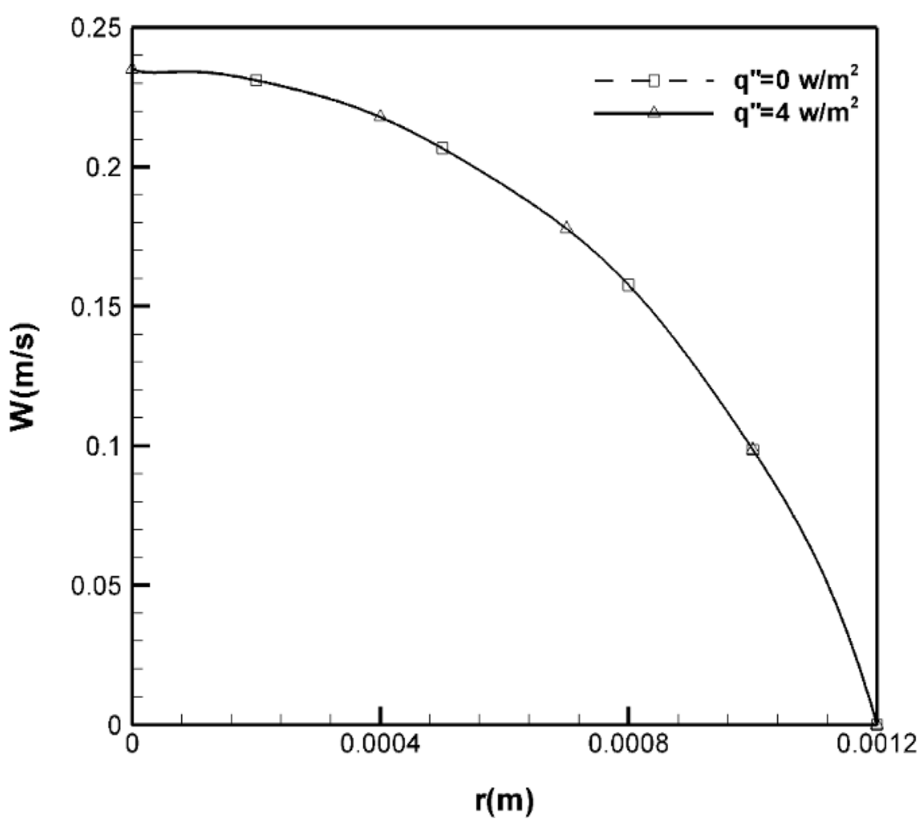

Fig. 5 The radial velocity of blood in the stenosis artery.

