Numerical investigation of flow parameters for solid rigid spheroidal particle in a pulsatile pipe flow

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Abstract. Quantifying, forecasting and analysing the displacement rates of suspended particles are essential while discussing about blood flow analysis. Because blood is one of the major organs in the body, which enables transport phenomena, comprising of numerous blood cells. In order to model the blood flow, a flow domain was created and numerically simulated. Flow field velocity in the stream is solved utilizing Finite Volume Method utilizing FVM unstructured solver. In pulsatile flow, the effect of parameters such as average Reynolds number, tube radius, particle size and Womersley number are taken into account. In this study spheroidal particle trajectory in axial direction is simulated at different values of pulsating frequency including 1.2 Hz, 3.33 Hz and 4.00 Hz and various densities including 1005 kg/m³ and 1025 kg/m³ for the flow domain. The analysis accomplishes the interaction study of blood constituents for different flow situations which have applications in diagnosis and treatment of cardio vascular related diseases.

1. Introduction

Bio medical stream issues are regularly extremely complex in view of multifaceted geometries, moving walls and high precision required to totally cover happening flow phenomena. The human body is a complex framework that requires transport of materials, for example, air, water, nutrients and minerals for survival and working. Nowadays, Computational fluid dynamics is emerging as a means of enhancing understanding of fluid flow in arteries and the associated forces. In the coming future, the study of arterial blood flow will lead to the prediction of individual haemodynamic flows in any patient, the development of diagnostic tools to quantify disease, and the design of devices that mimic or alter blood flow. Although extensive experimental, theoretical and numerical studies have been conducted in this area, to the best of our knowledge, there is yet no study that has revealed a direct relationship between blood fluid dynamics and the development of atherosclerosis. The purpose of this work is to perform a computer simulation method of blood flow using a spheroidal particle and modeled as a blood cell to investigate blood flow behaviour at the microscopic level. The motion of a single deformable red blood cell and the thrombogenesis can be studied as problems at the capillary level. When a particle, or a cloud of particles of low concentration, is introduced into an air stream the response of the particle depends on the relative velocity of the particle and the fluid. This relative velocity determines the drag, which is the sole force determining the motion of the particle if it is assumed that there is no particle interaction and further that the presence of the particles does not change the basic flow pattern. The cyclic nature of the heart pump creates pulsatile conditions in all
arteries making the study of flow more complicated, which can quantified by Womersley or Witzig number. Abhinav et al. [1] suggested that for the Reynolds number ranging from 650 to 1200, flow in a straight tube is practically oscillatory and transverse velocities are small. Chandan Paul et al. [2] concluded that the velocity magnitude within the coil embolized aneurysm becomes negligible after coil insertion and the wall shear stress within that aneurysm decreases to a great extent for both Reynolds numbers 500 and 1500. Jae Sung Park et al. [3] concluded that the asymmetry of fluid velocity results in a lower pressure on the wall side than on the centreline side, leading the sphere to migrate away from the center line until the wall repulses it. Takayuki et al. [4] carried out the experimental and numerical investigation on an alumina particle in a vertical pipe flow. Sarath et al. [5] investigated the introduction of spherical particle in a pulsatile pipe flow and its trajectory was studied.

To resolve certain blood flow associated diseases, numerical investigations were done to find out inter constituent interactions of blood considering the wall shear stresses acting on these constituents. The methodology used for the numerical simulation was discussed and thereafter comes the details of geometry and meshing. The results and conclusions were discussed after the proper analysis of simulation results.

2. Methodology

2.1. Governing Equations and Mathematical Modelling

Flow modelling need the conservation principles of mass and momentum to be satisfied simultaneously. The solver was advanced based on Finite Volume Method in Computational fluid dynamics. The momentum equation for particle motion was added to the FVM solver to understand the transport mechanism of solid spheroidal particle in pulsatile flow. The simulation was carried out to find the trajectory of the particle in axial direction with variation of time. The following equations include Continuity equation and Navier Stokes equation which will govern the fluid flow inside the pipe.

\[ \nabla \cdot \vec{u} = 0 \] (1)

\[ \rho \left( \vec{u} \cdot \nabla \vec{u} + \frac{\partial \vec{u}}{\partial t} \right) = -\nabla P + \mu \nabla^2 \vec{u} \] (2)

