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Blood Flow Peculiarities in Vessels Bifurcation.

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ABSTRACT

In this article we study the blood flow in models of branching blood vessels. Blood is a heterogeneous fluid and owing to the complex composition (erythrocytes, platelets, leukocytes, plasma) and the presence of special rheological properties (viscosity, pseudoplasticity, thixotropy), it can be attributed to non-Newtonian fluids. Red blood cells, called erythrocytes, responsible for transporting oxygen to tissues; white blood cells (platelets) for the regulation of the coagulation system activity. All blood components tend to deform and orientate in the stream and gather in clusters, which introduces significant changes in the behavior of blood flow. In the simplest terms, blood can be considered as a suspension of blood cells in physiological solution. The red cells are able to accumulate in the molecular chain and modify its configuration (shape and orientation in the flow). In our study, the blood flow simulation is implemented using rheological viscoelastic FENE-P model. It predicts the properties corresponding to real biological fluid such as the anomaly of viscosity, variable longitudinal viscosity and the finite time of relaxation of stresses. Governing parameters of the flows of such fluids is the Weissenberg number We, which characterizes the ratio of viscous to elastic properties, the Reynolds number Re describing the ratio of inertial to viscous properties, the ability of erythrocytes to change their orientation in the flow, the degree of disentanglement of the chains L2 and the coefficient of retardation characterizing the concentration of red blood cells. This article discusses the loss of symmetry of the fluid flow under given values of model parameters.

Keywords: Blood flow, the T-junction channel, the symmetry loss effect of blood flow, FENE-P rheological model, finite volume method

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INTRODUCTION

Human blood circulatory system is quite complex, and its operation is affected by many factors [1]. Malfunction of the circulatory system leads to significant negative and sometimes fatal consequences. Particularly vulnerable are the areas of anatomic and/or pathological narrowing or widening and vascular bifurcation, where the occurrence of, for example, stenosis/aneurysm leads to the impaired blood circulation [2]. The numerical simulation made it possible to get an idea about the flow of blood and other biological materials in vessels of different diameters by using a variety of fluids. The study of blood circulation both in the body in general and in its certain area is impossible without analyzing changes in blood rheological properties. For each individual case, the properties depend on many factors. For example, the blood has a viscosity anomalies (Fig. 1) [3].

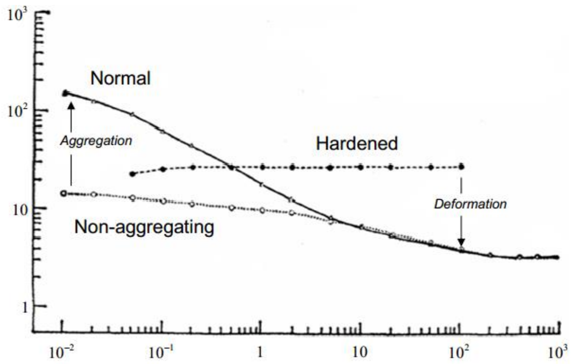

Fig. 1 –Viscosity and shear rate dependence

At rest, the dynamic viscosity values are $\approx 4 \div 6\ Па \cdot с$, the viscosity increases during physical exercises, but decreases several times in diseases such as diabetes or tuberculosis [4,5]. Depending on the shear rate the ability to form clusters of erythrocytes changes (Fig. 2).

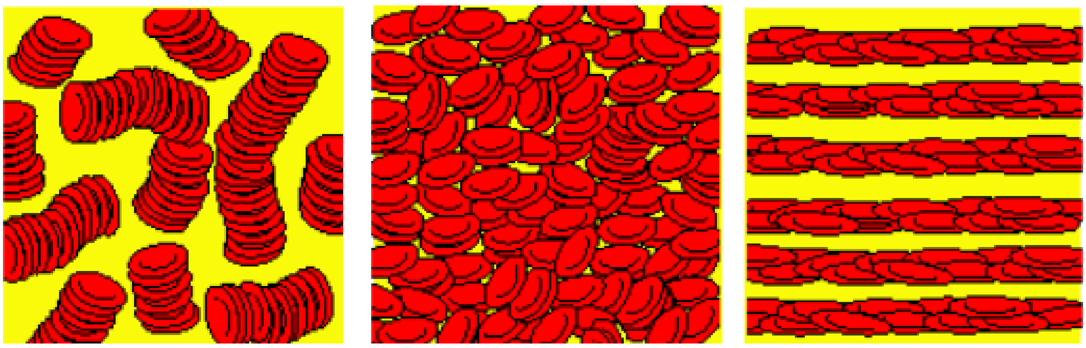

Fig. 2 – Red blood cells aggregation depending on shear rate (from left to right - low, medium, high)

