Review Article GU J Sci 31(4): 1213-1227 (2018)

Gazi University

Journal of Science

http://dergipark.gov.tr/gujs

The Application of Computational Fluid Dynamics (CFD) Method and Several Rheological Models of Blood Flow: A Review

Esmaeel FATAHIAN[1,*], Naser KORDANI[2], Hossein FATAHIAN[1]

[1]*Young Researchers and Elite Club, Nour Branch, Islamic Azad University, Nour, Iran*

[2]*Department of Mechanical Engineering, University of Mazandaran, Mazandaran, Iran*

Article Info

Received: 19/06/2018
Accepted: 02/07/2018

Keywords

Rheological models
Blood flow
Non-Newtonian fluid
Computational fluid dynamics

Abstract

Computational fluid dynamics (CFD) method can be applied for gaining insights to the most fluid processes and related phenomena. Applying CFD method in the investigation of physiological flows especially blood is one of the interesting topics for many researchers. Because of its significant effect on various human cardiovascular diseases and arterial diseases, extended knowledge of blood flow in physiological conditions is required. This review provided an overview of recent studies on the application of CFD method of blood flow inside the corkscrew artery, arterial stenoses, human patient-specific left ventricle and arteries affected by multiple aneurysms. Also, several rheological models for describing the blood rheology were discussed. Based on this review, it was concluded that the application of CFD method can help the medical practitioners in the patients' treatment decision in the investigation of blood flow.

1. INTRODUCTION

A fluid with properties which are different in any way from those of Newtonian fluids is a non-Newtonian fluid. Many molten polymers and salt solutions are non-Newtonian fluids including substances such as starch suspensions, (STF)/fabric composites, paint, ketchup, custard, maizena, toothpaste, blood and shampoo which are found many commonly [1,2]. Blood is a non-Newtonian fluid since its fluid properties are not described with a constant value of viscosity and the relationship between strain rate and shear stress is non-linear. Since the blood apparent viscosity reduces with increased stress, it is considered to be a shear thinning liquid. This caused in free flow at higher rates and low flow at slow rates of deformation [3]. The blood including semisolid components and some particles for example, the proteins, cells, ions, and lipoproteins [4]. Furthermore, several experimental studies concluded that the blood viscosity has in some range of the shear rate, the characteristics of thixotropic, shear thinning, viscoelasticity, and yield stress [5-7] and also the blood viscosity depends on the flow shear rate [8]. Blood is a suspension of white blood cells, red blood cells, nutrients, etc. in tubes with large internal diameters and in aqueous solution. The change in viscosity can be neglected when compared to the size of the red blood cells [9]. However, changes in apparent viscosity are evident in tubes with an internal radius of less than 0.5 mm [9]. In the aorta, the artery travelled by the blood is large and has high enough shear rates that it has been generally accepted for modeling blood flow as Newtonian [9,10]. The majority of studies conducted using blood as a non-Newtonian fluid take place in either bifurcated arteries or stenosed. This is intuitive to put the non-Newtonian properties of blood in both of these cases as the size of the artery which is remarkably smaller than for the aorta and the results vary due to the diameter change [11-14]. Many researchers have attracted the investigation of the blood flow over the past years. Because of its significant effect on various human cardiovascular diseases and arterial diseases, detailed knowledge of blood flow in physiological conditions is required. Nowadays, Applying CFD method in the investigation of physiological flows especially blood is an interesting topic for researchers [15-18]. In the analyzing of the blood flow mechanics in arteries indicates an important topic of vascular research and plays a significant role in the individual's health. CFD models can be validated by measurement

*Corresponding author, e-mail: esmaeelfatahian@gmail.com

techniques which are available [19-21] can be useful in the prediction of future disease progression [22]. Also, in order to describe the rheology of blood there are several non-Newtonian rheological models include Carreau-Yasuda [23,24], Casson [25], power law [26], Cross [27], Herschel-Bulkley [28], Oldroyd-B [29], Quemada [30], Yeleswarapu [31], Bingham [32], Eyring-Powell [33], and Ree-Eyring [34]. Besides, blood is modeled as a Newtonian fluid [25,35] and this approximation is good for large vessels with high shear rates in many circumstances. In the present study, the application of CFD method in different physiological conditions of blood flow and also several rheological models of blood flow are discussed.

2. THE USE OF CFD METHOD IN BLOOD FLOW

The prediction of fluid flow fields can be obtained by computational fluid dynamics based on numerical methods relating to continuity, momentum and energy equations [36]. Applying CFD method in the investigation of physiological flows especially blood is one of the interesting topics for many researchers. The assumption of non-Newtonian behavior of blood flow in CFD method has accepted for small vessels while Newtonian flow assumption is acceptable for large-sized arteries with high shear rates [37]. The validation of Newtonian assumption is still not completely clear for medium-sized vessels, especially in the stenotic case. Currently, for representing the viscous properties of blood, there is no universal agreement for the right model [38]. Consequently, modelling of blood non-Newtonian behavior is dramatically conducted and several non-Newtonian models are applied for studying their effects on blood flow characteristics including wall shear stresses, flow field, secondary flow patterns [39]. Table 1 illustrates the main researches using CFD method in blood flow.

Table 1. *The main researches of blood flow using CFD method*

Authors	**Methods**	**Modeling approaches**	**Operating/Boundary conditions**	**Findings**
Doost et al. [8]	CFD	Carreau-Yasuda model, Casson model, K-L, Cross and Generalized power-law (GP)	Quasi-steady condition, the inlet and outlet boundaries was set pressure outlet and wall boundary condition	The local apparent viscosity had a large amount in the apex and the middle of the left ventricle (LV) in different non-Newtonian models, which caused to the low shear rate in these locations
Sharifi and Moghadam [40]	CFD	Carreau-Yasuda model	Incompressible fluid, laminar flow, velocity inlet boundary condition was used for the inlet of the artery and No-slip boundary condition for the vessel walls	The analyzing of blood flow in Buerger's disease is significant because it helps better understanding of the possible prevention of disease and its progression
Manimaran [41]	CFD	Non-newtonian fluid model	Incompressible fluid, steady flow, No-slip boundary conditions on the stenosis wall	The pressure drop across a stenosed artery at low Reynolds numbers was unaffected by surface irregularities
Adib et al. [42]	CFD	Non-newtonian fluid model	Incompressible fluid, steady flow condition	They predicted the behavior of the blood flow velocity pattern under steady flow condition which can help the medical practitioners in their decision on the patients' treatments

