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CFD Simulation of Non-Newtonian Effect on Hemodynamics Characteristics of Blood Flow through Benchmark Nozzle

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ABSTRACT

Blood flowing through medical devices may be subject to hemolysis and thrombosis. For hemolysis, this relationship is often expressed as a shear stress/exposure time relationship. The earlier research found that the blood is a Newtonian fluid, yet blood vessel stream and stress pattern can be influenced by rheological properties of the blood. Anyway, later, examination on blood stream in a carotid bifurcation demonstrates the speed dispersion of a stream could be influenced by shear diminishing non-Newtonian property of blood. Objective of present study is to compare the hemodynamics properties between Newtonian and non-Newtonian model namely, Carreau-Yasuda. The simulation was performed on the idealized nozzle for cardiovascular medical device at Reynolds number of Re = 500. The results were obtained using CFD software Ansys Fluent. The result successfully reveals the mode shape of the velocity graph which was obtained in previous study are identical. Result also found that Newtonian produce more intensity of hemodynamic properties. Furthermore, result also shows that the Newtonian blood viscosity has a high number of wall shear stress by 3% and it will potentially cause blood clots and thrombosis to the patient. This present study can be acknowledged as references for new anticipated of non-Newtonian effect of this cardiovascular medical devices. This paper presented the initial step toward more general goal of simulate implanted in body medical device and to help to improve CFD for biomedical field.

Keywords:
Computational fluid dynamics; Newtonian effect; non-Newtonian effect; nozzle

1. Introduction

Computational fluid dynamics (CFD) was early developed and mainly used in various branch of engineering such as an aerospace [1], oil and gas [2], automotive [3], and many more. However,

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nowadays, it was evolved in numerous industries and branches of science that involve fluid flow such as the biomedical field [4]. Examples are blood flow in cardiovascular, nasal flow, flow in human brain and many more. Nevertheless, CFD is yet matured in the biomedical field. One of the main reasons why it falls behind is due to complexity of body fluid behavior.

Many biomedical devices or prosthetic such as mechanical heart valve, syringe, Left Ventricular Assist Device (LVAD), hemodialysis set, cannulas, etc., which consist of complex fluid flow motion such as flow separation, reattachment, recirculation flow, high and low shear zone and adverse pressure gradient which similar to the happen in other engineering fields. These flow characteristics in hemodynamics blood may lead to serious complication such as blood clot, hemolysis and osteoporosis [5].

In early research, the research found that the blood is a Newtonian fluid, yet blood vessel stream and stress pattern can be influenced by rheological properties of the blood. Anyway, in late research [6] found from their examination on blood stream in a carotid bifurcation demonstrate the speed dispersion of the stream could be influenced by shear diminishing non-Newtonian property of blood. Most of the researcher use Newtonian fluid properties in simulation biomedical fluid flow [7][8]. A Non-Newtonian fluid is a fluid whose viscosity is variable based on applied stress or force. The physical behavior of a non-Newtonian fluid depends on the forces acting on it from second to second. This project aims to study the Computational Fluid Dynamic (CFD) Simulation of Non-Newtonian effect on hemodynamics characteristics of blood flow.

2. Previous Works

Many cells in the body fluid make it behave like Non-Newtonian. Water, organic solvents, and alcohol are some example of Newtonian fluids. Blood is a body fluid in people and other creatures that transfers vital substances, for example, supplements and oxygen to the cells and carriage metabolic waste items. A Newtonian fluid is the flow performance of fluids with a simple linear relation between shear stress [mPa] and shear rate [1/s]. Newtonian fluids the stress feedback to a basic shear rate is linear. The linearity steady μ relies upon the thermophysical states of the fluids (temperature and pressure) [9].

