Human arteries blood flow simulation as porous medium

Mohammed K. Al-Saad[1], Sana J Yassen[1], Camilo Suarez-Afanador[3,4], Ahmed Kadhim AlShara[2]

1. Mechanical Department/Engineering College, Basrah University, Basrah, Iraq
2. Mechanical Department/Engineering College, Misan University, Misan, Iraq (dr.ahmed_alsara@uomisan.edu.iq)
3. Aix Marseille Université, CNRS, Centrale Marseille, LMA, Marseille, France.
4. Department of Engineering, Institute of Computational Engineering, University of Luxembourg, Luxembourg

Abstract
Simulations of blood flow as a porous medium through an elbow artery have been investigated. The arteries have treated as a porous medium. The blood is represented as a Newtonian fluid. The blood is supplied with various geometries of arteries, which have different diameters. The no-slip boundary condition is applied for velocity components along the rigid arterial walls. Numerical simulations have presented the details of blood flow patterns and the local distribution of blood flow along the artery. The effects of permeability, with respect to the changes in the Reynolds number (Re = 0.1,1 and 5) as well for varying porosity levels has been discussed. The effect of blood vessel diameter on the resultant of distribution of velocity inside the vessel has been studied. Results are presented in the form of variations of velocity distributions and local variations of flow rates through the vessel dimensions. The numerical results of simulation are compared with the available data and a good agreement is found. The study shows to be potentially useful to evaluate the role of porosity and flow conditions when the body is subjected to diseases.

Keywords: Blood flow, porous media, finite volume

Introduction
Biomechanical engineering is an emerging multidisciplinary field that integrates engineering and medicine. It involves several academic disciplines and professional specialisations aiming to improve the quality of healthcare diagnosis and ways of treatment. It combines the design and problem-solving skills of engineering with medical and biological expertise.
The study of the circulatory system under normal and pathological conditions is one of the most important elements in the field of biomechanical engineering. Hemodynamic is one of the major and larger systems connecting several structures at different scales in the human body. It is, therefore, essential to develop tools that can successfully study the hemodynamic of blood vessels, allowing to investigate the complications encountered in cardiovascular diseases, and extending this to the simulation of alternative surgical procedures estimating their clinical impact on the hemodynamic condition of the patient. Is a fact that contemporary numerical simulations are a good substitute for experimental studies, which are expensive and time-consuming. Consequently, its application has been widely used to uncover physical phenomena in many emerging fields of research.

Many researchers are considered blood as a bio-fluid that can behave as Newtonian fluid when it flows through arteries of human body [1-3]. From the state of art, it seems to be appropriate to model blood as a Newtonian fluid when it flows in narrow arteries. Some researchers were dealt with the flow in narrow arteries as a biological porous flow (e.g. GUO

[4] at 1980 s). where Some biological capillaries are examined as a porous media that is led to build a porous media model.

The mathematical modelling was presented by Song et al. [5] to treat the blood flow in the narrow arteries as porous medium. They showed that the increase in the threshold significantly increases the frictional resistance. Others researchers have considered the porous media based energy equations to show the temperature distributions inside the body of tissue phantoms[6]. In general, a porous medium is a material volume that consists in a solid material with an interconnected void space that can be simply characterized via the volume fraction of voids immersed in the solid space [7-9]. Most studies of the flow in porous media have used the Darcy law that can be define as a relationship between the velocity of flow to the pressure gradient across the porous medium according to mathematical modelling [10]. In addition permeability is represented one of the porous medium's parameters that is the measure of flow conductivity in the porous medium [11]. Tortuosity and curvature vessel are considered an important for the combination of the fluid and the porous medium which is represented the hindrance to flow diffusion imposed by local boundaries or local viscosity. Where tortuosity is considered an important when it is related to the medical applications [8]. In recent decades, CFD analysis is become a popular tool to analyse medical applications. [12, 13] have used porous media to model aneurysm coiling. An ideal geometry was applied by [14, 15] to calculate the properties of blood flow. In addition, a model is showed by [16-18] to implement porous medium representation on aneurysm diverting stent.
A numerical analysis is presented by [19] to assess blood hemodynamic inside the unruptured aneurysm. They presented a model (coiled aneurysm) as a porous volume with porosity and permeability related to the coil size and compactness value to study the effect of endovascular embolization. The results of this study demonstrated that smaller coil diameter can be led to less flow circulation within the aneurysm, in which it can be increased the chances of thrombosis compactness value. The CFD analysis will be introduced in this paper as a method to overcome the most limitations and difficulties of porous flow. To permit modelling of fluid flow such as blood flow through an elbow artery various useful features can be provided. The further analysis of the flow through an elbow vessel as a porous media is explored in this numerical test. The aim is to show how the characteristics of flow will take a location inside of curvature vessel after the blood flow has been released. The effect of the different diameter of geometry will also be studied. The numerical simulations of blood flow models are examined and compared with experimental data available in the literature.

