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NUMERICAL SIMULATION OF HUMAN BLOOD FLOW IN MICROVESSELS

*ATTA ULLAH, I.R. CHUGHTAI and M. NADEEM

Department of Chemical & Materials Engineering, PIEAS, P.O. Nilore, Islamabad, Pakistan.

In this research, steady state flow of human blood in vascular system has been studied. Computational fluid dynamics has been used to predict pressure drop in human arteriole, artery, capillary, venule and vein. Viscosity of human blood has been treated in different ways by employing Newtonian, Power law and Herschel-Bulkley models. It has been observed that the Herschel-Bulkley model predicts the pressure gradients in all diameters reasonably whereas Newtonian and Power laws have their limitations.

Keywords: Blood flow, Non-newtonian models, Pressure drop, Microvessels, Power law, Herschel-Bulkley

1. Introduction

The term hemodynamics describes the physical factors governing blood flow within the circulatory system. Blood flow through an organ is determined by the pressure gradient driving the flow divided by the resistance to flow. Resistance to flow is directly related to the viscosity of the blood. The viscosity of whole blood is about three to four times the viscosity of water owing to the presence of red cells and proteins. Blood viscosity normally does not change much; however, it can be significantly altered by changes in hematocrit and temperature and by low flow states. Hematocrit is the volume of red blood cells expressed as a percentage of a given volume of whole blood. Vessel radius is the most important factor determining resistance to flow [1].

The variation of velocity with the change of diameter can be viewed in Fig. 1. Blood rheology is a complex phenomenon and there is no agreeable single model for its representation. The power law and Herschel-Bulkley models are popular non-Newtonian models and affect hemodynamics quantities under many conditions [2]. Besides the influence of cellular components in plasma flow conditions, the size of the flow domain impacts the shear-thinning behavior of blood. Both in medium and large size arteries, non-Newtonian viscosity influence hemodynamics factors [3]. In some capillaries, small vessels with a diameter close to the size of cells, the non-Newtonian property of blood is more predominant. In this study, the finite volume method is used to investigate hemodynamics predictions of each of the models in reference to pressure drop. To implement the finite volume method, the computational fluid dynamics software Fluent 6.2 has been used.

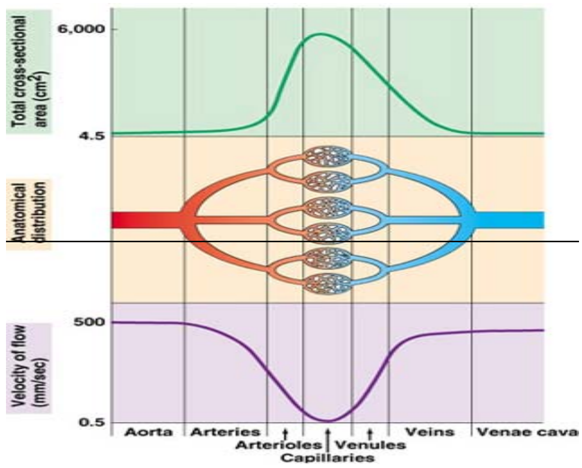

Figure1. Variation of velocity and cross section for various vessels of human vascular system.

2. Governing Equations

In this work materials will be considered without gradients in temperature, and the conserved quantities of interest are therefore mass and momentum. These two conserved quantities lead to the continuity equation and the equation of motion. A third equation, the constitutive equation,

* Corresponding author : atta@pieas.edu.pk

relates the shear rate with the shear stress, and we have a set of equations that completely determines a shear flow. In practical the flow of human blood in vascular system is pulsating in nature, however, the flow of the blood is assumed to be in steady state conditions for this work. Moreover the tubes of vascular systems have been assumed to be cylindrical which in real are more elliptic. Along with the steady and laminar flow, a no slip boundary condition has been applied as a boundary condition. Furthermore, the walls of the vascular system have been assumed to be rigid which if not rigid would change diameter with the pulse of the blood flow.

The continuity equation is derived on the assumption of mass conservation whereas the equation of motion is derived from the conservation of momentum. Shear stress and shear rate variation differs for the three types of flow regimes as will be stated later on.

