CFD Letters

Newtonian and Non-Newtonian Blood Rheology Inside a Model of Stenosis

Open Access

Mohammed Ghalib Al-Azawy[1,*], Saleem Khalefa Kadhim[2] , Azzam Sabah Hameed[3]

1   Department of Mechanical Engineering, College of Engineering, Wasit University, 52001 Al Kut, Wasit, Iraq
2   Control and System Engineering Department, University of Technology, 10066, Baghdad, Iraq
3   Department of Mechanical Engineering, College of Engineering, Wasit University, 52001 Al Kut, Wasit, Iraq

ARTICLE INFO

ABSTRACT

In order to imitate the atherosclerosis artery disease and determine the key issues, Computational Fluid Dynamics (CFD) is able to play a leading rule in the analysis of flow physics within the clogged arteries, in particular the stenosis artery. The problem of blood flow blockage through the blood vessel has been investigated numerically within a stenosis artery. In this work, a CFD technique was employed to solve the three-dimensional, steady, laminar and non-Newtonian Carreau model blood flow through a stenosis artery using Star-CCM+ software. The shape of stenosis that has been selected is a trapezoidal with two cases (70% and 90% blockage). Shear rate, streamlines, vorticity and importance factor are examined to assess the influence of non-Newtonian model through the test section, the Carreau model was compared with Newtonian model. The clinical significance of the shear rate is reported for the examined cases, observing that the levels of non-Newtonian model are predicted to be higher in the 90% blockage than that observed within the 70%; the same finding as related with the axial velocity and vorticity. The levels of re-circulation areas and vorticity are showed to be enlarged in the Carreau model compared with the case of Newtonian.

1. Introduction

Arteries are large blood vessels that deliver the blood away from the heart to all parts of the body. Narrowing of these vessels is called stenosis, and this may be causing many diseases such as stroke.

Fluid mechanical studies inside the arteries have been ongoing since 1960s in an attempt to understand the behavior of blood flow in order to predict and avoid the blood damage. Previously, the researchers investigated the flow behavior with simplifications such as laminar, steady, and Newtonian fluid [1, 2]. Hariharan *et al.,* [3] performed an experimental investigation using particle image velocimetry (PIV) in order to assess the blood flow parameters related to medical device safety

---

* *Corresponding author.*
E-mail address: mgalazawy@uowasit.edu.iq (Mohammed Ghalib Al-Azawy)

through a nozzle model that proposed by the US Food and Drug Administration (FDA). Pressures and fluid velocities were examined in this model as well as the turbulent flow quantities.

Furthermore, the researchers noticed that serious problems associated with the flow of blood after the stenosis especially as related with the non-Newtonian effects [4–7]. Johnston *et al.*, [6] used five different blood viscosity models (Carreau, Walburn-Schneck, Power law, Casson and Generalised power law model) as well as the Newtonian model in order to study the wall shear stress effects within different arteries. The authors examined local and global non-Newtonian importance factor through these models and they advised to use the non-Newtonian model to achieve better estimate of wall shear stress at low shear. Furthermore, Molla and Paul [8] used five different models of non-Newtonian (Power low, Cross, Carreau, Quemada and modified-Casson). In this study, the authors evaluated the levels of these models on the pressure distribution and wall shear stress. The results showed that the reduction in shear stress was bigger when considering the effects of blood viscosity models.

In addition, Carreau Yasuda model was used by Halder *et al.*, [9] to examine the blood flow within artery stenosis using several variants of pulsatile flow and different inlet velocity profile. The authors investigated the wall shear stress, velocity fields, strain rate and vortex distribution for Newtonian and non-Newtonian models and noticed that there were significant differences between these models models. More recently, a study in 2020 by Foong *et al.,* [10] evaluated the flow of blood inside an artery using Newtonian and non-Newtonian approaches numerically with applying a constant het flux. The authors reported the temperature and Nusselt number of blood flow using different parameters of the non-Newtonian (Sisco) model. In this study the authors got different values of temperatures in case of Sisco model comparing with the Newtonian one. Yan *et al.*, [11] continued the work by investigating the behavior of blood flow within the artery using a cone shape of stenosis and Sisko fluid model was used a non-Newtonian model. In this study, the authors applied a constant heat flux on the wall in order to evaluate the velocity profile through the artery, noticing that there were no affect due to different directions of heat flux; whereas the non-Newtonian flow of blood prepared higher temperature than that of Newtonian flow because of higher heat transfer rate; as a result this variation affected on the health.