Numerical methodology

The flow of blood has been described as a laminar flow, steady state, and 2D incompressible viscous blood, Newtonian fluid, and unidirectional flow. The present set of simulations has been performed for different sizes of the blood vessels diameters (100-500μm). The length of the tube is assumed to be large enough compared to its diameter. The permeability of the porous medium has been assumed to vary with the radial direction of the vessel. The governing mass and momentum conservation equations for solving isothermal fluid flow inside the blood vessels are given by [20]:

$$\frac{D\rho}{Dt} + \rho\nabla.\mathbf{v} = 0 \qquad (1)$$

$$\frac{D\mathbf{v}}{Dt} = -\frac{1}{\rho}\nabla P + \frac{1}{\rho}\nabla.\boldsymbol{\tau} + \mathrm{S} \qquad (2)$$

Where $D,\ \rho,\ t,\ \mathbf{v},\ P,\ \boldsymbol{\tau},\ S$ represent the fluid parameters essential derivative, density, time, velocity vector, pressure of the fluid, shear stress and volumetric source term respectively.

Meanwhile the flow of blood inside porous vessel region has been described by the Darcy–Brinkman equation as shown by Eq. (3). The source terms in Eq. (3) represent the viscous and the form drag interactions between the fluid and the walls.

$$\frac{1}{\varepsilon}\frac{\partial \mathbf{v}}{\partial t} + \frac{1}{\varepsilon^2}\mathbf{v}.(\nabla^2 \mathbf{v}) = \frac{1}{\rho}\nabla P + \frac{\nu}{\varepsilon}\nabla^2 \mathbf{v} + \frac{\mu}{K}\mathbf{v} \qquad (3)$$

Where μ is the dynamic viscosity $(m^2 s^{-1})$, ε is the porosity of the porous medium and $K(m^{-2})$, being the permeability. The axial velocity gradient is presented along the axis of symmetry. The arterial wall is considered as fixed.

Numerical method

The numerical modelling for the determination of distributions of hydrodynamics of blood flow inside vessel as a porous model has been described. This section discusses the numerical modelling aspect resulting according to the geometry. The porous media-based bio-flow transfer model and the coupling with the Brinkman equation to obtain the hydrodynamics resultant distributions.

All the simulations have been performed using FVM. Time step and grid size have been used until convergence is reached. The numerical simulations estimate the impact of the leading parameters such as geometry, permeability, and porosity.

To investigate the effect of vessel geometry on the blood flow, blood vessels with 90^{o} bend was chosen. Figure (1) shows the two-dimensional vessel configurations and geometric parameters of the model. The boundary conditions and flow parameters used in the simulations were the same as described previously. A fine mesh setting is used for the domains. Aiming to a mesh independent study, a mesh with 2.1 million nodes with the maximum element size of $5\text{x}10^{-4}$ µm has been used (Figure (1)). The Convergence residuals criteria have set to 1×10^{-7} for all flow variables.

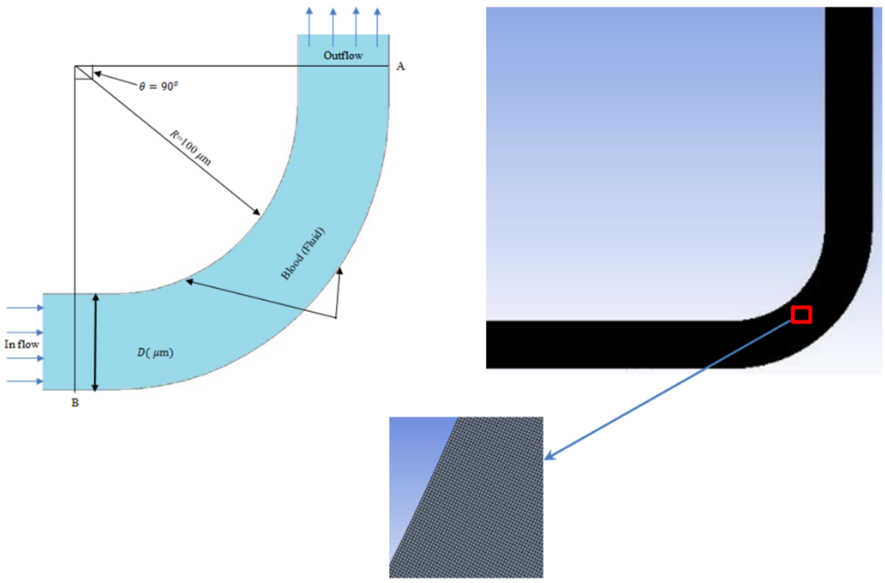


Figure 1: The geometry of vessel (90°) with mesh

The geometries in this study consist of two domains: the vessel and blood flow. As has been pointed before, high accuracy is ensured by choosing a fine mesh discretization respecting the convergence criteria, which it will influence on the time required for each simulation. The influence of the spatial resolution of fluid elements on numerical results is presented in Figure (2).