The concentration of red blood cells affects the blood viscosity. During reduction in the blood flow rate, the red blood cells form their agglomerations, which leads to an increase in viscosity. However, a decrease in vessel diameter (arterioles and capillaries, which walls have no muscle fibers and cannot contract) leads to reduction in viscosity. This is a so-called Fahraeus Lindqvist effect. It has known as the red blood cells are oriented along the axis of the receptacle and slide in the plasma [6]. The component of the blood – plasma – is Newtonian (purely viscous) fluid. Despite the fact that the flows of blood and biological materials, usually laminar, the various adverse effects of the blood flow may experience in the vessels bifurcation at converging and diverging flows.

The aim of this work is to study blood flow structure in the branching element of the circulatory system. If *We* = 0.01, the chosen fluid model allows obtaining the results for the flow of the blood plasma with insufficient concentration of red blood cells.

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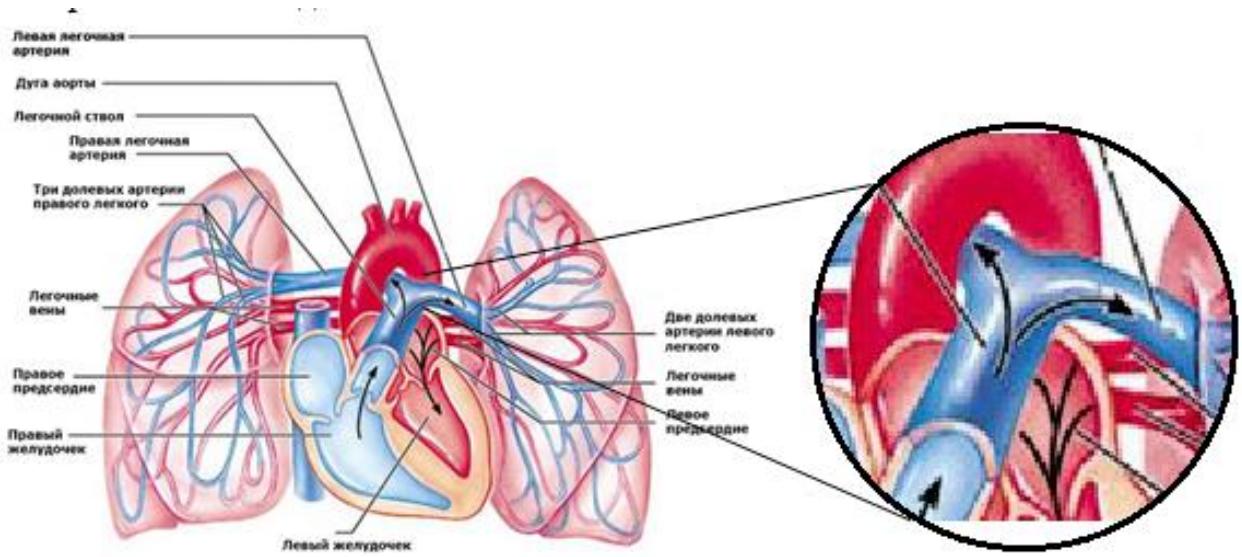
Problem statement

Human blood circulatory system contains multiple branching vessels: both large arteries and veins and small capillaries (Figure 3).



Left pulmonary artery		
Aortic arch		
Pulmonary trunk		
Right pulmonary artery		
Three right pulmonary lobar arteries		
Pulmonary veins		Two left pulmonary lobar arteries
Right atrium		Pulmonary veins
Left ventricle		Left atrium
	Left ventricle	

Fig. 3 – Schematic representation of the pulmonary circulation (pulmonary artery)

T-shaped channel was used for the simulation of blood flow in a blood vessel (Figure 4.) with the following assumptions – a two-dimensional (plane) flow in the solid-wall channel is considered. Despite the fact that the walls of blood vessels are elastic, this elasticity is not so clear in the bifurcated area.