Even though stenosis arteries have been assessed with different assumptions such as viscosity effect and nature of flow [7, 12] and various simulations have been demonstrated [13] but in simulating the rheology of blood inside the arteries, one of the significant issues that need to be taken into account is how to treat the flow of blood in order to evaluate correctly the strain rate and other parameters that related with the main problems such as thrombosis. Therefore, in the current study, a non-Newtonian Carreau model has been utilized in order to investigate the blood flow through 3D stenosis artery utilizing STAR-CCM+ v.12.02.011. Hence, the aim of the present study is evaluating the impact of using non-Newtonian models through the stenosis artery (Trapezoidal shape).

2. Problem Description

In the current investigation, blood vessel is modelled as a tube having blockage area. The shape of blockage area is presented as trapezoidal whereas the other parts as tube to point out the stenosis artery as shown in Figure 1. Table 1 illustrates the cases that used in the present work. The diameter of the artery and the whole length of stenosis are 3 and 10 mm respectively. In order to ensure fully developed flow, the inlet was located 100 diameter of the artery upstream of the stenosis area, and the outlet was located 80 diameter of the artery downstream the stenosis area; following Hariharan *et al.,* [3]. The Newtonian model, as well as the non-Newtonian model, Carreau, is used through the

entire test sections. Two different area stenosis are include in the present investigation: 70% (moderate) and 90% (severe), as calculated by Kamangar *et al.,* [14].
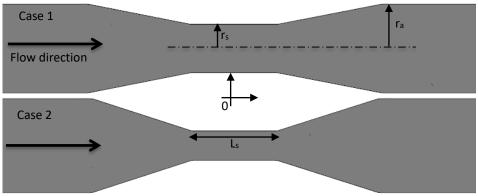

Fig. 1. Model geometry of the cases used in the present work

Table 1
Details of the cases used in the present work (All the dimensions are in mm)

Description	Case 1 (Moderate 70%)	Case 2 Severe (blockage 90%)
r_s (radius of stenosis)	0.82	0.47
r_a (radius of artery)	1.5	1.5
L_s (length of stenosis)	3	3

3. Computational Details

CFD is one of the common tools that used to investigate the flow physics through the medical devices. All simulations in the present work are executed using a commercial CFD software STAR-CCM+ v.12.02.011 [15]. This code was employed to solve the steady Navier-Stokes equations based on a finite volume method as follows [16]

$$\frac{\partial u_i}{\partial x_i} = 0, \quad \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\mu(S)\frac{\partial u_i}{\partial x_j}\right] \tag{1}$$

where u_i is the velocity gradient, $u_i = (u, v, w)$, x_i is the Cartesian coordinate, $x_i = (x, y, z)$; while p is the pressure and ρ is the density. $\mu(S)$ is the blood viscosity that depends on the shear rate magnitude which is computed from the shear rate tensor as following

$$S = \sqrt{2S_{ij}S_{ij}}, where \ S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{2}$$

Blood was assumed as laminar. Furthermore, in order to assess the effects of non-Newtonian models on the flow behaviour within the model especially after the stenosis area, the flowing blood is treated as non-Newtonian and characterised by Carreau model; on account of superior performance of non-Newtonian flow effects through the medical devices as identified previously by the present author Al-Azawy *et al.,* [4, 17] and the other researchers such as Johnston *et al.,* [6] and Molla and Paul [8]. The flowing blood is treated as non-Newtonian and characterised by Carreau model. The Carreau model complies with the following form

$$\mu(S) = \mu_\infty + (\mu_0 - \mu_\infty)(1 + (\lambda S)^2)^{(n-1)/2} \tag{3}$$

where μ_∞ is the infinite shear viscosity ($\mu_\infty = 0.00345$ Pa.s), μ_0 is the viscosity of blood at zero shear rate ($\mu_0 = 0.056$ Pa.s), λ is the relaxation time constant ($\lambda = 3.313$ s) and $n = 0.3568$ [18].