The complex nature of the fluids in the human body is a principle reason for concern for the accuracy of the results of blood stream simulation. For example, for the generation of atherosclerosis in the bifurcation area, the application of a Newtonian blood stream model is a reasonably good approximation [10]. However, to study the stream inside the artery in greater detail, a non-Newtonian model is more appropriate. The non-Newtonian characteristics are commonly validated at low shear rates, which can exist close bifurcation sites and at recirculation zones creating in the arteries. Since the generation of atherosclerosis has been related with low (< 0.5 Pa) WSS values, it turns out to be certain that non-Newtonian models should be utilized to acquire more reliable estimates.

A few studies demonstrate that the numerical result of divider wall shear stress (WSS) distribution in an artery may be distinctive when blood was treated differently (i.e. Newtonian or non-Newtonian), particularly at low shear rates.

Non-Newtonian models have been utilized of other vascular components, for example, the aorta, the cerebral, and the coronary arteries. The distinctions in the forecasts of different rheological models are introduced in a comparative study of [11].

The small nozzle which inspired from Food and Drug Administration (FDA) study is a standard benchmark model for medical device design. It shares characteristic of blood carrying medical device as mention earlier. The problem that has been identified causes blood harm in the medical device was designed to incorporate accelerating flow, decelerating flow, varieties in shear stress and velocities, and recycling flow. The blood tubing, hemodialysis set, catheters, cannulas, and syringes are blood contacting device and the nozzle must attribute like blood contacting device. Geometrically, the model incorporates a progressively converging section, a throat region and a sharp-edged sudden extension [12].

3. Methodology

3.1 Governing Equation

The governing equation used in present study is common Navier Stokes Equation in Eq. (1)-(4). The equations are 3 dimensional.

For all flows, the Conservation Equations for Mass, Momentum and Transport equations for fluid in each flow geometry can be determined numerically using ANSYS 16.1 software. For this case, the governing equations which involved continuity equation and momentum equation is used as shown in Eq. (1)-(4).

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

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+v\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+v\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial x^2}\right) \tag{3}$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+v\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

where p, ρ, (v, u, w) and v is pressure, density, velocities and viscosity respectively. Navier-Stokes equations include the possibility of including the viscosity of the fluids in which determine the rheology properties of blood either Newtonian or Non- Newtonian.

The simulation was conduct using transient simulation with adaptive time step with error < 0.01. The convergence criteria for all equation was set < 10^{-3}.

3.2 FDA Nozzle Geometry

The dimensions of the nozzle geometry were achieved from the published literature [13]. The proposed idealized nozzle model comprises of four sections containing characteristics of some blood-passing on medical devices. There are inlet and outlet tubes with diameter

0.012 m and a nozzle throat with diameter 0.004 m followed by a sudden contraction and 20° conical diffuser. There is additionally a cone-formed tube interfacing the channel tube with the nozzle throat. For this geometry, flow in one direction is a sudden expansion issue, while flow in the opposite direction is a conical diffuser issue.

Table 1 shows the parameter of the FDA benchmark nozzle model that described a simplified medical device; it is shown in Figure 1(a) and 1(b) with dimensions. The inlet and outlet were set longer to have parabolic profile at inlet and to avoid entrance effect.

Table 1
Parameter for FDA geometry

Parameters	Dimensions
Inlet diameter	12 mm
Throat diameter	4 mm
Throat length	40 mm
Conical angle	20°
Conical length	22.69 mm
Exit diameter	12 mm