Continuity Equation

$$\nabla.(\rho u) = 0 \tag{1}$$

Equation of Motion

$$\nabla.(\rho\mu\mu) = -\nabla_p + \nabla.(\tau) + \rho\vec{g} \tag{2}$$

Newtonian Model

$$\tau = \mu\gamma \tag{3}$$

Power Law Model

$$\tau = k(\gamma)^n \tag{4}$$

Herschel-Bulkley Model

$$\tau = \tau_0 + k(\gamma)^n \tag{5}$$

3. Input Parameters

All the parameters used for the purpose of simulation are listed in Table 1 [4].

The power law index, n, in the Power law model was taken as 0.708 while the consistency index, k, was taken as 0.017. For the Herschel-Bulkley model the power law index and consistency index were taken as 0.7844 and 0.01352 respectively with a yield stress value of 0.005N. The yielding viscosity was taken to be 0.003 kg/m.s. Normal values density and viscosity were taken to be 1057 kg/m^3 and 0.003 kg/m.s [5].

Table 1. Diameters and velocities used in CFD analysis.

Vessel	Diameter (m)	Velocity (m/s)
Artery	0.004	0.45
Arteriole	0.00005	0.05
Capillary	0.000008	0.001
Venule	0.00002	0.002
Vein	0.005	0.1

4. Results and Discussion

The focus of this research has been to determine the pressure drop in various vessels of human vascular system. The parameters used in the calculations of pressure gradients have been derived from experimental human physiology.

Figures 1-5 is a comparison of pressures at the inlet and outlet of various vessels of human vascular system. In the arteriole, minimum pressure drop has been estimated by the Herschel-Bulkley model which also takes into consideration of blood's yield stress into account. On the contrary maximum pressure drop is obtained if the fluid is treated to obey Power Law. However in the case of human arteries, Newtonian and Herschel-Bulkley models give almost the same pressure drops. This proves the generally accepted approach that in large vessels human blood acts as a Newtonian fluid. Similar trend of same pressure drop is observed in venules as well for Newtonian and Herschel-Bulkley models. Maximum pressure drop is encountered if the fluid is treated as Power law fluid. However in veins, all the models predict different pressure drops. Herschel-Bulkley model predicts maximum whereas Newtonian model predicts minimum pressure drop. In the smallest of all vessels viz. capillaries Newtonian model predicts negligible pressure which is obvious as pressure drop is proportional to velocity which is also negligible at the smallest level. Herschel-Bulkley model predicts a pressure drop less than that of Power law.

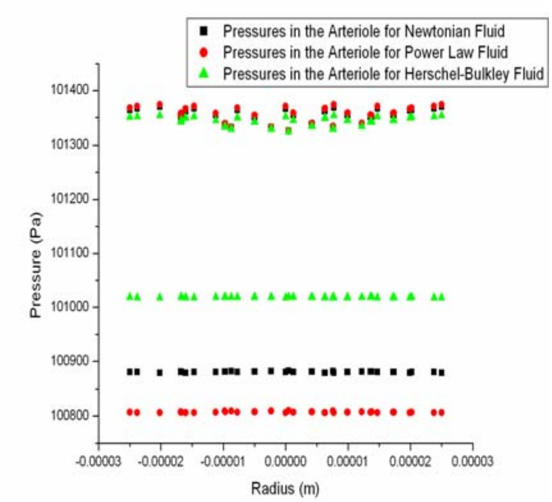

Figure 1. Pressures at the Inlet and Outlet of Human Arteriole.

