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CFD Analysis of Blood Flow in Artery with Blockage

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Abstract: **-- Blood flow is the topic of interest for mankind from the ancient time because of its usefulness. Blood is a very complex fluid which is nonhomogeneous and non-Newtonian in nature. Blood flows in the body with pulsating nature. Study of blood flow can be very helpful to improve the understanding of human body. Due to such complex nature it is very hard to study the blood flow in by experimental analysis, but with the help of CFD, it is possible. CFD can be a very useful tool to analyze the flow of blood in complex parts of the body. Diseases related to blood flow such as atherosclerosis can be efficiently analyzed using CFD. In the present study, blood has been simulated in 2D artery considering the 75 % blockage in the artery using the commercial software ANSYS FLUENT. The grid has been generated using the ANSYS MESH. The blood flow has been analyzed at various hematocrit for three Reynolds number. The effect of the variation of hematocrit on the flow and the effect of blockage is analyzed in the present study.**

Keywords: Hematocrit; Non-Newtonian fluid; Atherosclerosis; RBC; WBC; CFD.

I. INTRODUCTION

Blood is made of RBC and WBC. Which are suspended in plasma. The constitute of RBC varies from the 30 to 50 % [1]. Blood is non-Newtonian fluid. Blood is one of the most complex fluid in the nature because it is non-homogeneous shear thinning fluid which flow with pulsating nature in body. Blood can be easily simulated using the CFD as a multiphase fluid. Huang [2] analyzed the behavior of blood using the kinetic theory of fluids. Karino [3] simulated the blood flow in the backward facing step. Peter simulated the blood and compared various shear thinning models of fluid [4]. Chubin et al. studied the transport of blood cells [5]. In the present study the blood has been simulated in the artery with blockage to understand the flow behavior of blood after blockage.

III. MATHEMATICAL APPROACH

The blood has been simulated as two phase fluid considering blood as non-Newtonian fluid. In blood, RBCs (dispersed phase) are suspended in plasma (Continuous phase). Eulerian-Eulerian approach of multiphase was used because of it applicability to wide range of volume fraction [6]. The governing equations describing the multiphase model of blood can be summarized as:

2.1 Continuity equation

Continuity equation for each phase (c = plasma, RBCs) is given by

$$\frac{\partial(\rho_c \varepsilon_c)}{\partial t} + \nabla.\left(\rho_c \varepsilon_c \vec{v_c}\right) = 0 \tag{2}$$

where ρ is density, ε is the volume fraction, t is time, and v is velocity.

2.2 Momentum equation

Momentum equation for each phase is given by

$$\frac{\partial\left(\rho_c \varepsilon_c \vec{v_c}\right)}{\partial t} + \nabla.\left(\rho_c \varepsilon_c \vec{v_c}\,\vec{v_c}\right) = -\varepsilon_c \nabla p + \nabla.\bar{\bar{\tau}}_c + \rho_c \varepsilon_c \vec{g} + \sum_{l \neq c} \alpha_{pq}\left(\overrightarrow{v_q} - \overrightarrow{v_p}\right) + \vec{F_c} \tag{3}$$

where p is the pressure, τ is stress strain tensor, F is the external forces such as virtual mass, rotational and shear lift. In drag force, the subscripts p and q represent the plasma and RBCs respectively. α_pq represents the interphase momentum exchange co-efficient.

2.3 Blood Rheology

The mixture viscosity of blood is the function of shear rate and hematocrit (volume fraction of RBCs). The Quemada viscosity model [7, 8] was used to simulate the blood flow. The viscosity of blood is given by,

$$\mu = \mu_p \left[1 - \frac{\varepsilon_q}{2} \left(k_\infty + \frac{k_0 - k_\infty}{1 + \left(\dot{\gamma}/\dot{\gamma}_c \right)^b} \right) \right]^{-2} \qquad (4)$$

where k_∞ and k_0 are the intrinsic viscosities. γ ̇ is local shear rate. γ ̇_c is critical shear rate.
These parameters are given as,

$b = 0.5$ (5)
$k_0 = 4.33$ (6)
$k_\infty = 1.88$ (7)
$\dot{\gamma}_c = 2.07$ (8)

III. NUMERICAL APPROACH

The solution of governing equations has been obtained using the Eulerian-Eulerian approach. ANSYS FLUENT is used for the simulation of blood flow in the present work. The velocity inlet condition and zero pressure outlet boundary condition has been used in the present simulation of blood flow. No slip condition has been applied to walls and walls are considered to be rigid. Quemada viscosity model has been used to simulate the shear thinning behavior of blood. The maximum residual level is set to the 10-5.
The mesh independent test has been carried out on the backward facing step geometry and the mesh with the 200k elements has been selected for simulation in the present work.