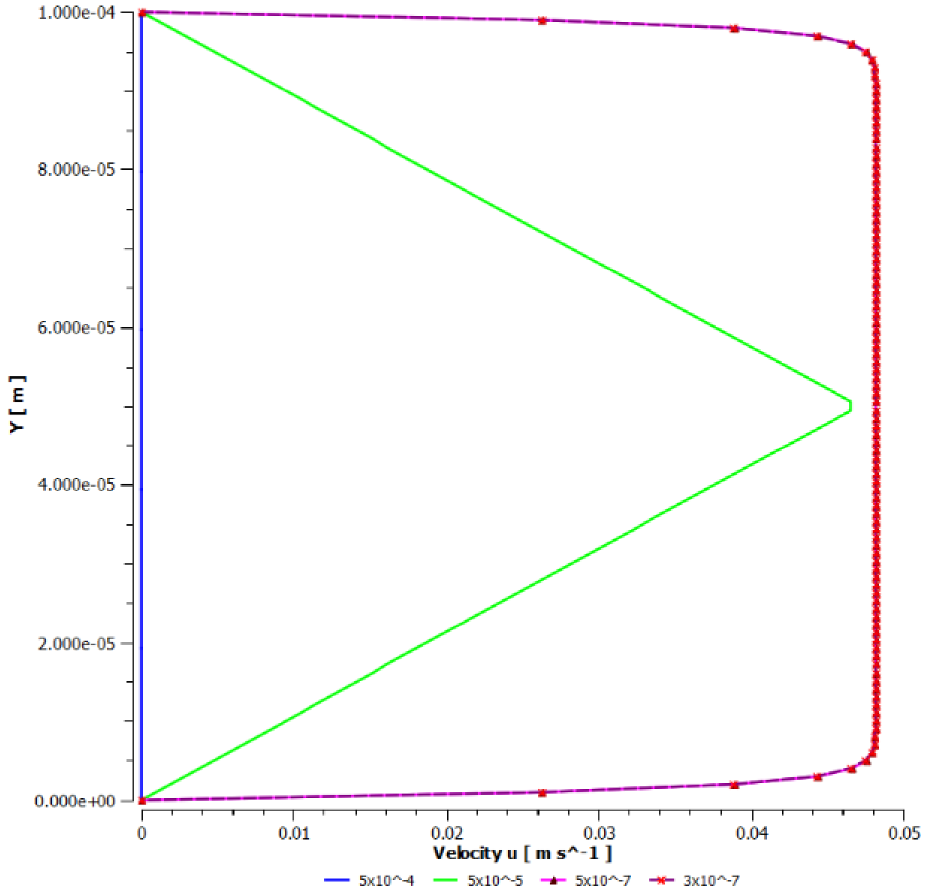


Figure 2: Velocity profiles of blood flow at different resolutions

A set of physically reasonable assumptions have been considered through the numerical model as presented in the numerical methodology section. In addition, it was also assumed that there is no variation of the properties during the process inside the vessel. The parameters of the simulation used in this work are presented in Table (1). It must be noted that the properties of permeability parameter are used according to Kozeny equation. (4). The range of Reynolds number is 0.1–5 for blood flow through vessels according to [21]. Finally the other numerical values involving parameters are used with the respect of physiological ranges referring to [22-24]

$$k = \frac{\emptyset r^2}{8} \qquad (4)$$

Porosity	Density (kg/m^3)	Re	Diameter of vessel (μm)	kinematic viscosity (kg /m.s)
0.5-1	1060	0.1-1-5	100-200-300-400-500	0.005

Table1: Model parameters and dimension of vessels

The porous media model has been used under the framework of the Finite Volume Method (FVM). This FVM-based model has been employed to handle the momentum across the porous blood vessel interfaces. A suitable discretization scheme that is capable to employ the flow in the porous and blood vessel domains has been used.

A good grid arrangement between the grid clustering at the interfaces and the outer walls of the domain has recommended, meanwhile all physical variables were located at the cell centre locations of the control volume. This arrangement was showed to be suitable for problems involving interfaces between porous and fluid flow regions. The numerical model in the present work uses the different geometry which was reported by [25].

The distribution of velocity profile has been shown for different locations inside the vessel. It is strongly dependent on the location which employed in the numerical model.

For numerical computations, the length of the vessel at the upstream and downstream is taken to be too long to avoid any distortion at the beginning of the vessel and to keep the fully developed flow [26, 27].

Results and Discussion

The numerical solutions are tested under physiological flow conditions. The results of blood flow simulation show when the steady state of flow is achieved. The effects of parameters such as permeability K which depends on eq. (4), Reynolds number, porosity and bend region were tested to investigate the effect of variable vessel geometry and on the fluid flow.

the process of flow can be controlled under some conditions. The steady flow of blood through a porous medium in a vessel, the condition of the wall as a non-slip condition and considering the blood flow as an incompressible fluid were tested. Also, the artery is represented as a bent tube in 2D.