Six separate meshes were generated to explore the spatial mesh resolution as shown in Table 2. In the present study, polyhedral mesh was employed for the CFD model using STAR-CCM+ v.12.02.011[15], as illustrated in Figure 2. A prism layer of 5 layers was employed to resolve the boundary layer.
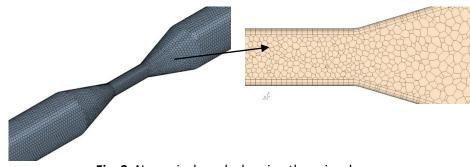

Fig. 2. Numerical mesh showing the prism layers

Table 2
Details of mesh models

Meshes	M1	M2	M3	M4	M5	M6
Total number of cells	93 924	213907	696 608	997 313	1 244 421	2 162 820

Figure 3 displays the variation of axial velocity and vorticity along a horizontal line (0.6 mm above the centerline) which represent a grid-independence study. It is clear from this figure that the prediction of axial velocity and vorticity for the meshes M5 and M6 are very close in comparison with the other four meshes. Consequently, the mesh M5 (1,244,421 cells) is selected for the following simulation to capture the properties of fluid through the entire body.

In addition, the same inlet velocity was applied to all simulations cases (v_{linet} = 0.6 m/sec), outflow boundary condition with no-slip conditions applied at the walls.
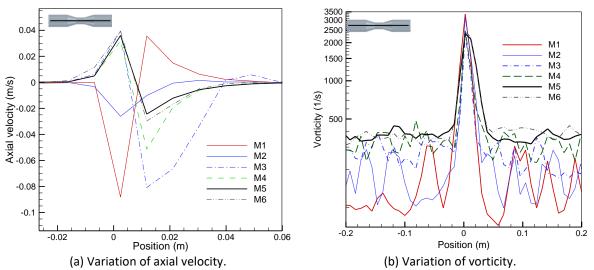

(a) Variation of axial velocity. (b) Variation of vorticity.

Fig. 3. Profiles of axial velocity and vorticity variation located along a horizontal line (0.6 mm above the centerline)

4. Results and Discussion

4.1 Examination of Blood Rheology

Validation with experimental data is important and crucial in order to appreciate the confidence of the numerical simulation. The present numerical simulation is validated with the available experimental data of Food and Drug Administration (FDA) nozzle model [3]. Figure 4 shows the axial velocity along a horizontal of the geometry (for more details, see Hariharan *et al.,* [3]).
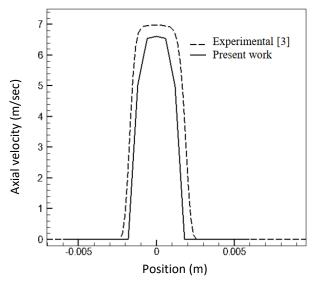

Fig. 4. Variation of axial velocity of the results that obtained from STAR-CCM+ software and the experimental data from Hariharan *et al.,* [3]

Apparent blood viscosity variation with shear rate was inspected by comparing the results of Newtonian model with those of non-Newtonian Carreau model as illustrated in Figure 5. From this Figure, it can be seen that the dynamic viscosity is almost constant when the value of shear rate be more than 1000 1/s.
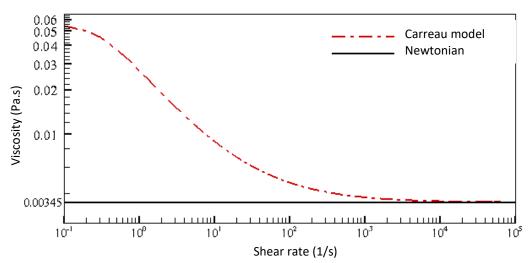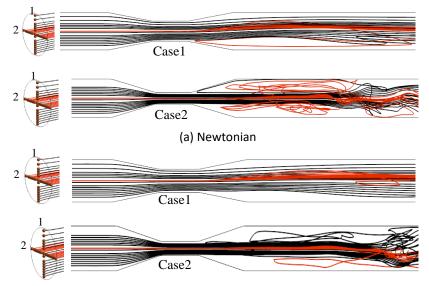

Fig. 5. Viscosity of blood for Newtonian and non-Newtonian models versus strain rate

Availability of blockage within the artery gives enlargement to complexity of the flow behaviour especially after the stenosis. Figure 6 depicts the streamlines originated from the inlet surface towards the whole body. In this figure, the streamlines are seeded from line 1 and line 2 for the sake of illustration. For case 2 line 1, it can be noted that the re-circulation areas are raised in the Carreau model (see line 1, Figure 6(b), case 2) comparing with case 2 of a (for Newtonian model).