2.1. CFD study of blood flow inside the corkscrew artery

Buerger's disease happens mostly in medium and small vessels due to the consume of Tobacco. One of the specifications of the Buerger's disease is the existence of corkscrew collateral [40]. Fujii et al. [43] concluded that there is a relationship between the type of the corkscrew collateral arteries and clinical intensity of the Buerger's disease and they classified the corkscrew collateral arteries according to the artery amplitudes. The CFD simulation of blood flow inside the corkscrew artery of the Buerger's disease was conducted by Sharifi and Moghadam [40]. The blood characteristics which were applied in the CFD simulation were the same as the blood characteristics of a Buerger's disease for a heavy smoker patient. In their study, the flow rate of blood was obtained from the experimental results of Van de Vosse et al. [44]. Figure 1 illustrates that the axial velocity profiles are in excellent agreement with the experimental results of Van de Vosse et al. [44] in Reynolds number of 300 at different cross-sections. Also, solid lines represent the numerical results of Sharifi and Moghadam [40] and spots show the experimental data of Van de Vosse et al. [44].

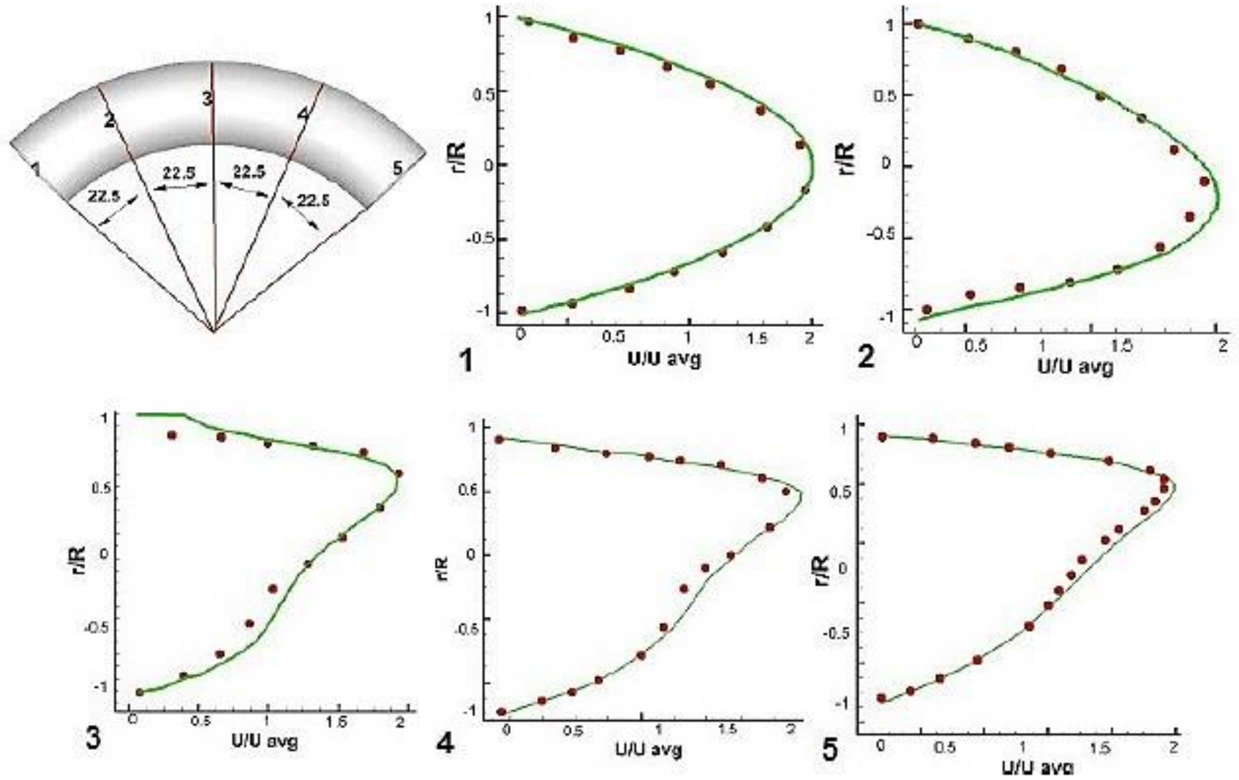

Figure 1. *The velocity validation of Sharifi and Moghadam results [40] and experimental data of Van de Vosse et al. [44]*

Their results indicated that the corkscrew artery geometry affects the blood flow patterns because it is very complex and cause to accumulate the flowing particles in blood like nicotine [40]. Moreover, many studies investigated the blood flow patterns impacts on stenting arteries and concluded that the hemodynamic can vary using different stent geometries [45]. As a result, the analyzing of blood flow in Buerger's disease is significant because it helps better understanding of the possible prevention of disease and its progression.

2.2. CFD Study of blood flow in arterial stenosis

Previously, the flow situation in stenosis models had studied for different constrictions of the cross-sectional area and different Reynolds numbers. To solve numerically, the steady state condition sufficiently describes the behavior of pressure and flow around constrictions of blood vessels within the arterial pipes [46]. Experimental and numerical studies of blood flow within arteries related to the formation of lesions and arterial narrowing have been done by many researchers [47,48]. Most of them, especially numerical modelling was concentrated on the carotid artery bifurcation [49,50]. Both in terms of simulation, this concentration was changed to the right coronary artery [51,52]. Manimaran [41] used CFD simulations in arterial stenoses with 48% areal occlusion and Non-Newtonian assumption was selected for the blood flow. In his study, three cases were considered for different Reynolds numbers. Figure 2 shows the pressure drop for various Reynolds number and viscosity models [41]. The Carreau model predicted the flow compared to the experiment results of Back et al. [46].

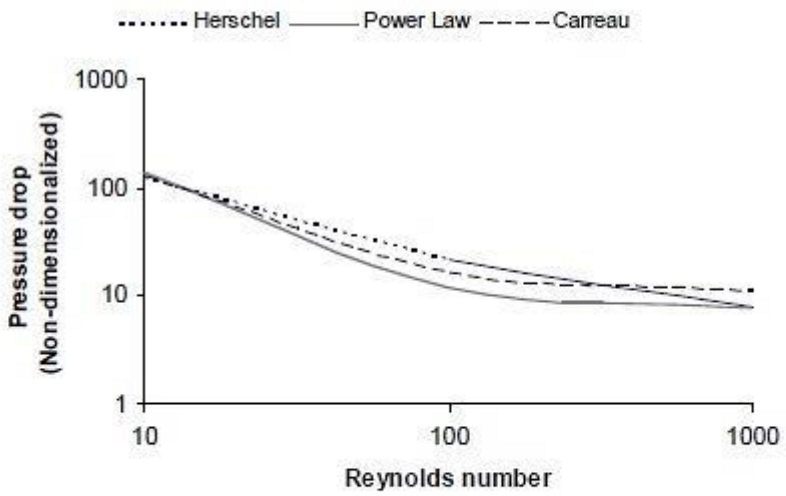

Figure 2. *Non-dimensional pressure based on Reynolds number [41]*

Also, the flow resistance with the presence of surface irregularities was conducted. It was found that the pressure drop across a stenosed artery at low Reynolds numbers was unaffected by surface irregularities [41].