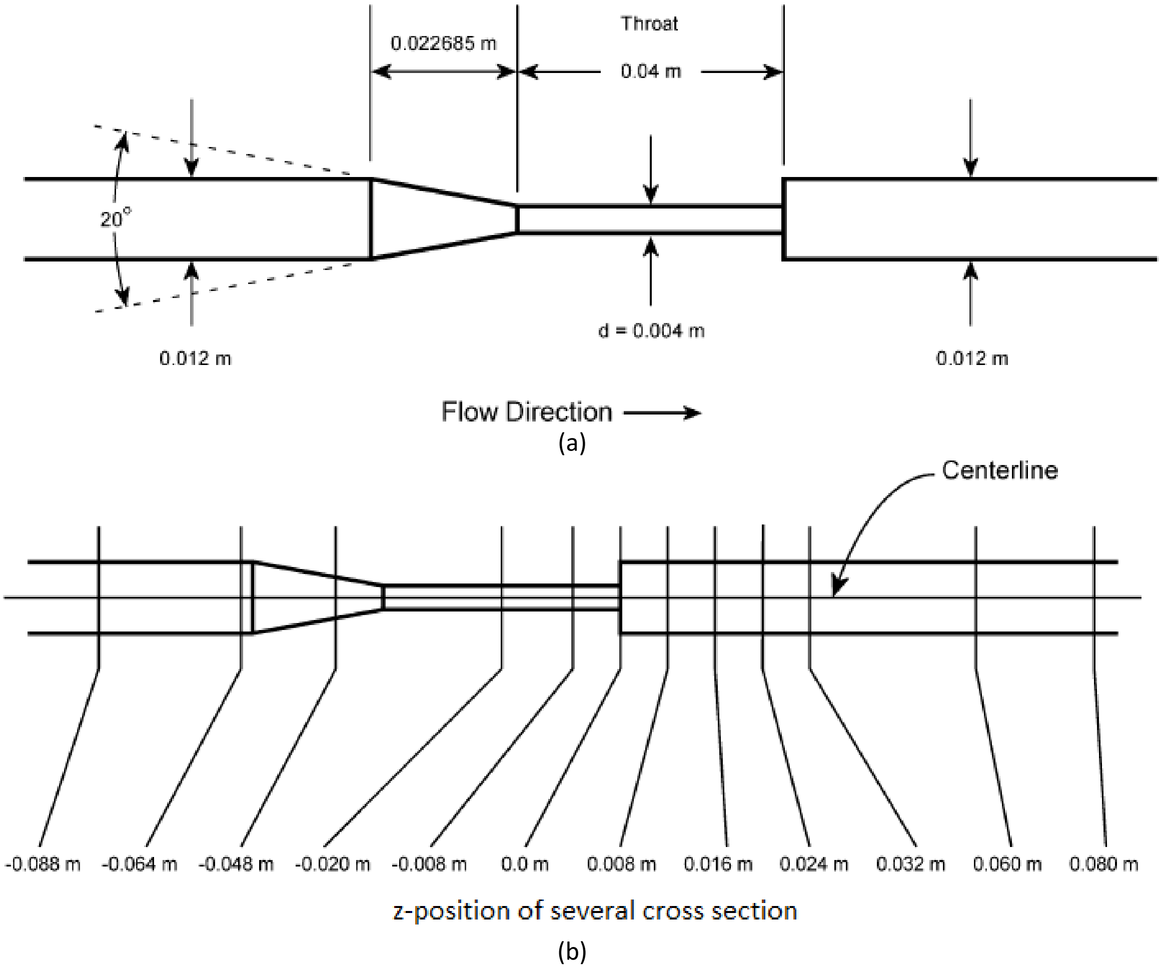

Fig. 1. Geometry and dimensions of the FDA nozzle

3.3 Boundary Condition and Meshing

The Reynolds number used in this study is Re=500 evaluate based on throat diameter. The inlet flowrate was set at 5.21 x 10-6 m3/s. The outlet pressure was set at 1200 Pa corresponding to pressure at the human artery. The other wall is set zero velocity.

For meshing type, hexahedral is used. The total of meshing elements get in this present study is 314K. In numerical computation, the quality of the mesh plays an important role to determine accuracy and stability. The mesh quality attribute with mesh quality is skewness and aspect ratio. The maximum number skewness of this nozzle is 0.55917. A separate grid independency using element number up to 617K was did not change the result, therefore element number 314K is used in the present study.

3.3 Blood Properties

Blood is modelled as an incompressible fluid with a density of 1056 kg/m3. It is simulated be a Newtonian fluid with a dynamic viscosity of 0.0035 N.s/m^2 [14].