Fig. 6. Snapshot of streamlines originated from lines 1 and 2 for (a) Newtonian, and (b) Non-Newtonian

4.2 Clinical Issues of Results

It is also suitable to investigate the shear rate levels within the model in relation to different shapes of stenosis in order to assess the risk of blood damage especially thrombosis (blood clotting). Figure 7 presents the contour behaviour of the shear rate at mid *xz*-plane.
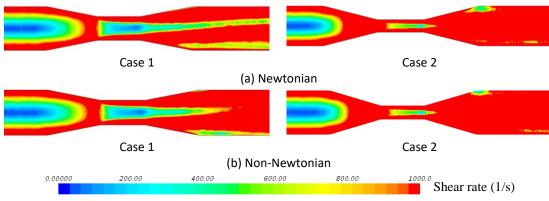

Fig. 7. Contour of shear rate at mid *xz*-plane

In addition, the vorticity magnitude at vertical lines before, through and after the stenosis was illustrated in Figure 8. This is computed as follows

$$|\omega| = \sqrt{2\omega_i\omega_i},$$ (4)

$$\omega_i = \epsilon_{ijk} \frac{\partial u_k}{\partial u_j} \tag{5}$$

where ω_i is the vorticity vector and ϵ_{ijk} is the Levi-Civita cyclic operator. Levels of vorticity observed within the stenosis artery were observed to be very similar before and during the stenosis for both Newtonian and non-Newtonian models (see line 1 and 2, Figure 8 case 1 and 2), indicated that vibration of dynamic viscosity is minimal. As declared in Figure 7. A higher degree of difference is observed at the area after the stenosis (see line 3), inconsistent with the previous lines that levels of vorticity different with the difference of blood model. Observing that the vorticity in case 2 (90%) is higher than that observed in case 1 (70%) and reaches to maximum value of 4000 and 10000 1/s at case 1 and case 2, respectively (see line 3, Figure 8). It should be noted that such smaller vorticity means less rotation of blood particles and this one of the factors that could accumulate the blood, as a results, this likely to cause thrombosis. The same behaviour has been noticed with the velocity magnitudes as shown in Figure 9.
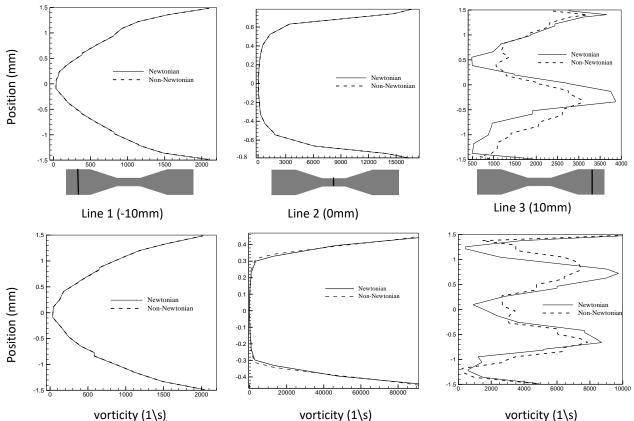
Fig. 8. Viartion of vorticity at three posions along lines as showed above. The above group is for case 1 while the lower group is case 2

Furthermore, in order to present a more quantitative examination of the non-Newtonian effects levels through the stenosis artery, the local 'importance factor'(IF) assessed as proposed by Johnston *et al.,* [19] and Al-Azawy *et al.,* [4]. The importance factor was calculated as follows

$$IF = \frac{\mu(S)}{\mu_\infty} \tag{6}$$

where $\mu(S)$ is the actual dynamic viscosity that be governed by the Carreau model (see Eq. (3)), and μ_∞ is the Newtonian shear viscosity. In general, the IF will be equal to 1 in the Newtonian model,

while the values that not equal to one will refer to the areas of the non-Newtonian flow. Figure 9 describes the IF for the Carreau model for both cases.