2.3. CFD study of blood flow in human patient-specific left ventricle

Although many researchers in their numerical study of the patient-specific left ventricle (LV) [53-55] ignored the impact of the blood non-Newtonian characteristic but the blood non-Newtonian characteristic might affect the flow properties of the patient-specific (LV) and this fact only conducted in simulations of a few researchers. For example, Schenkel et al. [56] used the Carreau-Yasuda model and Krittian et al. [57] applied the Carreau model for simulating the patient-specific LV. Doost et al. [8] simulated the imaged-based CFD of a patient-specific (LV) and to reconstruct the left ventricle (LV) geometry, the healthy human MRI images were applied. Figure 3 shows the schematic of the left ventricle (LV) and different boundary conditions. Both mitral and aortic valves were simulated as the orifices for capturing the movement of the valve leaflets because of the low spatiotemporal resolution of the MRI images [8].

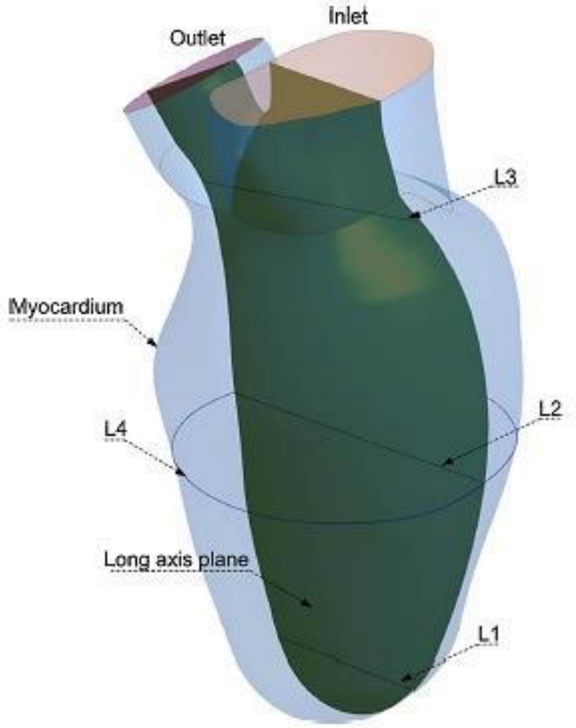

Figure 3. *The schematic of the Left ventricle (LV), inlet, outlet and myocardium as various boundary condition locations [8]*

They found that the local apparent viscosity had a large amount in the apex and the middle of the left ventricle (LV) in different non-Newtonian models, which caused to the low shear rate in these locations [8]. In the study of Adib et al. [42], a three-dimensional simulation was conducted to study the flow velocity pattern of heart regarding the left ventricle under steady flow condition. They investigated the velocity pattern of blood flow behavior under the steady condition that can help medical practitioners in patients' treatments decision [42]. Bavo et al. [58] used a patient-specific CFD model of the mitral valve and left ventricle (LV) to verify the abnormal flow patterns for impaired hearts. They applied moving boundaries for three cardiac pathologies according to the transesophageal ultrasound images. Their CFD Results showed that the intraventricular flow dynamics were consistent with diagnostic patient records. The combination of clinical images and CFD method caused to investigate deeply the intraventricular hemodynamics in pathophysiology [58]. A novel CFD study of the left ventricle (LV) was done in the study of Larsson et al. [59]. In their CFD modeling, a deviation of below 12% was obtained and it was evaluated the simulation pathway sensitivity when input parameters varied including evaluating clinician or image acquisition. Also, the average errors between CFD simulation and clinically acquired in-vivo flow measurements indicated below 11% so it verified the accuracy of the simulation pathway. Generally, applying patient-specific models may work as a precious tool for three-dimensional blood flow motion in future clinical researches because these models offer the detailed investigation of isolated flow phenomena in direct relation to defined pathologies [59].

2.4. CFD study of blood flow in arteries affected by multiple aneurysms

Several authors accomplished the various aneurysm geometries of patients over the last decade [60,61]. Wille [62] numerically studied the blood flow for tracing streamlines in moderately dilated rigid blood vessels. Also, Perktold [63] analyzed the path lines of the flow particles and Kumar and Naidu [64] investigated single aneurysm for different dilations. Arterial diseases are not fully understood due to hemodynamic factors. Bai et al. [65] applied CFD method for numerical simulations of affected blood vessels both in steady and unsteady conditions in arteries affected by multiple saccular aneurysms. In blood vessels, finite volume method (FVM) was used for studying the hemodynamic factors including streamline patterns, pressure, velocity and shear stress of wall. CFD method is significant for detecting and quantifying of multiple aneurysms act as a tool for surgical interference [65]. In order to provide a relatively low-cost alternative for benching top modeling, computer simulation models are useful for growth, rupture and development of an aneurysm and yet they have been criticized due to the lack of experimental validation. Moreover, the combination of CFD method and three-dimensional *x*-ray angiography which obtained by the application of biomorphometric techniques and CFD method are current approaches [66,67]. Lott et al. [68] investigated the flow properties in saccular cerebral aneurysm by using FVM method as a 2D model. They found that in order to prepare objective data on biophysical parameters, computer simulation of aneurysm flow can obtain flow events in vitro aneurysms when carefully developed [68]. Impressive flow simulation of aneurysms depends on the size of the parent vessel and aneurysm, flow input and etc. The important characteristics of flow include neck and proximal dome configuration and independent of size [68].

3. DIFFERENT RHEOLOGICAL MODELS OF BLOOD FLOW

In describing the blood rheology, there are several non-Newtonian rheological models including Carreau-Yasuda [23,24], Casson [25], power law [26], Cross [27], Herschel-Bulkley [28], Oldroyd-B [29], Quemada [30], Yeleswarapu [31], Bingham [32], Eyring-Powell [33], and Ree-Eyring [34]. Also, other fluid models which are less known [69] have applied for describing the blood rheology. The non-Newtonian relation of power-law model is as follows [70,71]:

$$\tau = m\dot{\gamma}^{n} \quad (1)$$

The constants of power-law model are n and m which represent the fluid consistency and the degree of non-Newtonian behavior, respectively.