Non-Newtonian fluid model uses in present study is Carreau- Yasuda (CY) model [15]. In particular, the viscosity model reads as follows

$$\mu = \mu_\infty + (\mu_0 - \mu_\infty)[1 + (k\,|\dot{\gamma}|)^a]^{\frac{n-1}{n}} \tag{5}$$

where $|\dot{\gamma}| = \sqrt{(1/2)\dot{\gamma}_{ij}\dot{\gamma}_{ij}}$ is the effective shear stress rate; $\dot{\gamma}_{ij} = (\partial_i u_j + \partial_j u_i)$ is the shear stress tensor, u_j being the velocity field; μ_0 and μ_∞ are the viscosities at zero and infinity shear rates; and {k,n,a} are constant paramet ers. The other parameters are set as μ_0 =0.16 Pa.s, μ_∞ =0:0035 Pa.s, k =8.2s, a =0.64, and n =0.2128.

3. Result and Discussion

The result of this velocity were being compare with the studies conducted by Trias *et al.,* [13]. We presented the comparison between different viscosity of blood model corresponding to either base Newtonian or Carreau Yasuda for the parameter represented to have effect on nozzle. The result of velocity obtained in the centerline of nozzle act as key pointer to validate the predictions of CFD performance.

The result that we obtained in Figure 2 were in an excellent agreement and reveals the mode shape of the velocity graph which was obtained by Trias *et al.,* [13]. The result that was obtained was slightly different for Newtonian model after the sudden expansion region. At the center plane of the nozzle also, the maximum velocity obtained with Newtonian model was slightly higher.

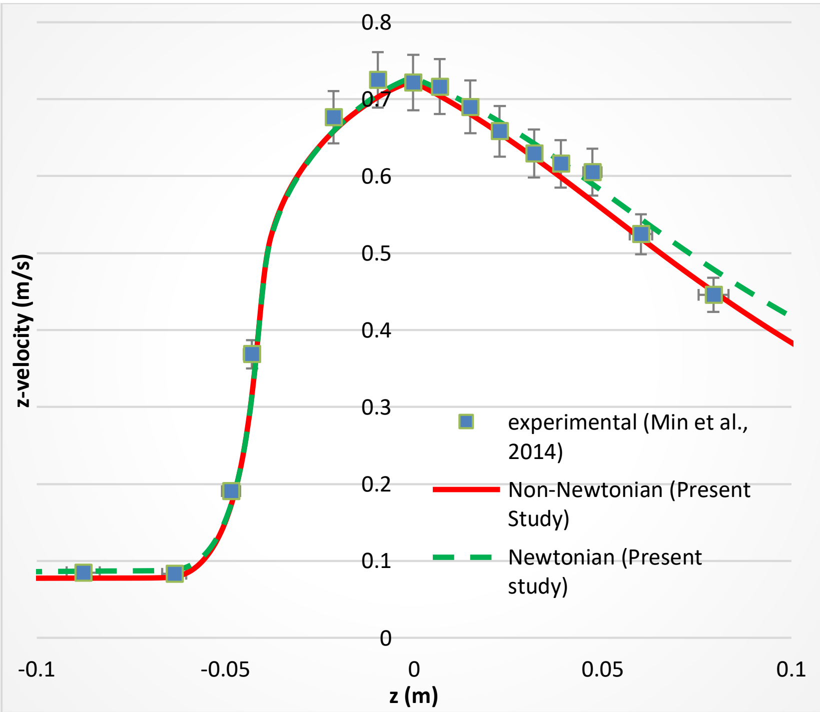

Fig. 2. Axial velocity along the nozzle centerline for the models

Non-Newtonian impacts on the axial velocity are little in the region upstream the sudden expansion, yet they turn out to be more significant downstream that point, in the recirculation zone as shown in Figure 3. The Newtonian model underestimates of blood viscosity at low shear pressure rates, or, in other words why Newtonian axial velocity is higher than the one acquired with alternate models. The flow encounters a gradual contraction of zone from the inlet tube to the throat, at that point a sudden expansion relating to laminar will be examined.