Fig.1 shows the details of the geometry which represent the length of vessel with the diameter and fluid regions maintained at every case. This representation carries the benchmarking for the mass and momentum equations. The results of the blood flow and the porous have been compared with those in the available literature[28]. Uniform flow profiles have applied at the inlet of the physical domain and hydrodynamic conditions at the outlet have been assumed.

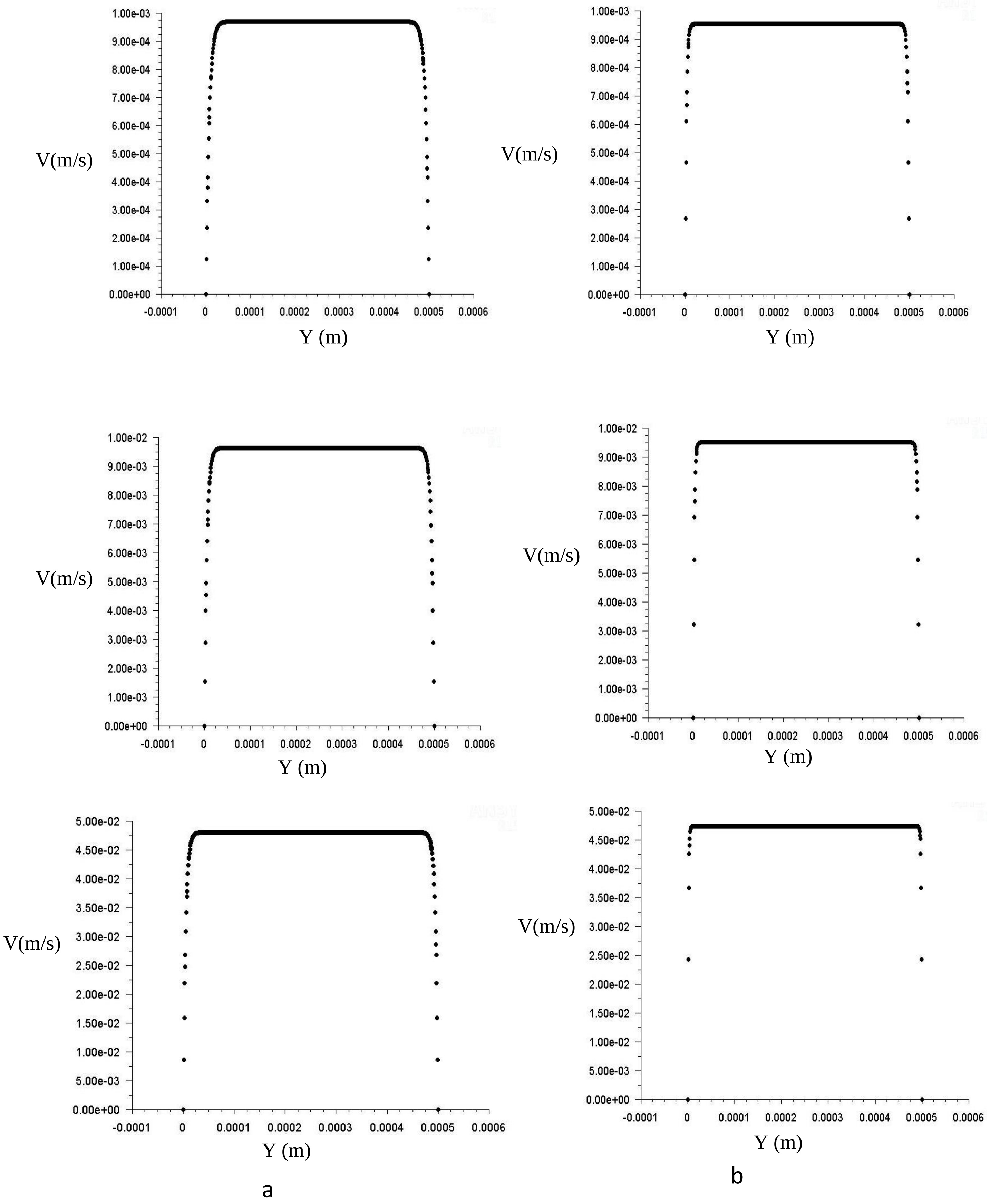


Figure 2: Velocity distribution of blood flow for diameter 500 µm and constant permeability. (a) Porosity =0.5. (b) Porosity =1. Variable Re (0.1, 1, 5).

Flow characteristics when blood flows through vessels in porous medium consideration were studied. The velocity distribution of blood flow using two different values of the porosity factor in the cases of a constant permeability for three different values of Reynolds number is shown in Figures 2(a) and 2(b), respectively. It is noted that in the case of constant permeability and the types of porosity, the velocity of blood flow increases as the porosity factor decreases. Moreover, it is shown from the figures that the magnitude of width of the plug flow region (flatness of the velocity profile) decreases as the porosity factor decreases.