Also, the power-law fluid viscosity is as follows [72]:

$$\eta = m\dot{\gamma}^{n-1} \quad (2)$$

The non-Newtonian apparent viscosity is η. By increasing the shear rate and significantly decreasing apparent viscosity, a shear thinning fluid is generated for $n < 1$. Also, by increasing the shear rate and progressively increasing apparent viscosity, a shear-thickening fluid is generated for $n > 1$ [73]. Finally, we have a Newtonian fluid for $n = 1$. In Figure 4, the flow curves of these power-law models have shown. The power-law model cannot describe many non-Newtonian fluids viscosity in locations where the shear rate is very low and very high and this is an obvious disadvantage of power-law model.

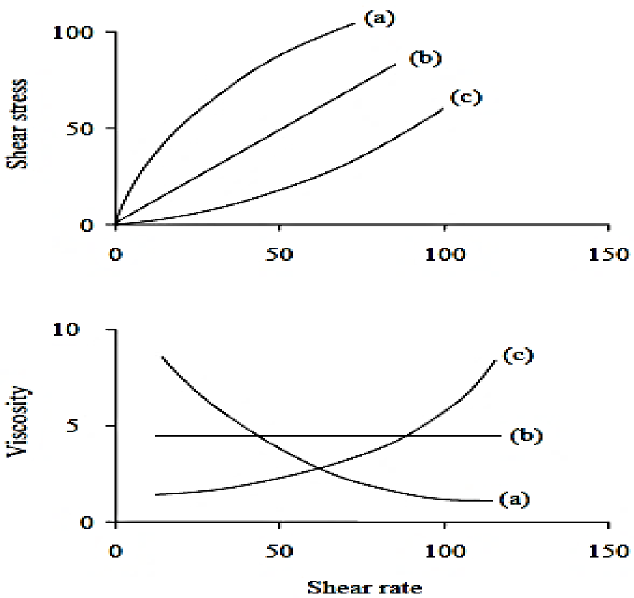

Figure 4. *Flow curves of power-law fluids: (a) shear-thinning fluid, (b) Newtonian fluid, (c) shear-thickening fluid [70,71]*

In non-Newtonian modeling, Carreau-Yasuda and Casson are the most popular models of blood flow which are reported in many researches. Besides, blood is modeled as a Newtonian fluid [25,35] and this approximation is good for large vessels with high shear rates in many circumstances under non-pathological conditions [74]. Analytical [75], stochastic [76,77], and numerical mesh methods; such as finite element [78], finite difference [79], finite volume [80], and spectral collocation methods [81] are diverse methods. In simulating and modeling non-Newtonian effects in blood rheology, these methods were used. The lattice Boltzmann method for simulation of the non-Newtonian shear-dependent viscosity models was used in the study of Boyd et al. [82]. For comparison of the two-dimensional non-Newtonian and Newtonian flows in both oscillatory and steady flows, the non-Newtonian blood viscosity models including Carreau-Yasuda and Casson were applied in curved and straight pipe geometries [82]. It was concluded that both the Carreau-Yasuda and Casson flows indicate remarkable differences in the steady flow situation compared to analogous Newtonian flows and these differences are significant for the investigation of atherosclerotic progression [82]. Sankar et al. [83] considered the impacts of blood non-Newtonian behavior, stenosis, and pulsatility. They investigated the pulsatile blood flow in stenosed artery and assumed the blood as a Herschel-Bulkley fluid. For analyzing the flow, a perturbation method was applied and the plug core region was assumed to change with axial distance. Figure 5 illustrates that the plug core radius reduces for the values of n, A, and δ_s as the radius R decreases [83].

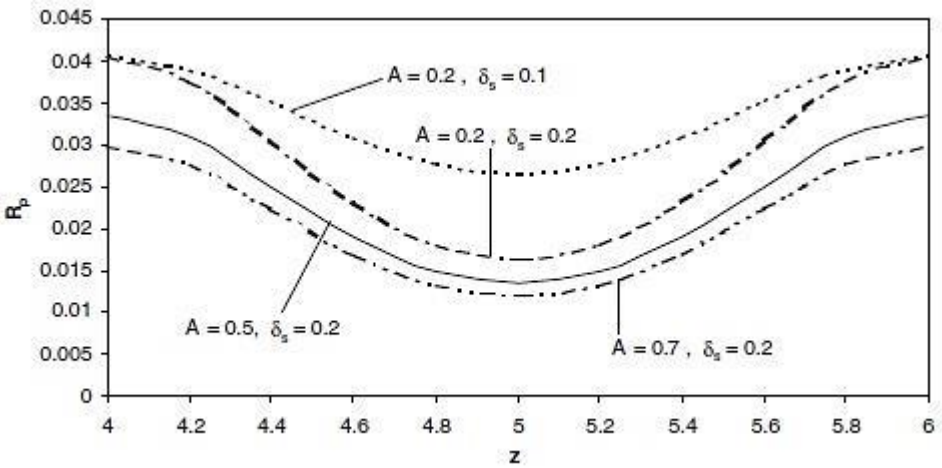

Figure 5. *Variation of plug core radius [83]*

Furthermore, they concluded that the pressure gradient increased with the increment of yield stress in steady flow and for a given flow rate, the Herschel-Bulkley fluid had more pressure gradient compared to the power law fluid [83]. Also, Sankar et al. [84] modeled blood as a two-fluid model including Newtonian and Herschel-Bulkley fluid. They studied the steady flow of blood through a catheterized artery. The catheter was inserted coaxially due to assuming the artery as a rigid wall and wall shear stress, flow rate, velocity, and frictional resistance parameters were analyzed [84]. Figure 6 to 9 indicate these parameters based on catheter radius ratio yield stress and peripheral layer thickness. As can be seen, by increasing the thickness of the peripheral layer, the frictional resistance and the wall shear stress decreased and flow rate and velocity increased. Moreover, when the catheter radius ratio or yield stress increased, the wall shear stress increased while the flow rate and velocity decreased [84].