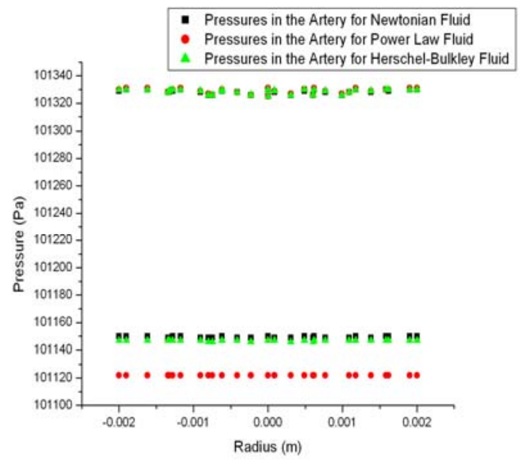

Figure 2. Pressures at the Inlet and Outlet of Human Artery

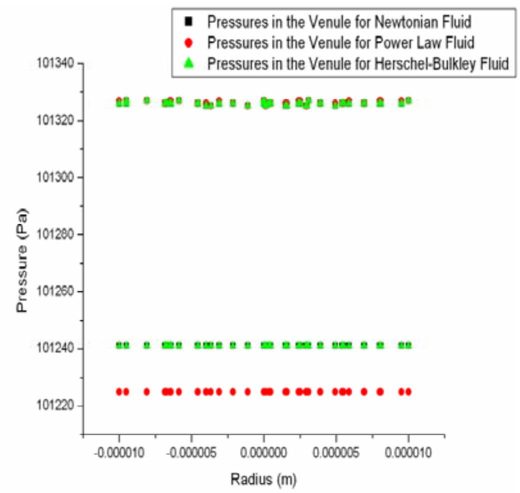

Figure 3. Pressures at the inlet and outlet of human venule.

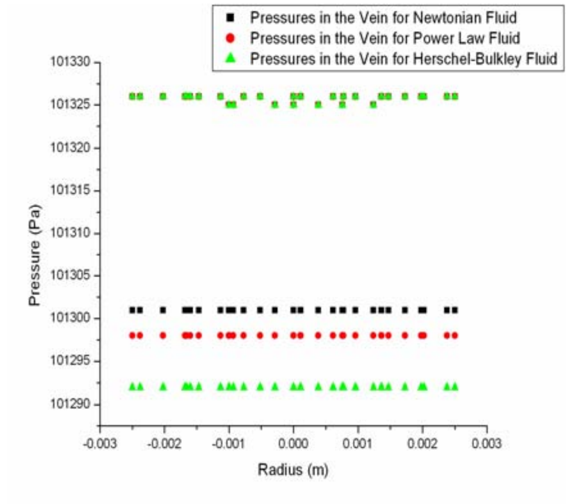

Figure 4. Pressures at the inlet and outlet of human vein

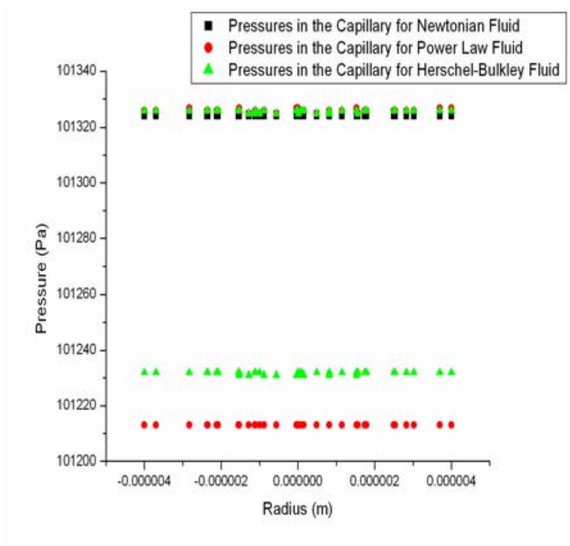

Figure 5. Pressures at the Inlet and Outlet of Human Capillary.

The pressure drops for various viscous models have been compared in Table 2. It can be readily visualized that the use of Newtonian model for the prediction of pressure drop in capillary level vessels is strongly defective as it predicts almost negligible pressure drop. The use of Power law in the smallest microvessels produces an over prediction in pressure drop. In general, the Herschel-Bulkley model will produce the most reasonable results in almost all types of microvessels as it takes into account the effect of yield stress at low velocities and thus at low shear rates.

Table 2. Pressure Drops in Various Vessels for Different Viscous Models.

Vessel	ΔP for Newtonian Model (Pa)	ΔP for Power Law Model (Pa)	ΔP for Herschel-Bulkley Model (Pa)
Arteriole	492	569	337
Artery	181	210.1	184.4
Capillary	1	114	95.1
Venule	85	102.4	85.1
Vein	24.8	28.5	34.8

5. Conclusions

It has been concluded from the comparative studies of three viscous models that in large vessels human blood can be considered as a Newtonian fluid. However, at the arteriole, venule and capillary level it follows non-Newtonian behavior. Among the Power Law and Herschel-Bulkley models, reasonable results have been achieved with the latter model for the steady flow simulation. Moreover, as the diameter is reduced to the capillary level, velocity of blood is also reduces. This reduces the number of iterations required to solve the flow field as the flow does not need any transition length for the flow to develop. It can therefore, be safely concluded that for the human blood flow the Herschel-Bulkley model predicts the most reasonable results.

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