The clinical relevance of the importance factor is described for the examined cases, observing that the levels of non-Newtonian model are predicted to be higher in the 70% blockage than that observed within the 90% (see Figure 10).
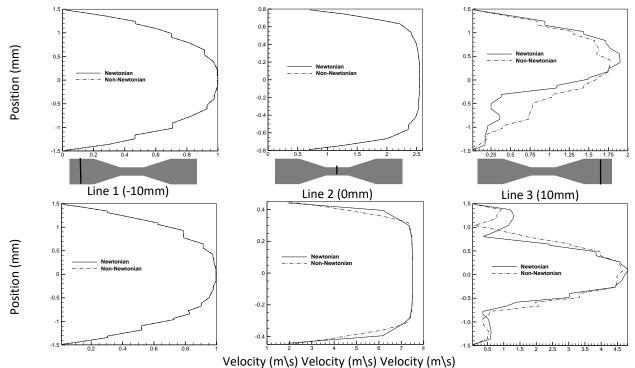

Fig. 9. Viartion of velocity magnitude at three posions along lines as showed above. The above group is for case 1 while the lower group is case 2
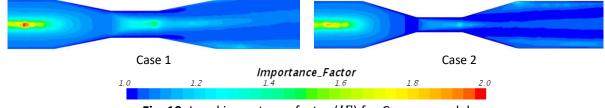

Fig. 10. Local importance factor (IF) for Carreau model

5. Conclusion

The present numerical investigation was accomplished to examine steady, laminar and non-Newtonian blood flow through a three-dimensional stenosis artery using a Carreau model. A trapezoidal shape of stenosis through an artery was examined and simulated numerically. The strain rate and importance factor were calculated, and flow inside areas of the artery noticed to lie within the range of non-Newtonian rheological effects can be present, verifying the necessity to treat blood as non-Newtonian fluid; especially, with the case of 70% blockage. An examination of streamlines through the artery advised that the re-circulation areas in the artery and after the stenosis stretched further in the Carreau model. The levels of vorticity are predicted to be higher in the 90% blockage than that observed within the 70%.

Acknowledgement

References
[1] Lee, Jen-Shih, and Yuan-Cheng Fung. "Flow in locally constricted tubes at low Reynolds numbers." (1970): 9-16. https://doi.org/10.1115/1.3408496

[2] MacDonald, D. A. "On steady flow through modelled vascular stenoses." *Journal of biomechanics* 12, no. 1 (1979): 13-20. https://doi.org/10.1016/0021-9290(79)90004-6

[3] Hariharan, Prasanna, Matthew Giarra, Varun Reddy, Steven W. Day, Keefe B. Manning, Steven Deutsch, Sandy FC Stewart et al. "Multilaboratory particle image velocimetry analysis of the FDA benchmark nozzle model to support validation of computational fluid dynamics simulations." *Journal of biomechanical engineering* 133, no. 4 (2011). https://doi.org/10.1115/1.4003440

[4] Al-Azawy, Mohammed G., A. Turan, and A. Revell. "Investigating the impact of non-Newtonian blood models within a heart pump." *International Journal for Numerical Methods in Biomedical Engineering* 33, no. 1 (2017): e02780. https://doi.org/10.1002/cnm.2780

[5] Amornsamankul, Somkid, Benchawan Wiwatanapataphee, Yong Hong Wu, and Yongwimon Lenbury. "Effect of non-Newtonian behaviour of blood on pulsatile flows in stenotic arteries." *International Journal of Biological and Medical Sciences* 1, no. 1 (2006): 42-46.

[6] Johnston, Barbara M., Peter R. Johnston, Stuart Corney, and David Kilpatrick. "Non-Newtonian blood flow in human right coronary arteries: steady state simulations." *Journal of biomechanics* 37, no. 5 (2004): 709-720. https://doi.org/10.1016/j.jbiomech.2003.09.016

[7] Basri, Adi Azriff, SM Abdul Khader, Cherian Johny, Raghuvir Pai, Mohammed Zuber, Zainuldin Ahmad, and Kamarul Arifin Ahmad. "Effect of single and double stenosed on renal arteries of abdominal aorta: A computational fluid dynamics." *CFD Letters* 12, no. 1 (2019): 87-97.