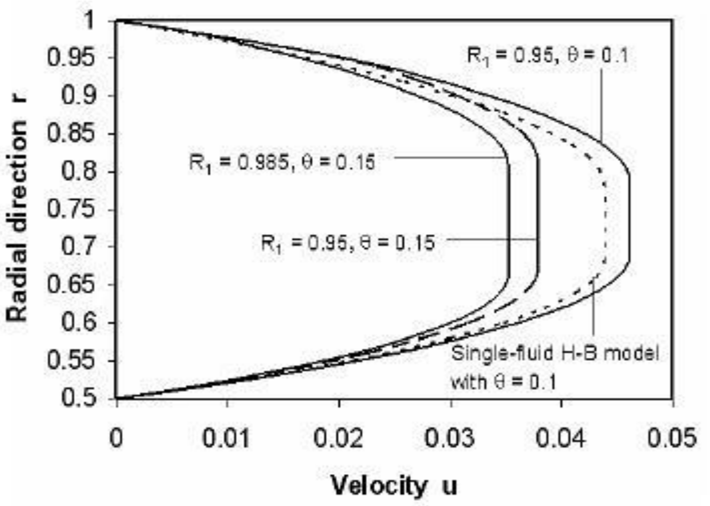

Figure 6. *Velocity distribution [84]*

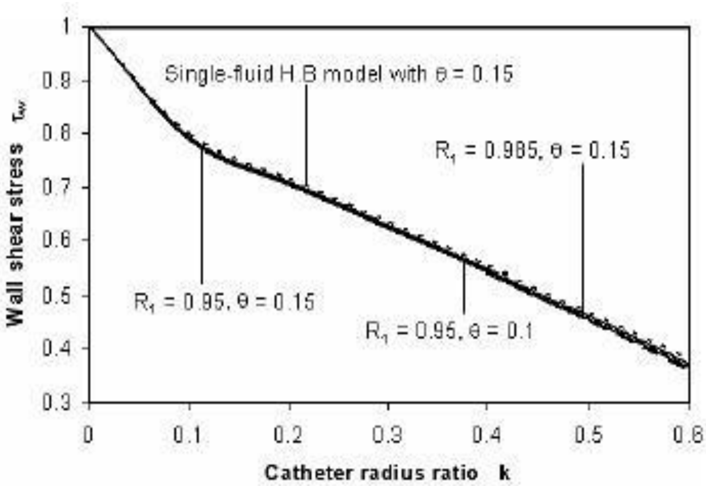

Figure 7. *Variation of wall shear stress [84]*

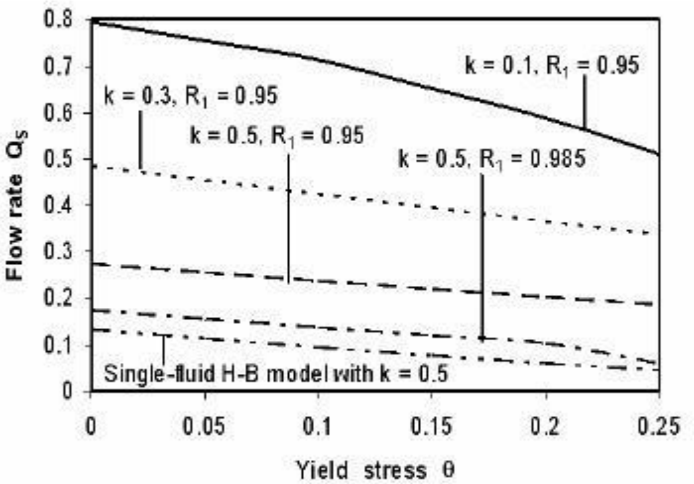

Figure 8. *Variation of flow rate [84]*

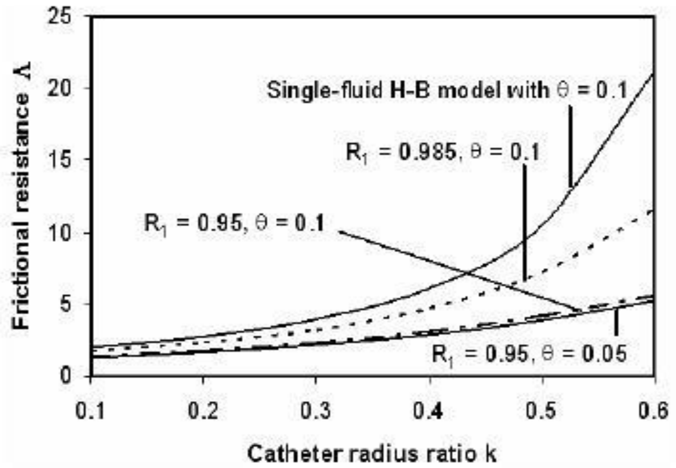

Figure 9. *Variation of frictional resistance [84]*

They found that by increasing the yield stress, the width of the plug flow region increased. As a result, in order to investigate the blood flow through catheterized arteries, the study of Sankar et al. could be effective [84].

4. CONCLUSION

The application of CFD method in different physiological conditions of blood flow and also several rheological models of blood flow are discussed in this study. The assumption of non-Newtonian behavior of blood flow in CFD method has accepted for small vessels while Newtonian flow assumption is acceptable for large-sized arteries with high shear rates. Currently, for representing the viscous properties of blood there is no universal agreement for the right model. Consequently, modeling of blood non-Newtonian behavior is dramatically conducted and several non-Newtonian models are applied for studying their effects on blood flow characteristics. The analyzing of blood flow in Buerger's disease is significant because it helps better understanding of the possible prevention of disease and its progression. Although many researchers in their numerical study of the patient-specific left ventricle (LV) ignored the impact of the blood non-Newtonian characteristic but the blood non-Newtonian characteristic might affect the flow properties of the patient-specific (LV) and this fact only conducted in simulations of a few researchers. Also, a three-dimensional simulation for studying the flow velocity pattern of heart regarding the left ventricle under steady condition can help the medical practitioners in patients' treatments decision. Knowledge of pressure, flow partition and shear stress caused to have a better understanding of the relationship between the fluid dynamics within pulsatile blood flow and arterial diseases. Also, in order to describe the blood rheology, there are several non-Newtonian rheological models. Besides, blood is modeled as a Newtonian fluid and this approximation is good for large vessels with high shear rates in many circumstances. The power-law model cannot describe many non-Newtonian fluids viscosity in locations where the shear rate is very low and very high and this is an obvious disadvantage of power-law model. In non-Newtonian modeling, Carreau-Yasuda and Casson are the most popular models of blood flow which are reported in many researches. As a result, both the Carreau-Yasuda and Casson flows indicate remarkable differences in the steady flow situation compared to analogous Newtonian flows and these differences are significant for the investigation of atherosclerotic progression.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

REFERENCES

[1] Da silva, J. L., Rao, M. A., "Rheological behavior of food gels", Rheology of Fluid and Semisolid Foods. Springer US, pp. 339-401, (2007).