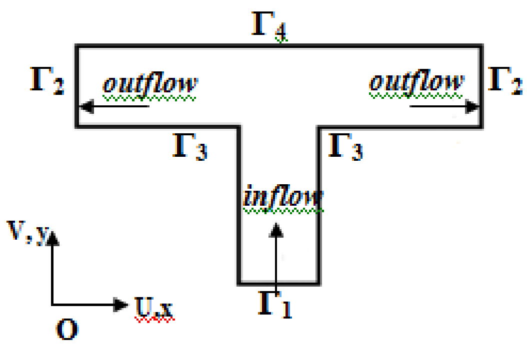


Fig. 4 – Schematic representation of the channel

Isothermal flow of non-Newtonian viscoelastic fluids is described by the equations of motion and continuity [8, 9, 14]:

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\vec{v}\cdot\vec{\nabla}\vec{v}\right)=-\vec{\nabla}p+\vec{\nabla}\cdot\tilde{\tau}, \quad (1)$$

$$\vec{\nabla}\cdot\vec{v}=0. \quad (2)$$

A stress deviator for the Newtonian fluid will be as follows:

$$\tilde{\tau}^S=2\eta^S\tilde{D}. \quad (3)$$

Newtonian fluid is characterized by a constant shear and extensional viscosity, as well as the lack of elastic properties.

The general stress for the FENE-P model, in accordance with the splitting stress principle, may be written as a sum

$$\tilde{\tau}=\tilde{\tau}^p+\tilde{\tau}^s \quad (4)$$

For non-Newtonian stress component equation can be written as follows:

$$\tilde{\tau}^p=\frac{\eta^p}{\lambda}\left[\frac{\tilde{A}}{1-\frac{tr(\tilde{A})}{3L^2}}-\frac{\tilde{I}}{1-\frac{1}{L^2}}\right], \quad (5)$$

$$\frac{\tilde{A}}{1-(tr\tilde{A})/(3L^2)}+We\overset{\nabla}{\tilde{A}}=\frac{\tilde{I}}{1-1/L^2}, \quad (6)$$

$$\overset{\nabla}{\tilde{A}}=\frac{\partial\tilde{A}}{\partial t}+\vec{v}\cdot\vec{\nabla}\tilde{A}-\vec{\nabla}\vec{v}\cdot\tilde{A}-\tilde{A}\cdot(\vec{\nabla}\vec{v})^T, \quad (7)$$

where $\vec{v}$ - the velocity vector; ρ - the fluid density; λ - the characteristic time of stress relaxation; $\eta^0=\eta^S+\eta^p$ - blood viscosity at zero shear rate; η^p - the dynamic viscosity of non-Newtonian fluid component at zero shear rate; η^s - the dynamic viscosity of the plasma; $\tilde{\tau}^p$ - non-Newtonian stress component; $\tilde{\tau}^S$ - Newtonian stress component; $\tilde{A}=\frac{3\langle\vec{Q}\vec{Q}\rangle}{Q_{eq}^2}$ - configuration tensor, where $\vec{Q}\vec{Q}$ - a dyadic product of configuration vectors; $\langle\vec{Q}\vec{Q}\rangle=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\vec{Q}\vec{Q}\cdot P_N(\vec{Q})\cdot d\vec{Q}d\vec{Q}d\vec{Q}$ - averaging over the ensemble, where $P_N(\vec{Q})$ - the probability that a randomly chosen chain of red blood cells has a predetermined size within the range of $\vec{Q}$ up to $\vec{Q}+d\vec{Q}$; $\tilde{D}=\frac{1}{2}\left(\vec{\nabla}\vec{v}+(\vec{\nabla}\vec{v})^T\right)$ - the deformation rate tensor, where $(\cdot)^T$ - the transpose procedure.

Using the standard procedure of reduction to characteristic scales the equations of motion are written in dimensionless form and contain the following dimensionless quantities (Table 1):

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Table 1. Dimensionless parameters

Newtonian fluid	$Re = \frac{\rho U l}{\eta}$
FENE-P viscoelastic fluid model	$We = \frac{\lambda U}{l}$, $Re = \frac{\rho U l}{\eta^0}$, $\beta = \frac{\eta^s}{\eta^0}$, $L^2 = 3\left(\frac{Q_0}{Q_{eq}}\right)^2$

where U - the characteristic velocity; l - the characteristic linear scale; Q_{eq} - the red blood cell chain configuration vector length under equilibrium; Q_0 - the maximum possible length of the configuration vector. Using the FENE-P viscoelastic fluid model the results of Newtonian fluid can be obtained. The value *We* = 0.01 means poor elastic properties. The stress relaxation time *λ* at this value of *We* is 0.008 seconds.