It can be observed that the blood cells having the biconcave shapes are persistently experiencing disfigurements all through the stream, which can be approximated as a spheroidal molecule for the examination. The equivalent spheroidal diameter by equating the volume of a spheroid with that of a sphere of diameter, d has the form

\[ d_v = \frac{2a}{AR^{0.5}} \] (3)

The momentum equation for a particle can be solved to obtain the particle velocity and from that the migrated position of particle in axial directions. Shear forces acting from the walls of fluid conduit were taken into account, so that the force acting on the particle from the boundary layer can also be considered. Many forces are acting upon the particle having mass which is introduced in a pulsatile pipe flow and the motion of the particle can be predicted using the simulation using the three dimensional FVM unstructured code. The drag force acting on a spheroidal particle can be expressed by

\[ F_D = 16U_m e^2 \pi \mu a (e(\sqrt{1-e^2}) - (1 - \frac{e}{2sin^{-1}e}) e^2)^{-1} \] (4)
The shear stress at the pipe wall is allied with slope of the velocity profile at the surface. The velocity profile stays unaltered in the hydrodynamically fully developed flow, the divider shear stress likewise stays consistent in that area. Wall shear stress, being highest at the pipe inlet having least boundary layer thickness decreases slowly to the fully developed value. The pressure drop is higher in the entrance regions of a pipe which is significant only for short pipes and is negligible for long ones. The wall shear stress for a laminar steady flow in a straight pipe is given by

$$\tau_{wall} = \frac{32\mu Q}{\pi D^3}$$  \hspace{1cm} (5)

The trajectory of the particle is obtained by applying Newton’s equations of motion after calculating the particle velocity. The instantaneous position of particle is updated during each time step.

$$s = s_0 + \int u_p dt$$  \hspace{1cm} (6)

The frequency of pulsatile wave was varied by changing the Wormersley parameter. Also the flow domain density is altered by considering the density of particle introduced in the pulsatile flow.

2.2. Modeling of geometry and Meshing

The study was performed in a circular pipe domain of radius 0.02 m and length 0.1 m. Solidworks was used to model the pipe geometry. The pipe was created with appropriate dimensions and meshed properly for importing it into the code for validation purpose. The pipe geometry modelled using the Solidworks is shown in Figure 1. The left end is considered to be the entry or inlet portion to the simulation.

![Figure 1. Pipe modeled in Solidworks model](image)

After preparing the geometry, it was meshed using ANSYS ICEMCFD in order to make the computational domain into the cells or nodes, which are the discrete representation of the geometry on which the flow is solved. Boundary conditions are applied to these grouped boundary nodes for better convergence and accuracy of solutions. The mesh size of the flow domain is comprised of 18, 91,391 unstructured tetrahedron meshes in order to maintain the mesh quality of the 85 percentage elements above 0.85, the mesh generated is shown in Figure 2. The fluid flow is introduced with a solid rigid spheroidal particle with dimensions major axis and minor axis 0.005 m and 0.005 m respectively. When the major axis and minor axis of the spheroid become equal, the case become that of a sphere.
2.3. Execution of the solver
The simulation was performed with Finite Volume Method (FVM) Unstructured solver and meshed geometry was imported into the solver in a readable format. The flow chart of execution of the code is shown in Figure 3.
3. Results and Discussions
The base solver of FVM code was validated using certain benchmark solutions like lid driven cavity, flow past a cylinder and flow through pipe. The results of base solver were compared with some previous literature and correctness of the solver was proved.

The validation was carried out for axial migration of spheroidal particle in z direction. While performing the validation, the dynamic viscosity was taken as 0.001 Pa-s for the fluid considered for the analysis. For the simulation, geometry was modeled using Solidworks with flow set on to z direction. The average Reynolds number for the flow domain was taken as 1864 and at the initial case velocity was set to zero. The mass density of particle is about 3600 kg/m³, which is close to the density of alumina particle. Simulations was carried out in steady flow conditions. Here, in this case the major axis and minor axis of spheroid turns to be equal (0.005 m).