[2] Kordani, N., & Vanini, A. S., “Optimizing the ethanol content of shear thickening fluid/fabric composites under impact loading”, Journal of Mechanical Science and Technology, 28(2): 663-667, (2014).

[3] Brown, S., “Computational Fluid Dynamic Modeling of Aortic Blood Flow”, (Doctoral dissertation), (2014).

[4] Rabby, M. G., Shupti, S. P., & Molla, M. M., “Pulsatile non-newtonian laminar blood flows through arterial double stenoses”, Journal of Fluids, 22(1): 122-134, (2014).

[5] Yilmaz, F., & Gundogdu, M. Y., “A critical review on blood flow in large arteries; relevance to blood rheology, viscosity models, and physiologic conditions”, Korea-Australia Rheology Journal, 20(4): 197-211, (2008).

[6] Nezamidoost, S., Sadeghy, K., & Askari, V., “Pulsatile flow of thixotropic fluids through a partially-constricted tube”, Nihon Reoroji Gakkaishi, 41(2): 45-52, (2013).

[7] Baskurt, O. K., & Meiselman, H. J., “Blood rheology and hemodynamics”, In Seminars in thrombosis and hemostasis, Thieme Medical Publishers, Inc., 212(1): 584-4662, (2003).

[8] Doost, S. N., Zhong, L., Su, B., & Morsi, Y. S., “The numerical analysis of non-Newtonian blood flow in human patient-specific left ventricle”, Computer methods and programs in biomedicine, 127(3): 232-247, (2016).

[9] Vlachopoulos, C., O'Rourke, M., & Nichols, W. W., “McDonald's blood flow in arteries: theoretical, experimental and clinical principles”, CRC press, (2011).

[10] Lantz, J., Gardhagen, R., & Karlsson, M., “Quantifying turbulent wall shear stress in a subject specific human aorta using large eddy simulation”, Medical Engineering and Physics, 34(8): 1139-1148, (2012).

[11] Chen, J., & Lu, X. Y., “Numerical investigation of the non-Newtonian pulsatile blood flow in a bifurcation model with a non-planar branch”, Journal of biomechanics, 39(5): 818-832, (2006).

[12] Siddiqui, S. U., Verma, N. K., Mishra, S., & Gupta, R. S., “Mathematical modelling of pulsatile flow of Casson’s fluid in arterial stenosis”, Applied Mathematics and Computation, 210(1): 1-10, (2009).

[13] Sultanov, R. A., & Guster, D., “Full dimensional computer simulations to study pulsatile blood flow in vessels, aortic arch and bifurcated veins: Investigation of blood viscosity and turbulent effects”, In Engineering in Medicine and Biology Society, Annual International Conference of the IEEE, pp. 4704-4710, (2009).

[14] Ternik, P., & Marn, J., “Numerical study of blood flow in stenotic artery”, Applied Rheology, 19(1): 130-145, (2009).

[15] Pedrizzetti, G., and Perktold K., “Cardiovascular fluid mechanics”, New York: Springer, (2003).

[16] Su, C. M., Lee, D., Tran-Son-Tay, R., & Shyy, W., “Fluid flow structure in arterial bypass anastomosis”, Journal of Biomechanical Engineering, 127(4): 611-618, (2005).

[17] Maurits, N. M., Loots, G. E., & Veldman, A. E. P., “The influence of vessel walls elasticity and peripheral resistance on the carotid artery flow wave form: a CFD model compared to in vivo ultrasound measurements”, Journal of Biomechanics, 40(2): 427-436, (2007).

[18] De Santis, G., Mortier, P., De Beule, M., Segers, P., Verdonck, P., & Verhegghe, B., "Patient-specific computational fluid dynamics: structured mesh generation from coronary angiography", Medical & Biological Engineering & Computing, 48(4): 371-380, (2010).

[19] Leuprecht, A., Kozerke, S., Boesiger, P., & Perktold, K., "Blood flow in the human ascending aorta: a combined MRI and CFD study", Journal of Engineering Mathematics, 47(3): 387-404, (2003).

[20] Kaazempur-Mofrad, M. R., Isasi, A. G., Younis, H. F., Chan, R. C., Hinton, D. P., Sukhova, G., ... & Kamm, R. D., "Characterization of the atherosclerotic carotid bifurcation using MRI, finite element modeling, and histology", Annals of Biomedical Engineering, 32(7): 932-946, (2004).

[21] Schumann, C., M. Neugebauer, R. Bade, B. Preim, and Peitgen, H., "Implicit vessel surface reconstruction for visualization and CFD simulation", International Journal of Computer Assisted Radiology and Surgery, 2(5): 275-286, (2008).

[22] Sousa, L. C., C. F. Castro, and Antonio, C., "Blood flow simulation and applications", Technologies for medical sciences. Springer Netherlands, pp. 67-86, (2012).

[23] Chen, J., X. Y. Lu, and Wang W., "Non-Newtonian effects of blood flow on hemodynamics in distal vascular graft anastomoses", Journal of Biomechanics, 39(11): 1983-1995, (2006).

[24] Molla, M. M., and Paul M. C., "LES of non-Newtonian physiological blood flow in a model of arterial stenosis", Medical Engineering & Physics, 34(8): 1079-1087, (2012).

[25] Fan, Y., W. Jiang, Y. Zou, J. Li, J. Chen, and Deng X., "Numerical simulation of pulsatile non-Newtonian flow in the carotid artery bifurcation", Acta Mechanica Sinica, 25(2): 249-255, (2009).

[26] Johnston, B. M., P. R. Johnston, S. Corney, and Kilpatrick D., "Non-Newtonian blood flow in human right coronary arteries: transient simulations", Journal of Biomechanics, 39(6): 1116-1128, (2006).

[27] Kim, Y. H., P. J. VandeVord, and Lee, J. S., "Multiphase non-Newtonian effects on pulsatile hemodynamics in a coronary artery", International Journal for Numerical Methods in fluids, 58(7): 803-825, (2008).

[28] Vajravelu, K., S. Sreenadh, P. Devaki, and Prasad, K., "Mathematical model for a Herschel-Bulkley fluid flow in an elastic tube", Open Physics, 9(5): 1357-1365, (2011).

[29] Pontrelli, G., "Blood flow through a circular pipe with an impulsive pressure gradient", Mathematical Models and Methods in Applied Sciences, 10(2): 187-202, (2000).