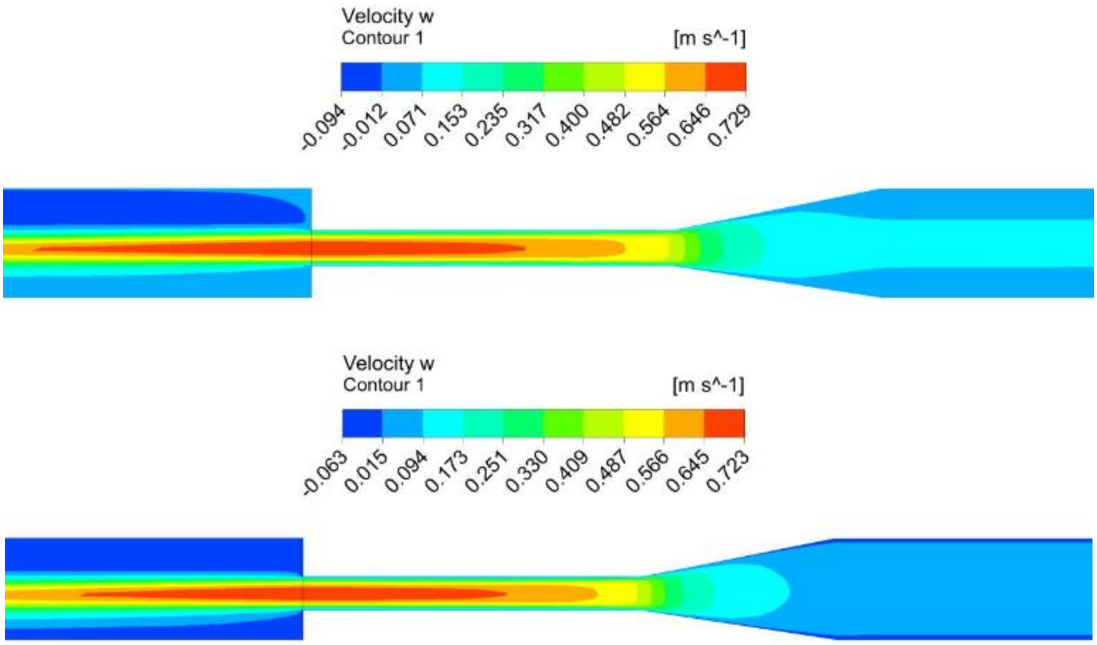

Fig. 3. Velocity contour at the center plane of the models for Newtonian (Top), and Non-Newtonian (bottom)

The pressure comparison between those two models also shows slightly distinction in Figure 4 and 5, where Non- Newtonian model produce higher pressure. Closer examination reveals that when the fluid passes the throat are (i.e., -0.64 ~- 0.02), the pressure drop for Newtonian is 233.26 Pa, while 237.8 Pa for Non-Newtonian model. At the sudden expansion area (i.e. -0.08 ~ 0.08), the pressure drop is 27.12 Pa and 26.77 Pa for Newtonian and non-Newtonian model respectively. Based on this data, for this nozzle and the flow region, CFD forecast to predict pressure data have narrow effect for non- Newtonian effect. For every, miscalculate of pressure drop that happens to the patient can cause the potential stenosis (abnormal narrowing in a blood vessel) can be miscalculated as well. If the pressure drop is higher than what it should be, it could be harmful to the patient.

Figure 6 shows the contour of wall shear stress profile versus Z coordinate along with the nozzle from CFD simulation with two different viscosity model of blood and experimental data that have been calculated by consider the viscosity model. The maximum shear stress is recorded at the throat of the nozzle where the forward and reverse of flow occurs. By comparing the viscosity model, the graph shows that the Newtonian has the lowest wall shear stress value along the centerline on the nozzle. However, both model yield shear stress < 10 Pa which is safe estimation of blood clot [5]. The high contribution comes from the conical and throat region, where mostly blood damage always occurred in this section. It also shows that maximum wall shear stress occurs between conical and throat regions.in CFD simulation, the researcher must well define the definition of the wall and it's contact with blood, which becomes a challenge and the root of the difficulty in the experiment. By comparing with two different viscosity model, it shows that the model has relative different and they were larger at low wall shear stress value.