IV. RESULTS

Multiphase model of blood flow has been validated using the backward facing geometry considering the 1 % RBC concentration (dia.=7.5µm, Density=1.13 g/cm3) as a secondary phase and the water as the primary phase. Simulation were performed at 7.57 cm/s (Re =12.2) and 23.3 cm/s (Re = 37.8) steady velocities. The reattachment location of flow after the expansion of flow has been found and shown in the table 1. The velocity contours for the same are shown in the figure 1. The reattachment location is in very good agreement with the experimental results of Karino and Goldsmith [3]. The table 2 shows the velocity at various points in vertex region and the velocities are compared with the experimental and numerical results [3, 6], are in good agreement with the results available in literature. Therefore this model of blood flow is used for the further simulation blood flow in the artery with blockage as shown in the figure 2 considering the 75 % blockage in artery.

Table 1. Reattachment location

Velocity (cm/s)	Present work	Experimental results [6]
7.57	210 µm	222 µm
23.3	600 µm	638 µm

The present work simulates the blood in artery with blockage as shown in the figure 2. considering the 30, 40, and 45 % of hematocrit for three different Reynolds number of 30, 40, and 50. The results have been plotted in terms of the contours and graphs of the pressure, velocity and shear stress as discussed below

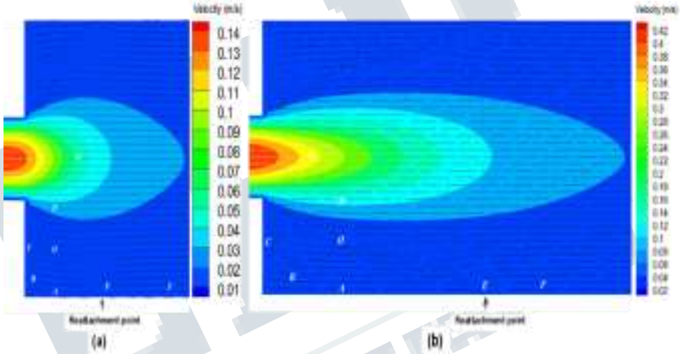


Figure 1. Velocity contours for (a) Re =12.2 and (b) Re = 37.8

Table 2. velocities (m/s) in vertex region.

Locations	**Velocities at Re = 12 .2**			**Velocities at Re = 37.8**		
In vertex region	Karino and Goldsmith [3] (Experimental)	Jung et al.[6] (Numerical)	Present work	Karino and Goldsmith [3] (Experimental)	Jung et al.[6] (Numerical)	Present work
O	0.54	0.825	0.92	2.44	4.426	5.17
A	0.64	0.375	0.36	3.59	5.313	3.88
B	0.36	0.522	0.26	3.03	6.122	1.41
C	1.46	1.567	0.82	6.93	12.082	4.05
D	11.8	24.39	13.	94.1	89.64	92.

		9	7		6	1
E	0.3	0.328	0.27	0.84	0.573	1.29
F	3.3	0.7	2.61	0.95	2.947	3.73
G	48.6	52.339	50.97	272	314.423	283

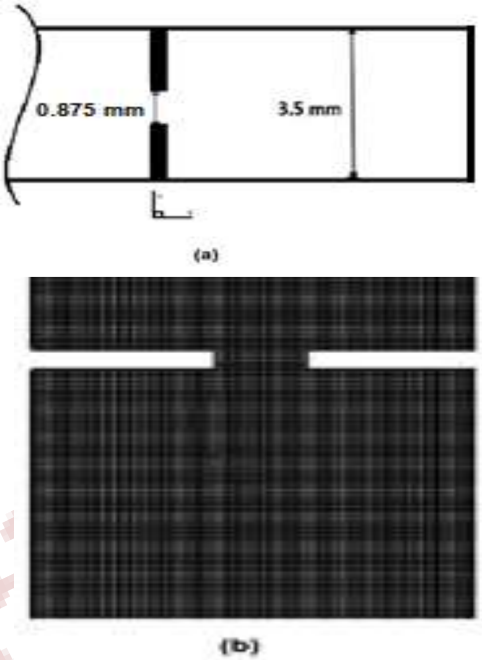


Figure 2. (a) Artery with 75 % blockage, (b) Mesh for artery with blockage.

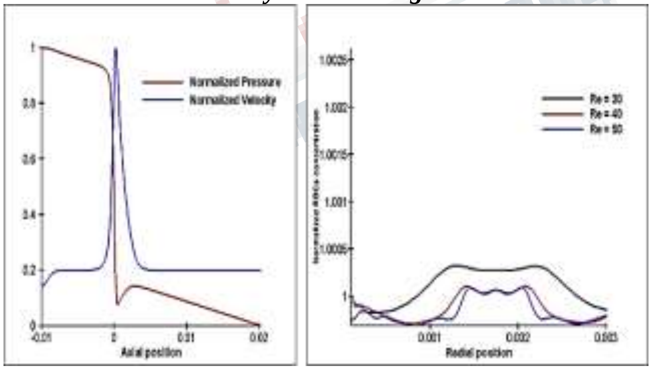


Figure 3. (a) The variation of normalize pressure and normalized velocity along centerline of artery for 45 % RBCs volume fractions at Re = 30, (b) Normalized distribution of RBCs along radial direction at 1.5 mm after blockage at 30, 40 and 50 Reynolds number