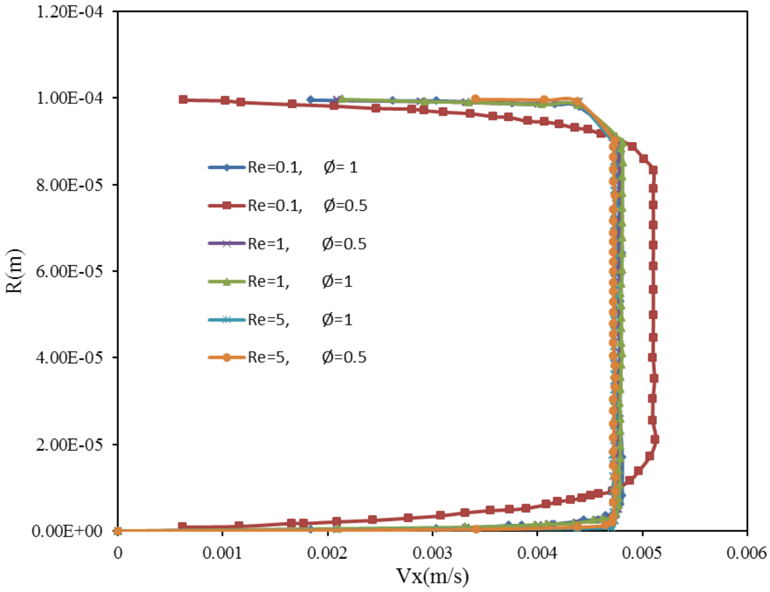


Figure 3: Velocity distribution of blood flow for diameter 100 µm different permeability. Variable porosity ε = 0.5,1. Variable Re (0.1, 1, 5).

The variation of flow rate for different values of the permeability factor in the cases of constant porosity (ε =0.5, 1) is shown in Figure 3. In both the cases of porosity, the flow rate increases rapidly as diameter increases from100 to500 µm. It is also observed that the variation of pressure gradually increases as the diameter of the vessel increases in the cases of constant porosity (ε =0.5, 1). Furthermore, the pressure is increased when the porosity factor increases at constant diameter as is shown in Figures 4(a, b).