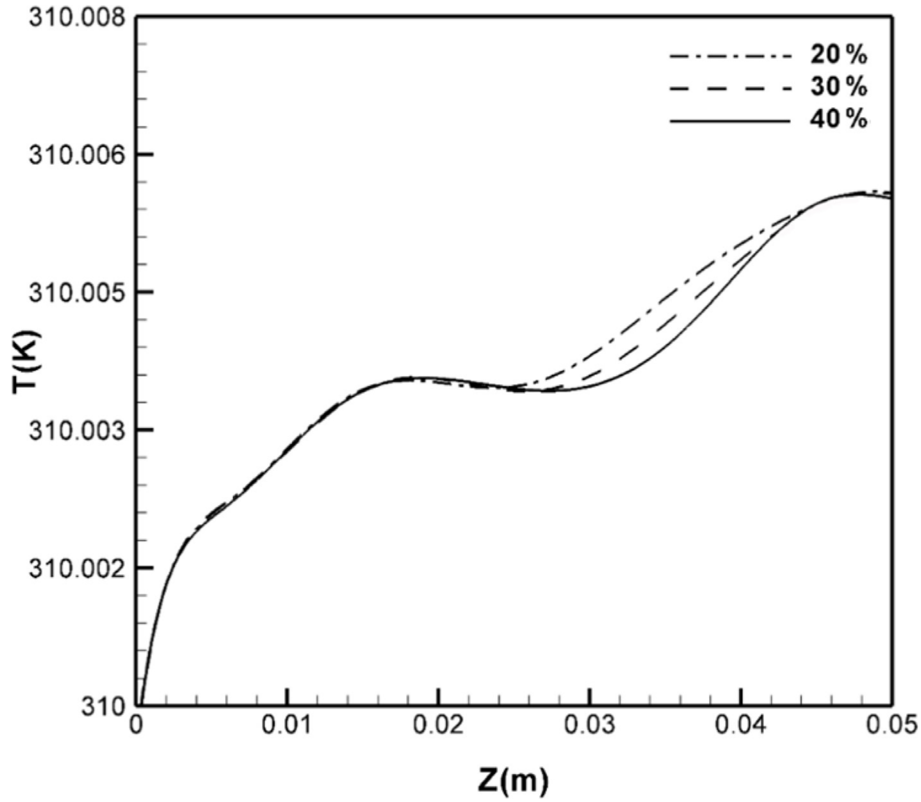

Fig. 6 The axial temperature of blood in the artery with different stenosis.

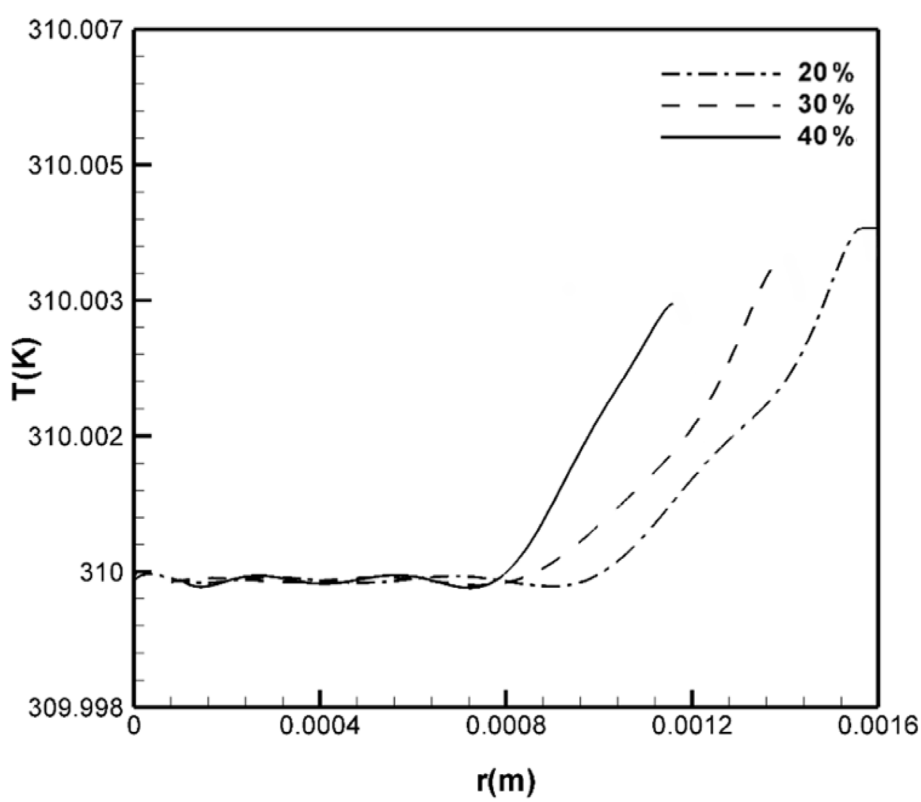

Fig. 7 Radial temperature of blood in artery with different stenosis.

in the vicinity of the walls. Because adjacent blood layers received heat flux and damped it completely so that it does not reach to the central layers of blood in the arteries. It is observed that, with increasing radial distance and reaching to vessel walls, the temperature suddenly rises with a sharp slope in adjacent layers of the arterial wall, which are receiving external thermal energy from heat flux. According to Fig. 7, the maximum temperature values for arteries with severities of 20 %, 30 %, and 40 % are 310.0042 K, 310.0035 K, and 310.003 K, respectively. Hence, the severity of the blockage leads to a change in temperature of 0.0012, which is a very small change, indicating that the blockage in the vessel is not dangerous for the increase in blood temperature and its effects on hematocrit.