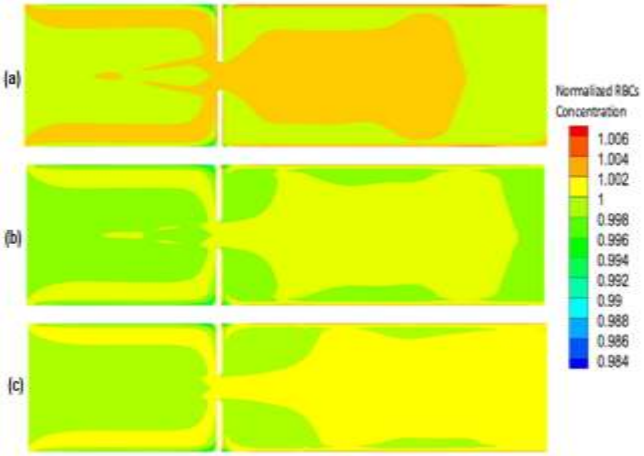
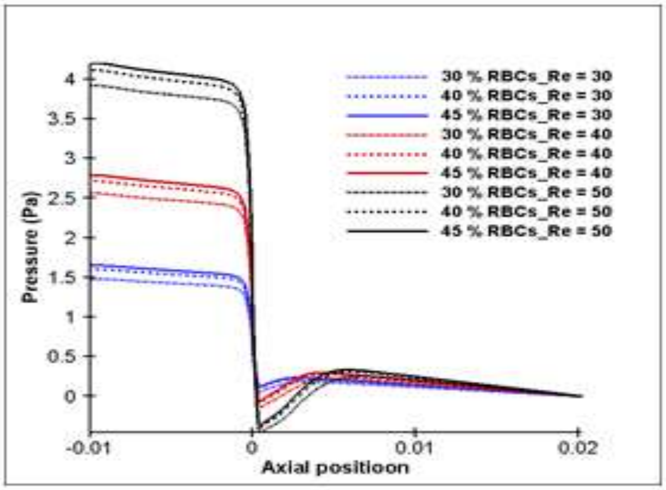
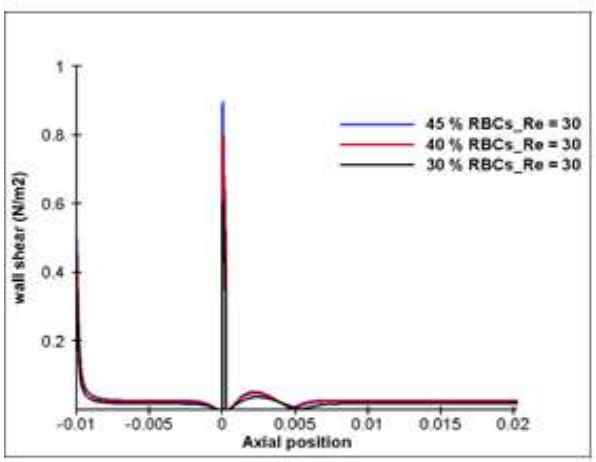


Figure 4. (a) Normalized RBCs concentration at Re = 30 at 45 % RBCs volume fraction, (b) Normalized RBCs concentration at Re = 40 at 45 % RBCs volume fraction (c) Normalized RBCs concentration at Re = 50 at 45 % RBCs volume fraction

The pressure is reduces due the blockage in the flow and the velocity increases which can be observed form the figure 3(a). The RBC distribution at various steady state velocity has been plotted at 45 % hematocrit as show in the figure 3(b). The contour shown in the figure 4 (a) shows the distribution of RBC before and after the blockage in the flow. The variation of pressure with the hematocrit and the Reynolds number is shown in the figure 5(a). The figure shows that the increase in hematocrit has less effect on the pressure drop, but Reynolds number affects pressure drop considerably. The pressure drop increases as the Reynolds number increases but it is less affected by the increase in the hematocrit



(a)



(b)

Figure 5. (a) Pressure variation along center of artery for 30, 40 and 45 % of RBCs volume fraction at 30, 40, 50 Reynolds number. (b) Wall shear stress variation with RBCs volume fraction at Re = 50.

V. CONCLUSION

The flow model is first validated with help of experimental and numerical data available than used for the study of flow of blood in the artery with the 75 % blockage. From the present study it is found that the increases in the hematocrit has very less effect on the reduction of pressure after blockage, it affects shear stress greatly, shear stress increases greatly with hematocrit. This study can be further applied to the more realistic conditions by taking the artery elastic in nature instead of rigid artery.

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