Fig. 5 shows a mesh of the computational region. The length of the input and output parts were established as 10 widths for the formation of the velocity profile at the input and establishing current in the output. The presented grid is non-uniform with 1:300 refinement on the way to the central area.

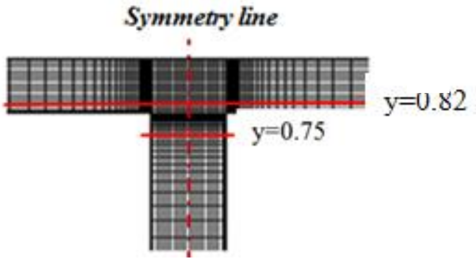

Fig. 5 – A computational domain with a superimposed grid

At the channel inlet (Γ_1) the following conditions are set:

$$U = 0, \quad V = const, \tag{10}$$

At the channel outlet (Γ_2) the Neumann conditions are set:

$$\frac{\partial U}{\partial x} = 0, \quad V = 0, \quad \frac{\partial \tau^p_{xx}}{\partial x} = \frac{\partial \tau^p_{xy}}{\partial x} = \frac{\partial \tau^p_{yy}}{\partial x} = 0, \tag{11}$$

On solid walls (Γ_3, Γ_4) the non-slip conditions:

$$U = 0, \quad V = 0, \tag{12}$$

Initial conditions:

At the initial time within the entire flow area

$$U = 0, \quad V = 0 \,. \tag{13}$$

The calculations are obtained on non-uniform grid using the finite volumes method (FVM) [10] in the software package OpenFoam [11].

The method of finite volumes (FVM) has the property of conservativeness, that is characterized by the implementation of the integrated balanced ratios. In the software package OpenFoam constructing grid equations corresponding to the differential equation is implemented by explicit schemes [12], where Courant number <1 is the stability criterion, the Courant number:

$Co = \frac{\delta t |U|}{\delta x}$ <1 is the criterion of sustainability, where Co - the Courant number, δt - the time step, $|U|$ - the flow rate passing through the boundary of the finite volume, and δx - the cell size [13].

RESULTS

The common view of blood flow behavior may be performed using the streamline patterns. Fig. 6 shows the results of simulation of the flow of a Newtonian fluid.

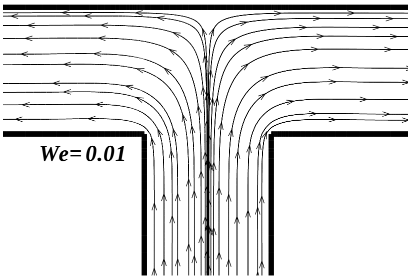

Fig. 6 - Streamline patterns for Newtonian fluid flow

For the Newtonian case the flow remains symmetrical. The flow pattern arises in cases where there is a lack of red blood cells.

Fig. 7a and 7b present the streamlines in the viscoelastic fluid flow for values of L^2 equals to 10 or 500.

a. **b.**

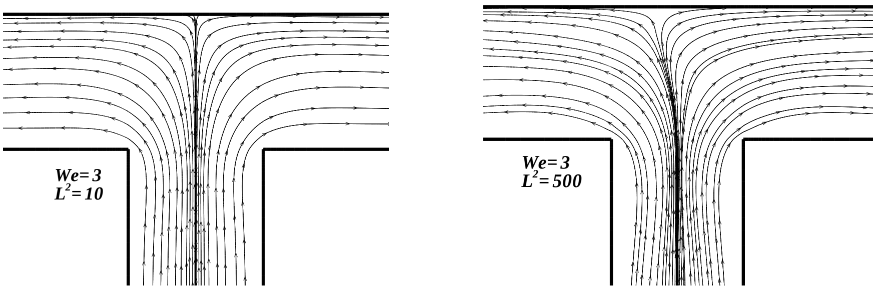

Fig. 7 - Streamlines for viscoelastic fluid flow

From figure 7a it follows that the disentangled chain of erythrocytes L^2 = 10 at We=3 predicts the conservation of the symmetrical shape of the fluid flow and the absence of stagnant zones near the corners. The formation of red blood cells accumulations leads to a narrowing of the main blood flow and the flow still remains symmetrical.