Figs. 8 and 9 present the effects of different cross-section areas on the temperature profiles of flow within arteries. Each

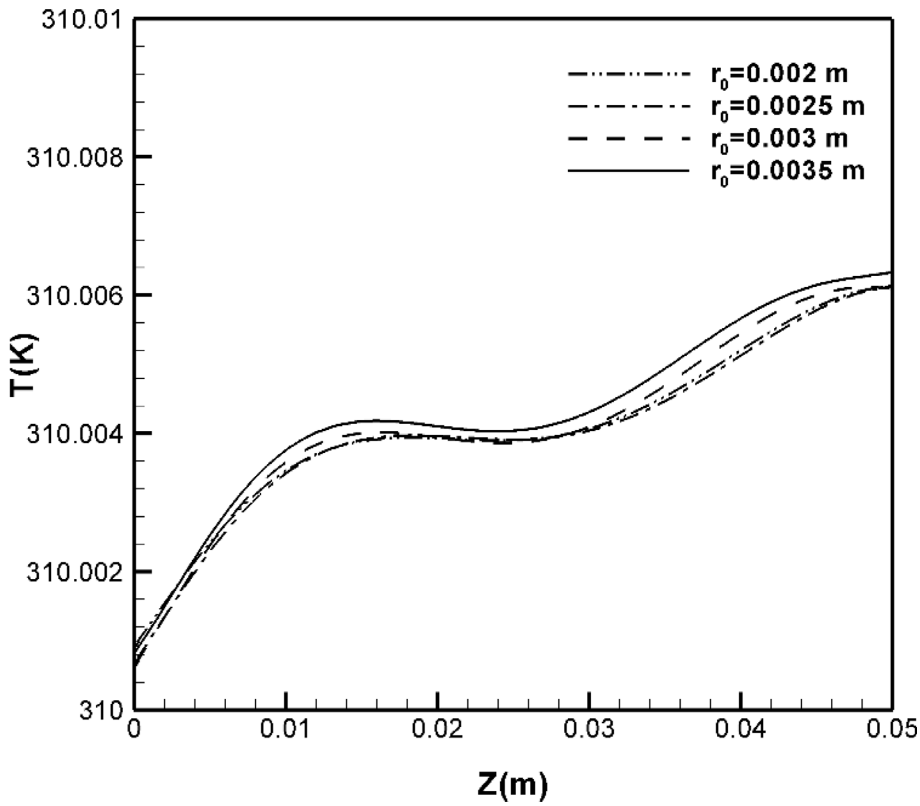

Fig. 8 Axial temperature of blood in stenosis artery with different radii.

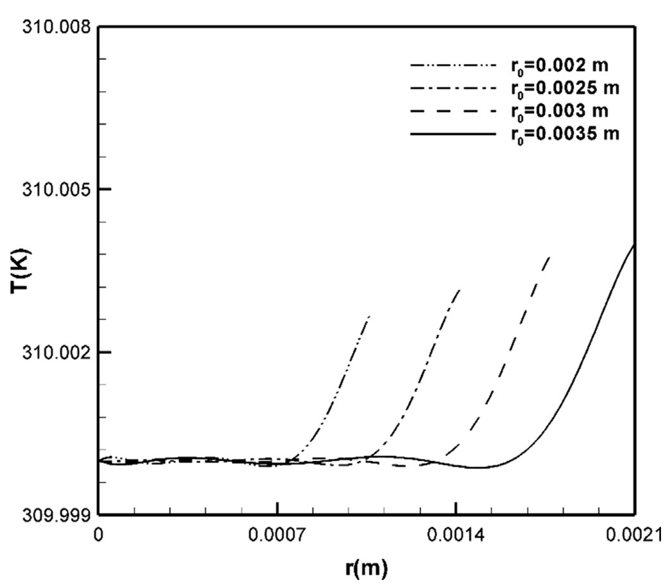

Fig. 9 The radial temperature of blood in the stenosis artery with different radii.