Shear stress rate data can give benefit to provide information for aortic valve mechanical stress, blood damage indicator, etc. If the blood has high shear stress value, the duration for the destruction of red blood cell can happen in a short time. So, it is important to keep wall shear stress at artery as low as possible. For low shear stress, the hemolysis can endure a longer time period.

Figure 7 shows the vertical structural using Lambda2 criterion as proposed by (Jeong & Hussain, 1995). It was determined through local pressure minimum due to a vortical motion. Vortical structural also can be used to identify the level of hemolysisi. For Newtonian model, the Lambda2 are -0.49 s^{-2}, while the value for non-Newtonian is 0.92 s-2. Also, there are chaotic and unstable of vertical structural for Newtonian compare to non-Newtonian case.

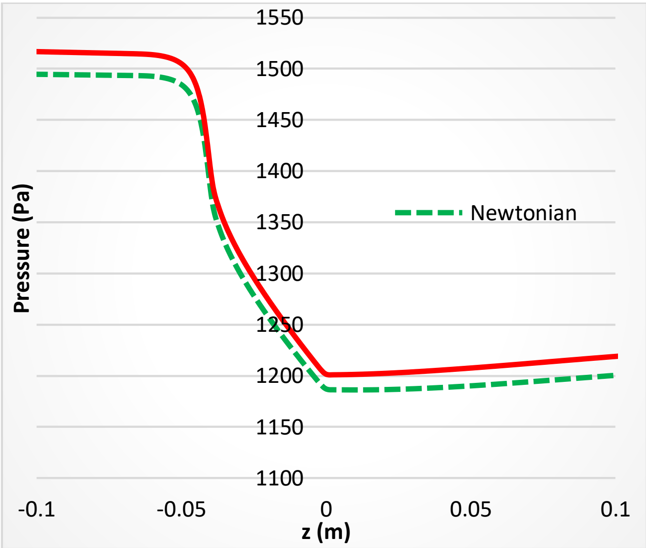

Fig. 4. Pressure along the nozzle centerline for the models

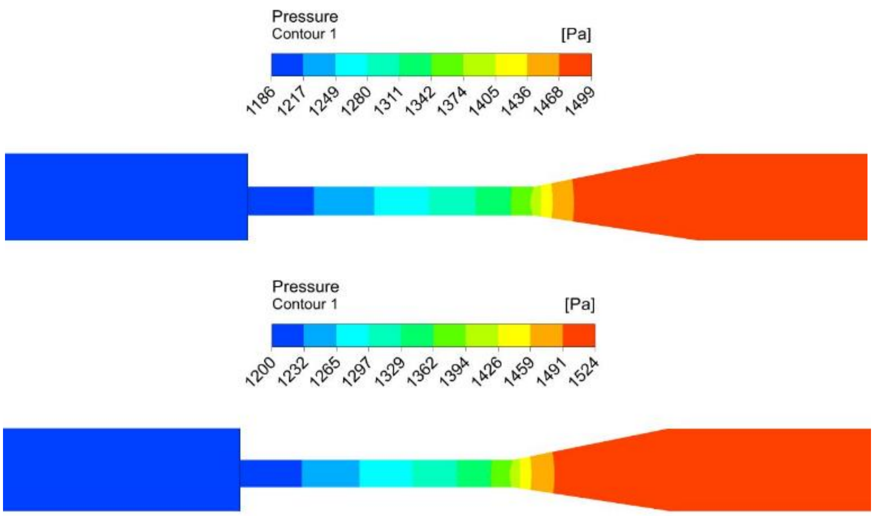

Fig. 5. Pressure contour at the center plane of the models for Newtonian (Top), and Non-Newtonian (bottom)