Flow pattern at L^2 = 500 and We = 3 (Fig. 7b) is significantly differ from the previous case. The observed effects increase in stagnant areas in the flow of fluid both before and after the corners of the channel and in the central part of the channel near the upper wall of the developing asymmetric form of the flow. Thus, there is a displacement of the point of complete inhibition of the flow (stagnation point) in the direction of the line of symmetry. The resulting asymmetry testifies to the ordered alignment of red blood cells near the upper wall of the vessel, and near the channel bifurcation. This is due to the interaction of plasma flow with red blood cells. And at the same time, the changed configuration of red blood cells affects the main flow. Arising normal stresses affect the flow, which can lead to significant deformation of the vessel walls.

Fig. 8 shows the distribution of values of pressure deviation in the cross-section *y*=0.82.

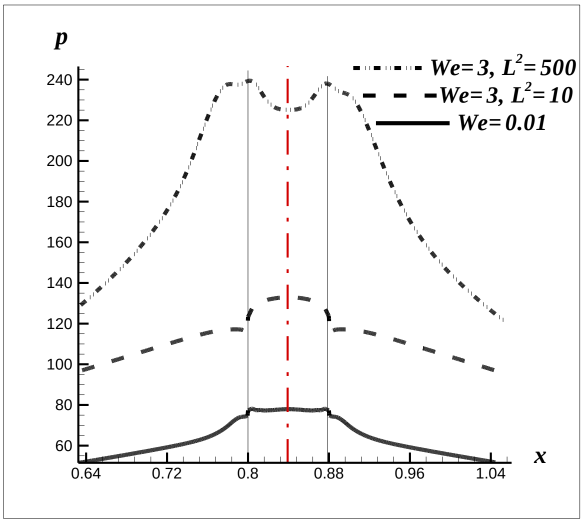

Fig. 8 – The pressure distribution in the channel branching area

At the values of parameters We=3; L^2=500 the emerging distribution shows two areas of increased pressure (near the corners x=0.8 and 0.88) and a decline between it. At the distance ≈ 3 of the channel widths the pressure decreases by 2 times away from the line of symmetry towards the outlet cross-sections.

Insufficient amount of erythrocytes (We=0.01) in the blood flow leads to that the entire central channel region has an elevated pressure with the increasing values between the corner points. Such pressure distribution in both cases is unfavorable.

The exception is the flow pattern at We=3; L^2=10, when the concentration of erythrocytes is within the normal range. Pressure slightly changes in channel's bifurcation and 2 - 3 times less in comparison with the cases considered.

Fig.9 shows a comparison of the contours of principal stress difference $\sigma_1 - \sigma_2$ for the cases We=0.01 and We=3 at L^2 = 10 и 500.

In accordance with optical law [11], this value characterizes the degree of optical anisotropy caused by the orientation of erythrocytes clusters in the flow.

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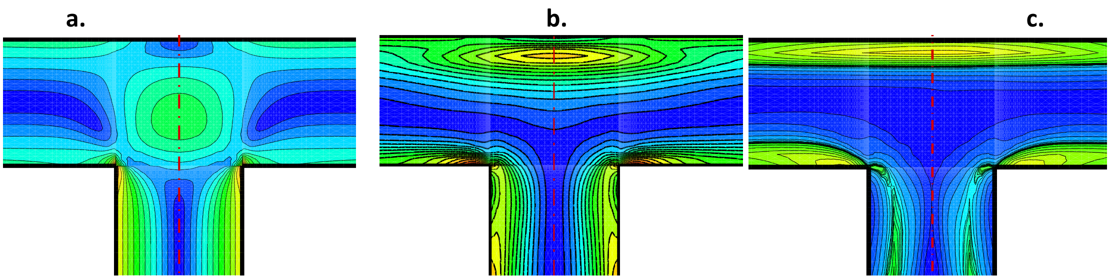

Fig. 9 – The isolines $\sigma_1 - \sigma_2$ in the channel for a Newtonian fluid (a) and viscoelastic fluid (b, c), at *We*=3, L^2=10, and *We*=3, L^2=500, respectively

For a Newtonian fluid maximum value of $\sigma_1 - \sigma_2$ is observed in the central zone of the channel and near the corner points (9a). For the value of parameter L^2=10 the zone of maximum values of the principal stress difference is displaced to the upper wall of the vessel, in this area, the erythrocytes gather in clusters, however, the flow remains symmetrical (Fig. 9b).