figure contains four profiles that are related to different artery radii. The severity of stenosis is fixed in 40 % of the cross-section area of the artery. Also, Sisko blood model is fixed in UDF code for the blood properties. For all above result, constant heat flux of 4 W/m^2 was prepared on the boundaries of vessels. As can be seen from Fig. 8, temperature profiles of blood flow within arteries with radii of 0.002, 0.0025, 0.0030, and 0.0035 are approximately matched together with a similar trend. It is seen in the section from entry at Z(m) = 0 to Z (m) = 0.1 m that profiles are enhanced from 310.0008 K roundly to around values of 310.0040 K due to entry effect. Afterward, they reach to stable condition in the section from Z(m) = 0.1 m to stenosis position at around of Z(m) = 0.02 8 m. After stenosis position, blood temperatures for all cases of radii are increased and reached to around values of 310.006 K. Because, velocity profiles are in rising and falling trends before and after stenosis positions which alters heat transfer rate. Therefore, this trend is convinced by the effect of velocity behavior under stenosis influences on the dynamic of blood flow within arteries. In fact, before stenosis, velocity is increasing and heat transfer rate is also increasing which causes temperature to be decreased in stenosis position. But after stenosis, velocity is decreasing and causes heat transfer rate to be decreased which leads to reduction in blood temperature. Also, it is clear from Fig. 8 that the level of profiles is increased in the order of increasing artery radius from 0.002 to 0.0025, 0.0030, and 0.0035 m, respectively. It means increasing artery radius causes the temperature of blood flow to be increased. Therefore, increasing the cross-section area of the vessel can decrease the heat transfer rate. Thus, with decreasing artery radius, blood temperature is increased. It is seen from Fig. 9, that temperature profiles of blood are completely stuck together in the middle section of the vein in radial distances from r = 0 m to r = 0.0007 m. But after r = 0.0007 m, they are increasing with a constant slope to reach their maximum values in the vicinity of walls at the boundaries of the artery. According to Fig. 9, differences between minimum and maximum values of temperature are as much as 0.0026 K, 0.0029 K, 0.0033 K, and 0.0038 K in order of employing an artery with radii of 0.002 m to 0.0025 m, 0.0030 m and 0.0035 m respectively. Therefore, although the cross-section area of the artery can change blood temperature, but its role can be ignorable in temperature enhancement and body healthy in this regard.

4. Conclusion

In this work, a numerical investigation was carried out to study the artery radius and stenosis on the blood flow behavior under boundary heat flux. It was seen that by reaching the location of the blockage, the arterial duct becomes narrowed; this causes narrower blood flow which means a reduction of the cross-sectional area of the vessel. Also, because of rising and falling trends of velocity before and after stenosis positions, heat transfer rate is altered. In fact, before stenosis, velocity is increasing and heat transfer rate is also increasing which causes temperature to be decreased in stenosis position. But after stenosis, velocity is decreasing and causes heat transfer rate to be decreased which leads to reduction in blood temperature. Also, it was reported that the highest temperatures is occured in the artery with an intensity of 20 % and lowest temperature is belonged to artery with intensity of 40 %. Thus, as the severity increases step by step, the temperature decreases, respectively. It was observed that the maximum temperature values for arteries with severities of 20 %, 30 %, and 40 % were 310.0042 K, 310.0035 K, and 310.003 K, respectively. Hence, the severity of the stenosis leads to variation in temperature as much as 0.0012, which is a very small change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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