[30] Das, B., G. Enden, and Popel A. S., "Stratified multiphase model for blood flow in a venular bifurcation", Annals of Biomedical Engineering, 25(1): 135-153, (1997).

[31] Hundertmark-Zaušková, A., and Lukáčová-Medvid'ová M., "Numerical study of shear-dependent non-Newtonian fluids in compliant vessels", Computers & Mathematics with Applications, 60(3): 572-590, (2010).

[32] Lou, Z., and Yang W. J., "A computer simulation of the non-Newtonian blood flow at the aortic bifurcation", Journal of Biomechanics, 26(1): 37-49, (1993).

[33] Zueco, J., and Anwar Bég O., "Network numerical simulation applied to pulsatile non-Newtonian flow through a channel with couple stress and wall mass flux effects", International Journal of Applied Mathematics and Mechanics, 5(2): 1-16, (2009).

[34] Marcinkowska-Gapińska, A., J. Gapinski, W. Elikowski, F. Jaroszyk, and Kubisz L., "Comparison of three rheological models of shear flow behavior studied on blood samples from post-infarction patients", Medical & Biological Engineering & Computing, 45(9): 837-844, (2007).

[35] Bodnár, T., A. Sequeira, and Prosi. M., "On the shear-thinning and viscoelastic effects of blood flow under various flow rates", Applied Mathematics and Computation, 217(11): 5055-5067, (2011).

[36] Augier, F., O. Masbernat, and Guiraud, P., "Slip velocity and drag law in a liquid-liquid homogeneous dispersed flow", AIChE journal, 49(9): 2300-2316, (2003).

[37] Bessonov, N., A. Sequeira, S. Simakov, Y. Vassilevskii, and Volpert, V., "Methods of blood flow modelling", Mathematical Modelling of Natural Phenomena, 11(1): 1-25, (2016).

[38] Shibeshi, S. S., and Collins W. E., "The rheology of blood flow in a branched arterial system", Applied Rheology, 15(6): 398-408, (2005).

[39] Guerciotti, B., Vergara, C., "Computational comparison between Newtonian and non-Newtonian blood rheologies in stenotic vessels", MOX-Report No. 19/2016, MOX, di Matematica Politecnico di Milano-Italy, (2016).

[40] Sharifi, A., and Moghadam M. C., "CFD simulation of blood flow inside the corkscrew collaterals of the Buerger's disease", BioImpacts, 6(1): 41-53, (2016).

[41] Manimaran, R., "CFD simulation of non-Newtonian fluid flow in arterial stenoses with surface irregularities", World Academy of Science, Engineering and Technology, 73(5): 804-809, (2011).

[42] Adib, M. A. H. M., & Hasni, N. H. M., "Modeling of Blood Flow Velocity into the Main Artery via Left Ventricle of Heart during Steady Condition", World Academy of Science, Engineering and Technology, International Journal of Medical, Health, Biomedical, Bioengineering and Pharmaceutical Engineering, 6(4): 97-101, (2012).

[43] Fujii, Y., J. Soga, S. Nakamura, T. Hidaka, T. Hata, N. Idei, Fujimura, N., "Classification of Corkscrew Collaterals in Thromboangiitis Obliterans (Buerger's Disease)", Circulation Journal, 74(8): 1684-1688, (2010).

[44] Van de Vosse, F. N., A. A. Van Steenhoven, A. Segal, and Janssen J. D., "A finite element analysis of the steady laminar entrance flow in a 90 curved tube", International Journal for Numerical Methods in Fluids, 9(3): 275-287, (1989).

[45] Kenji, T., K. Schjodt, A. Puntel, N. Kostov, and Tezduyar T. E., "Patient-specific computer modeling of blood flow in cerebral arteries with aneurysm and stent", Computational Mechanics, 50(6): 675-686, (2012).

[46] Back, L. H., Y. I. Cho, D. W. Crawford, and Cuffel R. F., "Effect of mild atherosclerosis on flow resistance in a coronary artery casting of man", Journal of biomechanical engineering, 106(1): 48-53, (1984).

[47] Ballyk, P. D., D. A. Steinman, and Ethier C. R., "Simulation of non-Newtonian blood flow in an end-to-side anastomosis", Biorheology, 31(5): 565-586, (1994).

[48] Berger, S. A., and Jou L., “Flows in stenotic vessels”, Annual Review of Fluid Mechanics, 32(1): 347-382, (2000).

[49] Berthier, B., R. Bouzerar, and Legallais C., “Blood flow patterns in an anatomically realistic coronary vessel: influence of three different reconstruction methods”, Journal of Biomechanics, 35(10): 1347-1356, (2002).

[50] Corney, S., P. R. Johnston, and Kilpatrick D., “Construction of realistic branched, three-dimensional arteries suitable for computational modelling of flow”, Medical and Biological Engineering and Computing, 42(5): 660-668, (2004).

[51] Feldman, C. L., O. J. Ilegbusi, Z. Hu, R. Nesto, S. Waxman, and Stone, P. H., “Determination of in vivo velocity and endothelial shear stress patterns with phasic flow in human coronary arteries: a methodology to predict progression of coronary atherosclerosis”, American Heart Journal, 143(6): 931-939, (2002).

[52] Giddens, D. P., Zarins, C. K., & Glagov, S., “Response of arteries to near-wall fluid dynamic behavior”, Applied Mechanics Reviews, 43(5): 98-102, (1990).

[53] Chnafa, C., S. Mendez, and Nicoud, F., “Image-based large-eddy simulation in a realistic left heart”, Computers & Fluids, 94(4):173-187, (2014).

[54] Khalafvand, S. S., Zhong, L., & Ng, E. Y. K., “Three-dimensional CFD/MRI modeling reveals that ventricular surgical restoration improves ventricular function by modifying intraventricular blood flow”, International Journal for Numerical Methods in Biomedical Engineering, 30(10): 1044-1056, (2014).

[55] Nguyen, V. T., Wibowo, S. N., Leow, Y. A., Nguyen, H. H., Liang, Z., & Leo, H. L., “A patient-specific computational fluid dynamic model for hemodynamic analysis of left ventricle diastolic dysfunctions”, Cardiovascular Engineering and Technology, 6(4): 412-429, (2015).

[56] Schenkel, T., Malve, M., Reik, M., Markl, M., Jung, B., & Oertel, H., “MRI-based CFD analysis of flow in a human left ventricle: methodology and application to a healthy heart”, Annals of biomedical engineering, 37(3): 503-515, (2009).