Figure 4. Comparison of axial motion for different pulsatile frequencies

The trajectories of spheroidal particle (spherical for validation) was compared with another spherical particle using experimental set up as studied by Takayuki et al. [4]. The equations for particle transport were incorporated with the base solver in order to modify the solver for obtaining desired outputs. The results for validation is shown in Figure 4. Comparing the results for both cases, the modified solver was validated since simulation results agrees with that of literature.

3.1. Variation of pulsating frequency
The geometry and meshing of the flow domain was done as per explained in the previous sections. The dimensional part of geometry was taken with respect to the geometric modeling section. The readable format for the mesh was imported into the FVM solver and simulations were carried out. The pulsating frequencies were provided for the flow as 1.20 Hz, 3.33 Hz and 4.00 Hz. The Reynolds number and viscosity were chosen as 1864 and 0.001 Pa-s. For each cases, other flow properties were kept constant and alumina particle was introduced into the flow.

The axial migration of spheroidal particle for different pulsating frequencies was plotted with respect to time was shown in Figure 5. Each cases showed some rises and downs in its trajectory for the spheroid, since the flow velocity reverses its direction over each cycle. From the plots, it is observed that the when the pulsating frequency of the flow increased, the migration rate also increases. The distance traveled by the particle which is introduced in the flow domain of higher pulsating frequency, which in turns increases the rate of migration of spheroid. For the present study, the alumina particle traverses more when the frequency was set to be 4.00 Hz.
Figure 5. Comparison of axial motion for different pulsatile frequencies

3.2. Variation of fluid density

Similar to the studies in previous section, geometry and meshing of the flow domain was performed. The pulsating frequencies were kept constant along with viscosity of fluid used for simulation. For the flow as 1.20 Hz, 3.33 Hz and 4.00 Hz. The Reynolds number and viscosity were taken as 1864 and 0.001 Pa·s respectively. Simulation was carried out for fluid having density of 1005 kg/m$^3$ (nearer to density of water at normal temperature) and fluid of density 1025 kg/m$^3$ (average blood density).
The trajectory of spheroidal particle for different fluid densities were plotted with respect to time was shown in Figure 6. Here also up and downs were observed in the plot for the motion of particle. It is evident that the when the density of the flow domain was increased, the migration rate decreased. The distance traversed by the spheroid which is introduced in the flow domain of higher density, shows lower migration rate. In this study, the alumina particle introduced in the fluid of density 1025 kg/m$^3$ undergoes less migration compared to the other case.

4. Conclusions
Simulations was done for axial motion of spheroidal particle by considering different pulsating frequencies. It can be concluded that when pulsating frequency increases, the distance travelled by the particle for a given particular time step will be more. The particle changes its direction over each cycles and high pulsatile flow holds high migration rate for particle, since the distance travelled by the body increases in every cycles.

The numerical simulations were carried out for spheroid considering fluid domains of different frequencies. The migration rate for particle introduced in high density fluid observed low migration rate. It happens since the particle experiences more resisting forces while introduced into the flow domain. The axial migration of spheroid is very complex when pulsatile nature is studied.

The present study can be extended to parameter study by including two phase algorithm to the base solver. Another wide study scope is enabled in the field of numerical simulation considering deformation of walls and particles.

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References

[1] Abhinav P, Rahul S, Panigrahi P K and Muralidhar K 2013 Chaotic flow in an aortic aneurysm Journal of Applied Physics 113 1214909

[2] Chandan P, Malay K D and Muralidhar K 2015 Three Dimensional Simulation of Pulsatile Flow through a porous bulge Springer Science Business Media Dordrecht Transp Porous Med 107(3) 843-870

[3] Jae S P, Suk-Heung S and Hyo-Il J 2009 Continuous focusing of micro particles using inertial lift force and vorticity via multi-orifice microfluidic channels The Royal Society of Chemistry 9(7) 939-948

[4] Takayuki H, Hitoshi F, Masahiro K and Hirohito T 2009 Transport Phenomena of solid particles in pulsatile pipe flow Advances in Mechanical Engineering 2 121326

[5] Sarath S, Jayakumar J S, Muralidhar K 2016 Numerical Simulation of motion of single rigid spherical particle in pulsatile flow Fluid Machines and Fluid Power 15-17