[8] Molla, M. Mamun, and M. C. Paul. "LES of non-Newtonian physiological blood flow in a model of arterial stenosis." *Medical engineering & physics* 34, no. 8 (2012): 1079-1087. https://doi.org/10.1016/j.medengphy.2011.11.013

[9] Samad, Abdus, A. Husain, M. Zunaid, and A. Samad. "Newtonian and Non-Newtonian Pulsatile Flows through an Artery with Stenosis." *The Journal of Engineering Research [TJER]* 14, no. 2 (2017): 191-205. https://doi.org/10.24200/tjer.vol14iss2pp191-205

[10] Foong, Loke Kok, Nima Shirani, Davood Toghraie, Majid Zarringhalam, and Masoud Afrand. "Numerical simulation of blood flow inside an artery under applying constant heat flux using Newtonian and non-Newtonian approaches for biomedical engineering." *Computer Methods and Programs in Biomedicine* 190 (2020): 105375. https://doi.org/10.1016/j.cmpb.2020.105375

[11] Yan, Shu-Rong, Majid Zarringhalam, Davood Toghraie, Loke Kok Foong, and Pouyan Talebizadehsardari. "Numerical investigation of non-Newtonian blood flow within an artery with cone shape of stenosis in various stenosis angles." *Computer Methods and Programs in Biomedicine* (2020): 105434. https://doi.org/10.1016/j.cmpb.2020.105434

[12] Khader, Shah Mohammed Abdul, Goutam Thakur, Raghuvir Pai, Mahima Kapoor, Soujata Borbaruah, and Keshava Ragavendra. "Numerical Study on Eccentric and Concentric Vascular Grafts Prototypes." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 51, no. 2 (2018): 99-107.

[13] Basri, Adi Azriff, Shah Mohammed Abdul Khader, Cherian Johny, Raghuvir Pai, Muhammad Zuber, Kamarul Arifin Ahmad, and Zanuldin Ahmad. "Numerical Study of Haemodynamics Behaviour in Normal and Single Stenosed Renal Artery using Fluid–Structure Interaction." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 51, no. 1 (2018): 91-98.

[14] Kamangar, Sarfaraz, Irfan Anjum Badruddin, N. Ameer Ahamad, Kalimuthu Govindaraju, N. Nik-Ghazali, N. J. Ahmed, A. Badarudin, and T. M. Khan. "The Influence of Geometrical Shapes of Stenosis on the Blood Flow in Stenosed Artery." *Sains Malaysiana* 46, no. 10 (2017): 1923-1933. https://doi.org/10.17576/jsm-2017-4610-31

[15] CD-adapco, S. "STAR CCM+ user guide version 12.04." *CD-Adapco: New York, NY, USA* (2017).

[16] Kadhim, Saleem Khalefa, Mohammad Shakir Nasif, Hussain H. Al-Kayiem, and Rafat Al-Waked. "Computational fluid dynamics simulation of blood flow profile and shear stresses in bileaflet mechanical heart valve by using monolithic approach." *Simulation* 94, no. 2 (2018): 93-104. https://doi.org/10.1177/0037549717712603

[17] Al-Azawy, Mohammed G., Ali Turan, and Alistair J. Revell. "An Overset Mesh Approach for Valve Closure: An LVAD

Application." In *BIODEVICES*, pp. 145-151. 2016.
https://doi.org/10.5220/0005663901450151

[18]   Carreau, Pierre J. "Rheological equations from molecular network theories." *Transactions of the Society of Rheology* 16, no. 1 (1972): 99-127.
https://doi.org/10.1122/1.549276

[19]   Johnston, Barbara M., Peter R. Johnston, Stuart Corney, and David Kilpatrick. "Non-Newtonian blood flow in human right coronary arteries: transient simulations." *Journal of biomechanics* 39, no. 6 (2006): 1116-1128.
https://doi.org/10.1016/j.jbiomech.2005.01.034