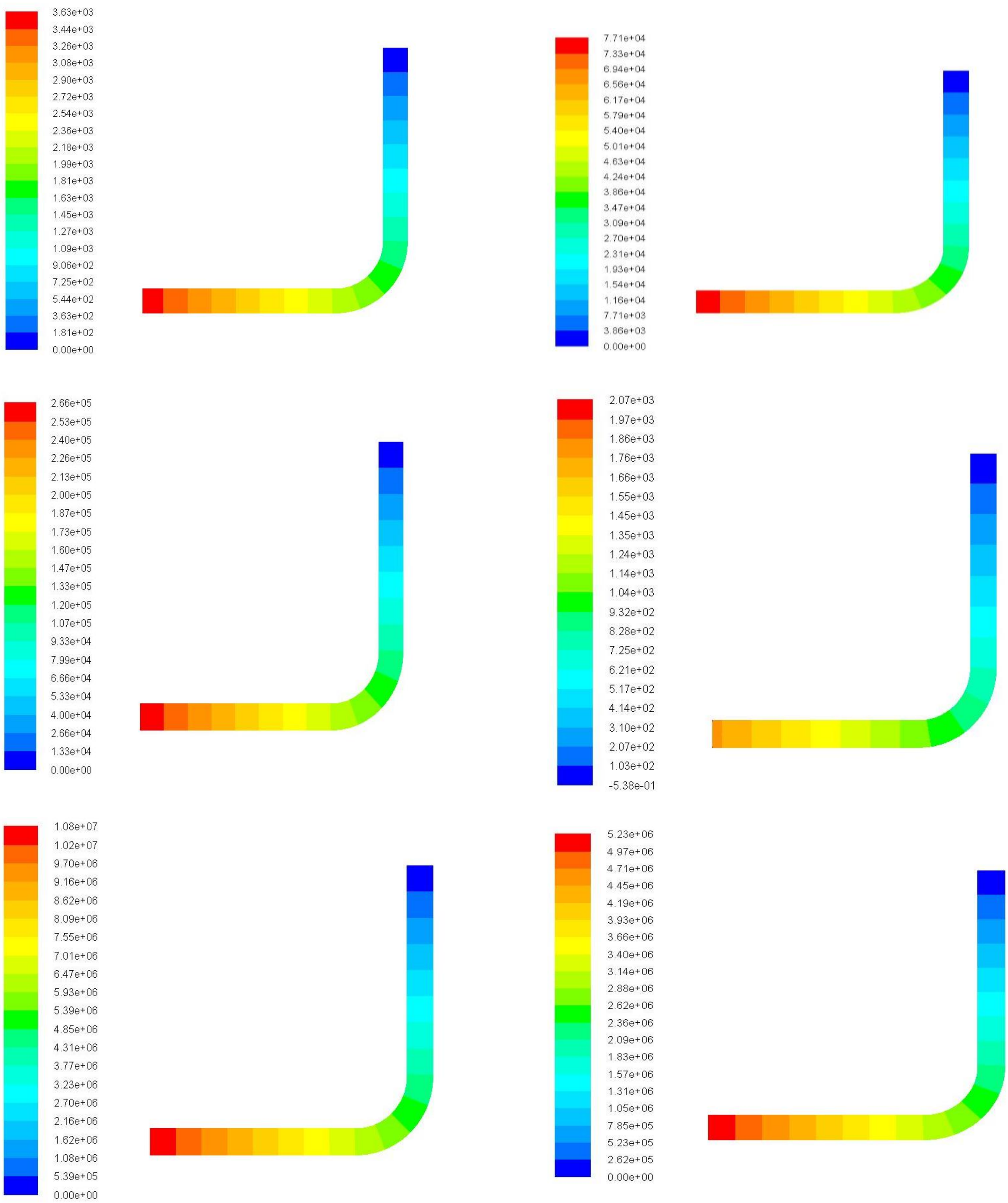
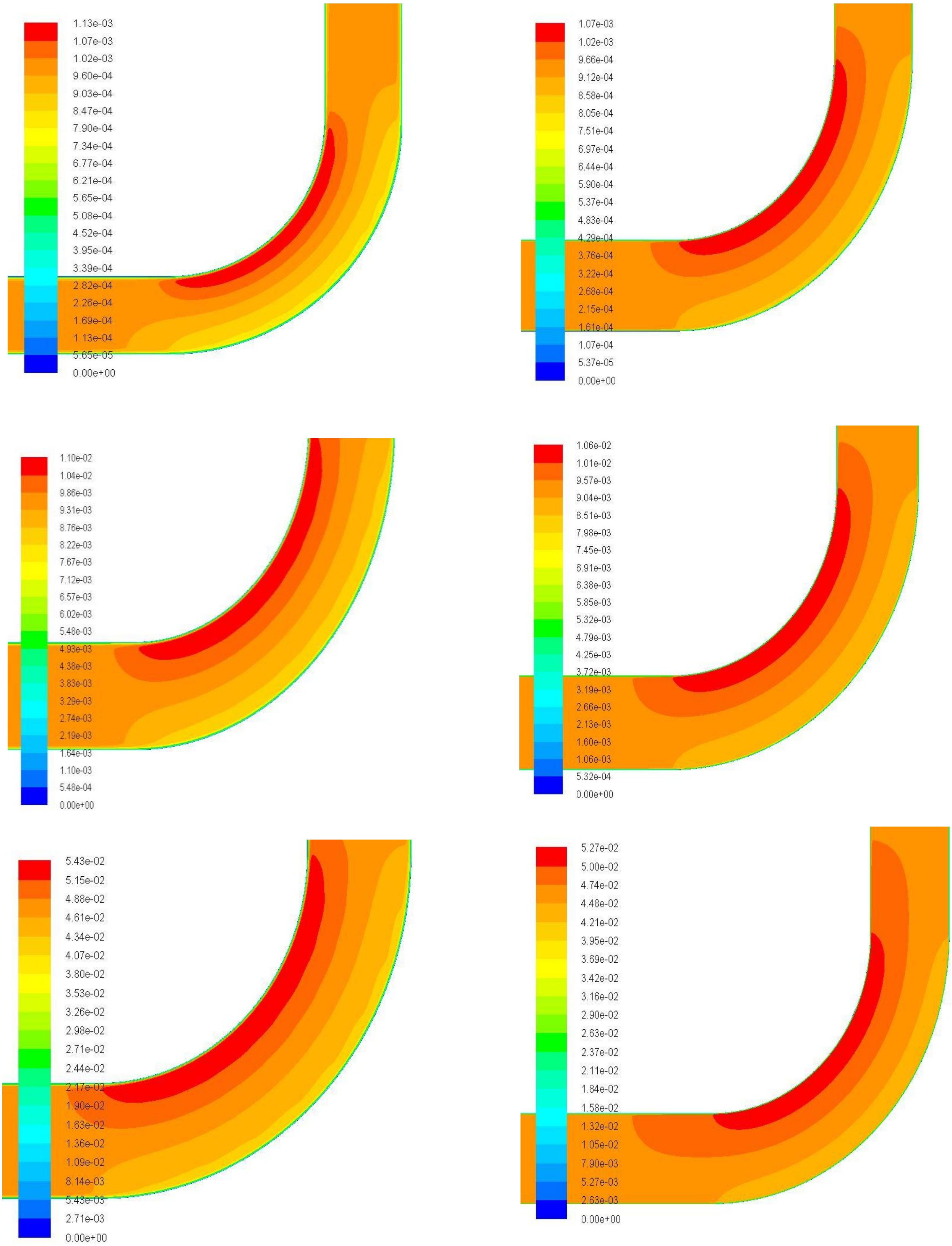


Figure 4: Pressure distribution of blood flow for diameter 300 µm constant permeability. (a) ε =0.5. (b) ε =1. Variable Re (0.1, 1, 5).