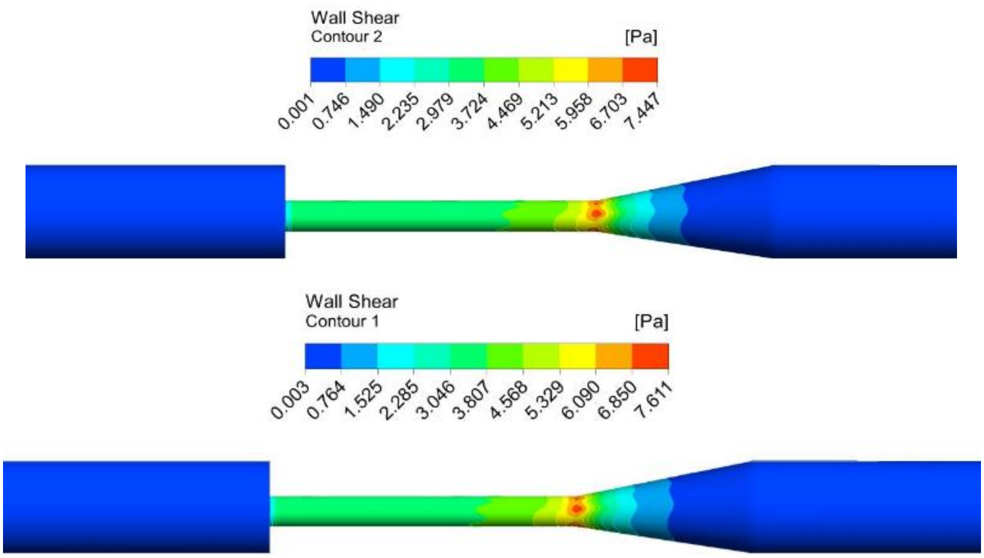

Fig. 6. Wall shear stress contour for Newtonian (Top), and Non-Newtonian (bottom)

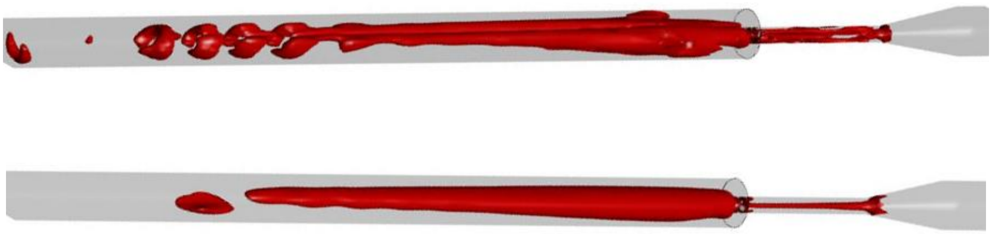

Fig. 7. Lambda-2 criterion of vortex core region for Newtonian (Top), and Non-Newtonian (Bottom)

4. Conclusions

The present study performed CFD simulation to show the blood flow through the device for Laminar Reynold number, analyze the data for experimental of benchmark FDA nozzle and validation study from the previous study [13]. This research has considered two rheological models for blood which is Newtonian and Carreau-Yasuda model. Besides that, the result that obtains by CFD simulation validated with the experimental method by FDA. The validation was conduct by validating the axial velocity along with the nozzle with two different model and one experiment. By using CFD simulation, the researcher can predict the data to give benefit in hemolysis studies wherein experimental there was a limitation to get the data measurement specifically at the throat region of the nozzle. This researcher work shows in this study served as early goals to provide simulation for implanted in-body medical devices using patient data that can obtain from CT scans or MRI technique. Hence, this report shows that the Newtonian blood viscosity has a high number of wall shear stress and it will cause blood clots and thrombosis to the patient.

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References

[1] Spalart, P. R., and V. Venkatakrishnan. "On the role and challenges of CFD in the aerospace industry." *The Aeronautical Journal* 120, no. 1223 (2016): 209-232.