At the value of the ratio L^2 = 500 (Fig. 9c) the oriented clusters of red blood cells affect flow both in the central area, where corner points exist, and at the input of the channel where the flow is due to both the shear and normal stresses. With respect to the line of channel symmetry, the erythrocytes orientation is higher in the left part than in the right. The distribution of $\sigma_1 - \sigma_2$ and the vertical component of velocity U_y shows that, indeed, the values of these parameters are slightly larger in the left part than in the right (Fig. 10a-10b).

a. b.

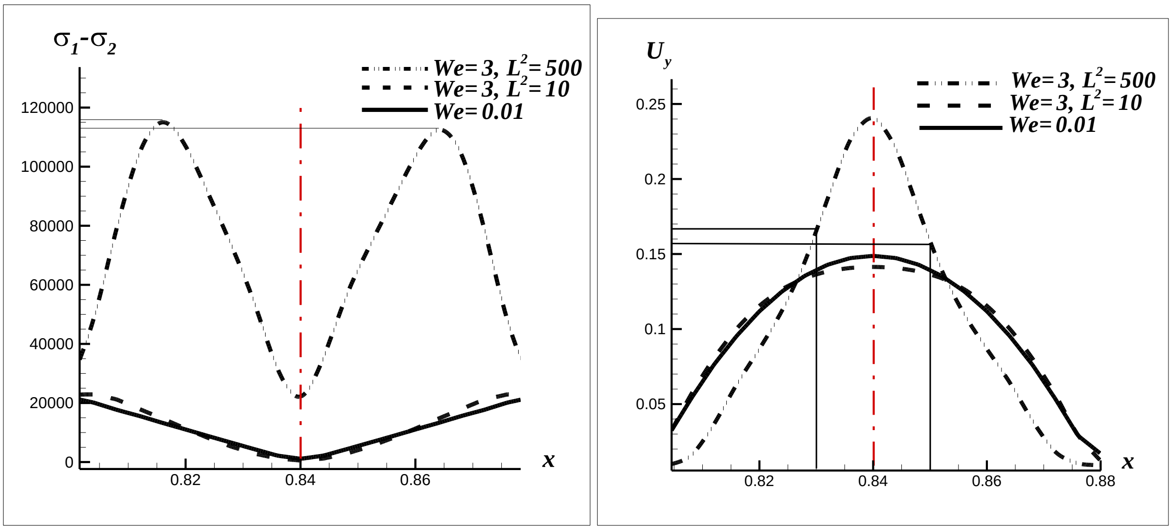

Fig. 10 – Distribution of $\sigma_1 - \sigma_2$ and U_y in the horizontal cross-section y=0.75

The performed distribution for both Newtonian and viscoelastic fluid (at We=3; L^2=10) flows is symmetrical. The principal stresses difference's value for the case of symmetry loss are 3-5 times greater than for We=0.01 and We=3; L^2=10. A similar pattern is observed for the distribution of this quantity along the line of symmetry of the channel (Fig.11).

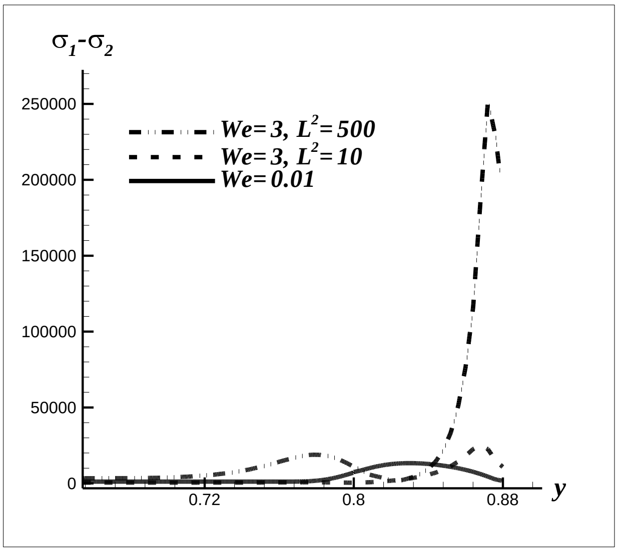

Fig. 11 – Principle stress difference's distribution along the channel's symmetry line

For the Newtonian case (blood with low red cells concentration), the peak of values $\sigma_1 - \sigma_2$ is in the central zone.