Figure 5 shows the velocity profiles at two different porosity values. Due to the curvature of the vessel, the velocity cannot be the same as in a straight tube. The maximum velocity will move towards the curvature axis. An increase in porosity will lead to decreases the velocity and it can move the maximum velocity away from the centre [28]. As it is pointed out in [29] the variation of flow velocity increases and accelerate towards the inner diameter of the bent part of the vessel in the cases of constant porosity (ε =0.5, 1). Furthermore, the Figure 5 shows the magnitudes of streamwise velocities to be gradually higher with decrease of Re at bend near the inner diameter. For all Re cases, the numerical results did not predict a huge increase in velocity along the bend vessel due to the small values of Reynolds number.



(a) (b)

Figure 5. Velocity contour in the tube bend at different Re(0.1,1,5) for two values of porosity (a=0.5, b= 1) at constant diameter =500 μm

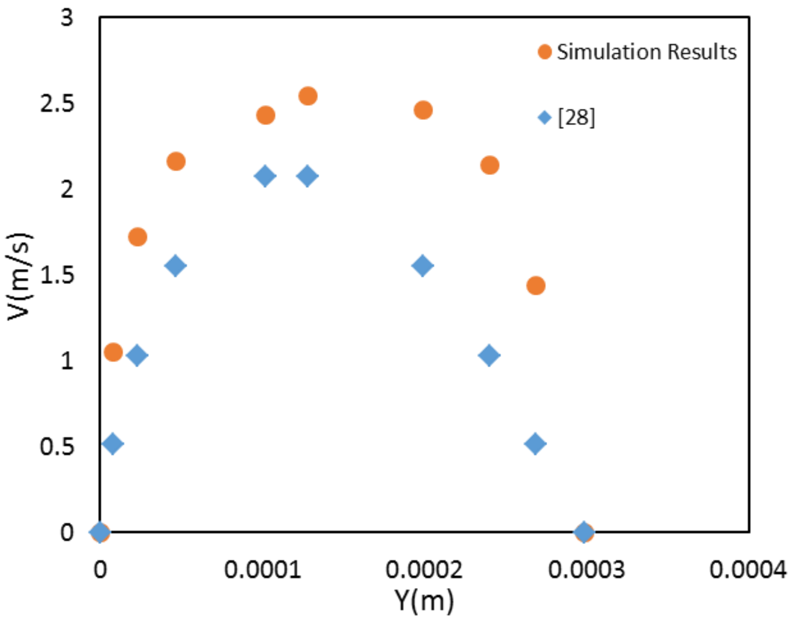


Figure 6. Comparison of velocity between simulation results and other researcher for values for Re=1 , at constant diameter =300 μm

Figure 6 shows the comparison between the present numerical simulation results and the most reliable and available results in literature [28]. In case of Re = 1 and D =300 μm, the maximum error is 47% for the peak velocity during the simulation, meanwhile the error over all the domain at steady state is 18%. Apparently, the comparison of the flow distribution in the vessel does not lead to large differences and it gives a good agreement. Despite have used a high order of convergence residuals of numerical scheme and fine grids, numerical errors can lead to affect the results

Conclusions

The study was tested and compared with the literature results for other standard cases. To study the response of the action of blood flow in vessels this study has been undertaken by varying the Reynolds number, the porosity of the vessel and permeability. The numerical simulations could be used as an indicator of how the blood flow velocity influenced in a bend vessel. In addition, the assumed penalty values such as different diameters used in the analysis discussed above can be more accurately estimated or calibrated by this study. Finally, the effect of the bend vessel on the blood flow has been examined. It was observed that the magnitude of velocity profile is change along the locations of the vessel. The numerical results also have a good agreement with other reference cases. This study also demonstrated that the hydrodynamic of velocity in a bend vessel can also be easily modelled using the developed numerical procedures.