[57] Krittian, S., Janoske, U., Oertel, H., & Böhlke, T., “Partitioned fluid–solid coupling for cardiovascular blood flow”, Annals of Biomedical Engineering, 38(4): 1426-1441, (2010).

[58] Bavo, A. M., Pouch, A. M., Degroote, J., Vierendeels, J., Gorman, J. H., Gorman, R. C., & Segers, P., “Patient-specific CFD models for intraventricular flow analysis from 3D ultrasound imaging: Comparison of three clinical cases”, Journal of Biomechanics, 50(1): 144-150, (2017).

[59] Larsson, D., Spühler, J. H., Petersson, S., Nordenfur, T., Colarieti-Tosti, M., Hoffman, J., ... & Larsson, M., “Patient-specific left ventricular flow simulations from transthoracic echocardiography: robustness evaluation and validation against Ultrasound Doppler and Magnetic Resonance Imaging”, IEEE Transactions on Medical Imaging, 36(11): 2261-2275, (2017).

[60] Hassan, T., Timofeev, E. V., Saito, T., Shimizu, H., Ezura, M., Tominaga, T., ... & Takayama, K., “Computational replicas: anatomic reconstructions of cerebral vessels as volume numerical grids at three-dimensional angiography”, American Journal of Neuroradiology, 25(8): 1356-1365, (2004).

[61] Hassan, T., Timofeev, E. V., Saito, T., Shimizu, H., Ezura, M., Matsumoto, Y., ... & Takahashi, A., “A proposed parent vessel geometry—based categorization of saccular intracranial aneurysms: computational flow dynamics analysis of the risk factors for lesion rupture”, Journal of neurosurgery, 103(4): 662-680, (2005).

[62] Wille, S. O., “Finite element simulations of the pulsatile blood flow patterns in arterial abnormalities”, Finite Elements in Biomechanics. John Wiley & Sons, (1982).

[63] Perktold, K., “On the paths of fluid particles in an axisymmetrical aneurysm”, Journal of Biomechanics, 20(3): 311-317, (1987).

[64] Kumar, B. R., & Naidu, K. B., “Hemodynamics in aneurysm”, Computers and Biomedical Research, 29(2): 119-139, (1996).

[65] Bai, H. G., Naidu, K. B., & Kumar, G. V., “Computer simulation of blood flow in arteries affected by multiple aneurysm”, Indian Journal of Computer Science and Engineering, 3(6): 807-811, (2013).

[66] Byun, H. S., & Rhee, K., “CFD modeling of blood flow following coil embolization of aneurysms”, Medical Engineering and Physics, 26(9): 755-761, (2004).

[67] Castro, M. A., Putman, C. M., & Cebral, J. R., “Patient-specific computational modeling of cerebral aneurysms with multiple avenues of flow from 3D rotational angiography images”, Academic Radiology, 13(7): 811-821, (2006).

[68] Lott, D. A., Siegel, M., Chaudhry, H. R., & Prestigiacomo, C. J., “Computational fluid dynamic simulation to assess flow characteristics of an in vitro aneurysm model”, Journal of Neurointerventional Surgery, 1(2): 100-107, (2009).

[69] Ishikawa, T., Guimaraes, L. F., Oshima, S., & Yamane, R., “Effect of non-Newtonian property of blood on flow through a stenosed tube”, Fluid Dynamics Research, 22(5): 251-264, (1998).

[70] Middleman, S., “flow of high polymers; continuum and molecular rheology”, Interscience, pp. 747-748, (1968).

[71] Munson, B. R., Okiishi, T. H., Rothmayer, A. P., & Huebsch, W. W., “Fundamentals of Fluid mechanics”, John Wiley & Sons, (2014).

[72] Bird, R. B., Armstrong, R. C., & Hassager, O., “Dynamics of polymeric liquids”, Fluid Mechanics, A Wiley-Interscience Publication. John Wiley & Sons, (1987).

[73] Baharvandi, H. R., Saeedi Heydari, M., Kordani, N., Alebooyeh, M., Alizadeh, M., & Khaksari, P., “Characterization of the rheological and mechanical properties of shear thickening fluid-coated Twaron® composite”, The Journal of the Textile Institute, 108(3): 397-407, (2017).

[74] Boyd, J., Buick, J. M., & Green, S., “Comparison of Newtonian and non-Newtonian oscillatory flows using the lattice Boltzmann method”, In World Congress on Medical Physics and Biomedical Engineering. Springer, Berlin, Heidelberg, pp. 3395-3399, (2007).

[75] Misra, J. C., & Maiti, S., “Peristaltic pumping of blood through small vessels of varying cross-section”, Journal of Applied Mechanics, 79(6): 55-69, (2012).

[76] Huang, C., Chai, Z., & Shi, B., “Non-Newtonian effect on hemodynamic characteristics of blood flow in stented cerebral aneurysm”, Communications in Computational Physics, 13(3): 916-928, (2013).

[77] Fu, S. C., So, R. M. C., & Leung, W. W. F., “A lattice Boltzmann and immersed boundary scheme for model blood flow in constricted pipes: Part 2-Pulsatile flow”, Communications in Computational Physics, 14(1): 153-173, (2013).

[78] Čanić, S., Hartley, C. J., Rosenstrauch, D., Tambača, J., Guidoboni, G., & Mikelić, A., “Blood flow in compliant arteries: an effective viscoelastic reduced model, numerics, and experimental validation”, Annals of Biomedical Engineering, 34(4): 575-592, (2006).

[79] Pontrelli, G., “Pulsatile blood flow in a pipe”, Computers & Fluids, 27(3): 367-380, (1998).

[80] Jonášová, A., & Vimmr, J., “Numerical simulation of non-Newtonian blood flow in bypass models”, PAMM, 8(1): 10179-10180, (2008).

[81] Pontrelli, G., “Blood flow through a circular pipe with an impulsive pressure gradient”, Mathematical Models and Methods in Applied Sciences, 10(2): 187-202, (2000).

[82] Boyd, J., Buick, J. M., & Green, S., “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(9): 160-179, (2007).

[83] Sankar, D. S., & Hemalatha, K., “Pulsatile flow of Herschel–Bulkley fluid through stenosed arteries—a mathematical model”, International Journal of Non-Linear Mechanics, 41(8): 979-990, (2006).

[84] Sankar, D. S., & Lee, U., “Two-fluid Herschel-Bulkley model for blood flow in catheterized arteries”, Journal of Mechanical Science and Technology, 22(5): 1008-1022, (2008).