[2] Zakaria, Mohamad Shukri, Kahar Osman, Ahmad Anas Yusof, Mohamad Hafidzal Mohd Hanafi, Mohd Noor Asril Saadun, and M. Z. A. Manaf. "Parametric analysis on boil-off gas rate inside liquefied natural gas storage tank." *Journal of Mechanical Engineering and Sciences* 6 (2014): 845-853.

[3] Cheng, See-Yuan, Shuhaimi Mansor, Mohd Azman Abdullah, and Mohamad Shukri Zakaria. "Numerical Study of Aerodynamic Performance of Hatchback Vehicle Fitted with a Strip Spoiler: Effect of Yaw Angle." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 47, no. 1 (2018): 108–118.

[4] Zakaria, Mohamad Shukri, Farzad Ismail, Masaaki Tamagawa, Ahmad Fazli Abdul Azi, Surjatin Wiriadidjaya, Adi Azrif Basri, and Kamarul Arifin Ahmad. "Computational Fluid Dynamics Study of Blood Flow in Aorta using OpenFOAM." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 43, no. 1 (2018): 81-89.

[5] Zakaria, Mohamad Shukri, Farzad Ismail, Masaaki Tamagawa, Ahmad Fazli Abdul Aziz, Surjatin Wiriadidjaja, Adi Azrif Basri, and Kamarul Arifin Ahmad. "Review of numerical methods for simulation of mechanical heart valves and the potential for blood clotting." *Medical & biological engineering & computing* 55, no. 9 (2017): 1519-1548.

[6] Gijsen, Frank JH, Frans N. van de Vosse, and J. D. Janssen. "The influence of the non-Newtonian properties of blood on the flow in large arteries: steady flow in a carotid bifurcation model." *Journal of biomechanics* 32, no. 6 (1999): 601-608.

[7] Zakaria, Mohamad Shukri, Farzad Ismail, Masaaki Tamagawa, Ahmad Fazli Abdul Aziz, Surjatin Wiriadidjaja, Adi Azrif Basri, and Kamarul Arifin Ahmad. "A Cartesian non-boundary fitted grid method on complex geometries and its application to the blood flow in the aorta using OpenFOAM." *Mathematics and Computers in Simulation* 159 (2019): 220-250.

[8] 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.

[9] Aldi, Nicola, Carlo Buratto, Michele Pinelli, Pier Ruggero Spina, Alessio Suman, and Nicola Casari. "CFD Analysis of a non-Newtonian fluids processing pump." *Energy Procedia* 101 (2016): 742-749.

[10] Apostolidis, Alex J., Adam P. Moyer, and Antony N. Beris. "Non-Newtonian effects in simulations of coronary arterial blood flow." *Journal of Non-Newtonian Fluid Mechanics* 233 (2016): 155-165.

[11] Karimi, Safoora, Mahsa Dabagh, Paritosh Vasava, Mitra Dadvar, Bahram Dabir, and Payman Jalali. "Effect of rheological models on the hemodynamics within human aorta: CFD study on CT image-based geometry." *Journal of Non-Newtonian Fluid Mechanics* 207 (2014): 42-52.

[12] Hariharan, Prasanna, Gavin A. D'Souza, Marc Horner, Tina M. Morrison, Richard A. Malinauskas, and Matthew R. Myers. "Use of the FDA nozzle model to illustrate validation techniques in computational fluid dynamics (CFD) simulations." *PloS one* 12, no. 6 (2017): e0178749.

[13] Trias, Miquel, Antonio Arbona, Joan Massó, Borja Miñano, and Carles Bona. "FDA's nozzle numerical simulation challenge: non-Newtonian fluid effects and blood damage." *PloS one* 9, no. 3 (2014): e92638.

[14] Jung, Jonghwun, and Ahmed Hassanein. "Three-phase CFD analytical modeling of blood flow." *Medical engineering & physics* 30, no. 1 (2008): 91-103.

[15] Boyd, Joshua, James M. Buick, and Simon Green. "Analysis of the Casson and Carreau-Yasuda non-Newtonian blood models in steady and oscillatory flows using the lattice Boltzmann method." *Physics of Fluids* 19, no. 9 (2007): 093103.