References

1. Dash, R., K. Mehta, and G. Jayaraman, *Effect of yield stress on the flow of a Casson fluid in a homogeneous porous medium bounded by a circular tube.* Applied scientific research, 1996. **57**(2): p. 133-149.
2. Sud, V. and G. Sekhon, *Arterial flow under periodic body acceleration.* Bulletin of Mathematical Biology, 1985. **47**(1): p. 35.
3. Al-Saad, M., et al., *Application of Smooth Particle Hydrodynamics Method for Modelling Blood Flow with Thrombus Formation.* CMES-Computer Modeling in Engineering & Sciences, 2020. **122**(3): p. 831-862.
4. Wanti, G.S.Y.D.W., *The physical characteristics of the porous media concerning flow in viscera [J].* Acta Mechanica Sinica, 1982. **1**.
5. Song, F.-q., Y.-s. Xu, and H.-m. Li, *Blood flow in capillaries by using porous media model.* Journal of Central South University of Technology, 2007. **14**(1): p. 46-49.
6. Vyas, D.C.M., S. Kumar, and A. Srivastava, *Porous media based bio-heat transfer analysis on counter-current artery vein tissue phantoms: Applications in photo thermal therapy.* International Journal of Heat and Mass Transfer, 2016. **99**: p. 122-140.
7. Das, B. and R. Batra, *Non-Newtonian flow of blood in an arteriosclerotic blood vessel with rigid permeable walls.* Journal of theoretical biology, 1995. **175**(1): p. 1-11.
8. Khaled, A.-R. and K. Vafai, *The role of porous media in modeling flow and heat transfer in biological tissues.* International Journal of Heat and Mass Transfer, 2003. **46**(26): p. 4989-5003.
9. Prasad, B. and A. Kumar, *Flow of a hydromagnetic fluid through porous media between permeable beds under exponentially decaying pressure gradient.* Computational methods in science and technology, 2011. **17**(1-2): p. 63-74.
10. Eldesoky, I.M., *Slip effects on the unsteady MHD Pulsatile blood flow through porous medium in an artery under the effect of body acceleration.* International Journal of Mathematics and Mathematical Sciences, 2012. **2012**.
11. Misra, J., A. Sinha, and G. Shit, *Mathematical modeling of blood flow in a porous vessel having double stenoses in the presence of an external magnetic field.* International Journal of Biomathematics, 2011. **4**(02): p. 207-225.
12. Umeda, Y., et al., *Computational fluid dynamics (CFD) using porous media modeling predicts recurrence after coiling of cerebral aneurysms.* PloS one, 2017. **12**(12).
13. Usmani, A. and S. Patel, *Hemodynamics of a Cerebral Aneurysm under Rest and Exercise Conditions.* International Journal of Energy for a Clean Environment, 2018. **19**(1-2).
14. Finnigan, P., A. Hathaway, and W. Lorensen, *Merging CAT and FEM.* Mechanical Engineering, 1990. **112**(7): p. 32.
15. Taylor, C.A., T.J. Hughes, and C.K. Zarins, *Finite element modeling of blood flow in arteries.* Computer methods in applied mechanics and engineering, 1998. **158**(1-2): p. 155-196.
16. Bouillot, P., et al., *Hemodynamic transition driven by stent porosity in sidewall aneurysms.* Journal of biomechanics, 2015. **48**(7): p. 1300-1309.
17. Karmonik, C., et al., *Relationships and redundancies of selected hemodynamic and structural parameters for characterizing virtual treatment of cerebral aneurysms with flow diverter devices.* Journal of biomechanics, 2016. **49**(11): p. 2112-2117.
18. Li, Y., et al., *Numerical simulation of aneurysmal haemodynamics with calibrated porous-medium models of flow-diverting stents.* Journal of biomechanics, 2018. **80**: p. 88-94.
19. Hamdan, M.O., et al., *Using CFD Simulation and Porous Medium Analogy to Assess Cerebral Aneurysm Hemodynamics after Endovascular Embolization.* Proceedings of the 4th World Congress on Momentum, Heat and Mass Transfer (MHMT'19), 2019: p. ENFHT 122
20. Fung, Y., *Biomechanics: Motion, Flow, Stress, and Growth, Edwards Brothers.* Inc., Ann Arbor, 1990.
21. Lyon, C.K., et al., *Flow through collapsible tubes at high Reynolds numbers.* Circulation research, 1981. **49**(4): p. 988-996.
22. Johnson, G., H. Borovetz, and J. Anderson, *A model of pulsatile flow in a uniform deformable vessel.* Journal of biomechanics, 1992. **25**(1): p. 91-100.

23. Mekheimer, K.S. and M. El Kot, *Influence of magnetic field and Hall currents on blood flow through a stenotic artery.* Applied Mathematics and Mechanics, 2008. **29**(8): p. 1093.
24. Taylor, D., *Blood flow in arteries. By DA McDonald. Edward Arnold, London, 1974. Pp. xviii+ 496.£ 12.* Quarterly Journal of Experimental Physiology and Cognate Medical Sciences: Translation and Integration, 1975. **60**(1): p. 65-65.
25. Liu, Q., D. Mirc, and B.M. Fu, *Mechanical mechanisms of thrombosis in intact bent microvessels of rat mesentery.* Journal of biomechanics, 2008. **41**(12): p. 2726-2734.
26. Abraham, J., E.M. Sparrow, and J. Tong, *Breakdown of laminar pipe flow into transitional intermittency and subsequent attainment of fully developed intermittent or turbulent flow.* Numerical Heat Transfer, Part B: Fundamentals, 2008. **54**(2): p. 103-115.
27. Kays, W. and M. Crawford, *Convective Heat and Mass Transfer, McGraw-Hill, New York, 1980.*
28. Wang, C., *Viscous flow in a curved tube filled with a porous medium.* Meccanica, 2013. **48**(1): p. 247-251.
29. Zeng, J., et al., *Flow and bathymetry in sharp open-channel bends: Experiments and predictions.* Water resources research, 2008. **44**(9).