For non-Newtonian fluid the "dangerous" values of model parameters are *We*=3; L^2=500. At these values the symmetry loss effect exist and the jumps of the value $\sigma_1 - \sigma_2$ occur in channel's branching zone and near the upper wall of the channel. The peaks of $\sigma_1 - \sigma_2$ are much greater than in cases of the flow symmetry preservation. The most favorable case is when *We*=3; L^2=10, when as the result of increase in $\sigma_1 - \sigma_2$, the change in the stressed state of the blood leads to no damages to red blood cells.

The vessel bifurcation area is an area of special attention, where the arising stresses can lead to irreversible consequences (Fig. 12).

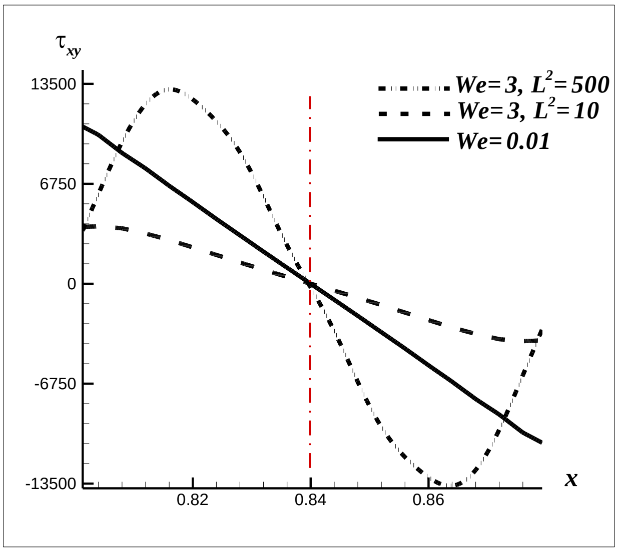

Fig. 12 - Distribution of shear stresses in the cross-section y=0.75

For We=0.01, there are substantial shear stresses on the channel walls, which values exceed the values of shear stresses for non-Newtonian fluids by 2-3 times (Fig. 12). The case of the loss of symmetry is notable for that the increased values τ_{xy} are observed in the main fluid flow and several times exceed the stresses on the vessel walls. Such a distribution of shear stresses can lead not only to an impaired integrity of the intima of the blood vessel, but also damage the red blood cells. When the concentration of red blood cells corresponds to normal (*We*=3; L^2=10), the stress state of the fluid is not critical.

SUMMARY

- In case of insufficient number of red blood cells (We=0.01), the flow will be symmetrical for any value of the unwinding degree of the chain of red blood cells.
- When *We*=3 and L^2=10, the simulation of blood flow shows the flow narrowing and formation of stagnant zones. The flow stays symmetrical. In this case, the distribution of the main characteristics of the blood flow is the most favorable.
- When *We*=3 and L^2=500, when the concentration exceeds the normal amount of erythrocytes, the blood flow, in addition to narrowing of the main flow and the formation of stagnant zones in the channel bifurcation zones, will show a disordered symmetry relative to the line of symmetry.

CONCLUSION

This paper discusses the blood flow simulation presented as a rheological constitutive relation of FENE-P viscoelastic fluid in a branching blood vessel. Blood is a complex biological fluid, in which flow behavior depends on many factors, and even the laminar flow state can be accompanied by undesirable effects, including loss of blood flow symmetry.

The effect of a disturbed symmetrical shape of viscoelastic fluid flow is associated with the interaction of red blood cells and plasma. Changes in the flow direction lead to changes in conformation of erythrocytes associated with their ability to form clusters and change their orientation in the flow. This non-equilibrium configuration, in turn, leads to a change of normal stresses that affect the flow pattern.

It has been shown that at a particular set of values of parameters *We* and L^2 the blood flow loses its symmetry in a branching vessel. If we accept the value *We*=0.01 for blood flow, then the flow pattern will be symmetrical for any value of the unwinding degree of the chain of red blood cells. When $We \geq 1$, the present numerical simulation of visco-elastic fluid flow at L^2>10 showed a narrowing of the flow and the formation of congestive zones. Gradual increases in L^2 increase the congestive zones and narrowing the main flow. When *We*=3 and L^2=500, the blood flow, in addition to previously described effects, showed a disordered symmetry relative to the line of symmetry. Changes in the flow direction lead to changes in conformation of erythrocytes. This non-equilibrium configuration, in turn, leads to a change of normal stresses that affect the dynamics of blood flow. The present analysis in context of blood flow is a qualitative study. The detail study as well as comparison with clinical data will be carried out in future work.

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