The fluid flow, containing flexible particles, in the channel of microfluidic devices

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Abstract. In this paper we investigated the flow of an elastic fluid, represented by the rheological constitutive relation FENE-P in a typical planar T-shaped channel as a part of microfluidic device. This model succeeds to predict necessary rheological properties of many real fluids. Distributions of the main flow characteristics for different sections were obtained for constant values of the simulation parameters (Reynolds number Re = 0.01, Weissenberg number We = 0.6, retardation coefficient β = 0.1 and degree of unraveling of the flexible particle L^2 = 50). The isolines and main flow quantities distributions are drawn, comparison of the results of the elastic and Newtonian fluids is provided, areas of increased stresses are considered.

1. Introduction

Construction of microfluidic devices contains a system of microchannels of various shapes, where different types of flow can be realized [1,2]. Peculiarity of above-mentioned fluids is the presence of flexible particles which can change their configuration in the flow. It leads to the appearance of nonlinear effects in the flow, even for small values of the Reynolds number (Re << 1). Such behavior is attributed to non-Newtonian fluids and caused by large stresses in comparison to Newtonian fluids where such kind of effects are absent [3].

The aim of the present paper is to investigate the viscoelastic fluid flow in a planar T-shaped microchannel under perpendicularly located input parts at small value of the Reynolds number (Re << 1).

2. Problem statement

The isothermal flows of viscoelastic fluids are described by the mass conversation equation and the momentum equations:

\[ \rho \left( \frac{\partial \tilde{v}}{\partial t} + \tilde{v} \cdot \nabla \tilde{v} \right) = -\tilde{\nabla}p + \tilde{\nabla} \cdot \tilde{\tau}, \]  \hspace{1cm} (1)

\[ \tilde{\nabla} \cdot \tilde{v} = 0, \]  \hspace{1cm} (2)

\[ \tilde{\tau} = \tilde{\tau}^p + \tilde{\tau}^s, \]  \hspace{1cm} (3)

\[ \tilde{\tau}^p = \frac{\eta^p \tilde{A}}{I - \text{tr}(\tilde{A})/3L^2 - I/\tilde{L}^2}, \]  \hspace{1cm} (3)

\[ \tilde{\tau}^s = 2\eta^s \tilde{D}. \]  \hspace{1cm} (4)
The modeling parameters are \( \text{We} = 1.5, \ \text{Re} = 0.01, \ \beta = 1/9, \ \text{L2} = 50 \). Governing equations are solved by the finite volume method (FVM) using the OpenFoam source - CFD (Computational Fluid Dynamics) software package [3].

![Schematic representation of the channel and refined mesh](image)

Fig. 1 – Schematic representation of the channel and refined mesh

The length of the channels was set to 10 channel’s width for the formation of the velocity profile at the inlet flow and to establish the outlet flow.

3. Results

At first glance, streamline patterns, obtained for Newtonian and viscoelastic fluids have minor differences (Fig. 2). The stagnant area emerges near the right corner for a viscoelastic fluid. Such formation is associated with the specific properties of the fluid (viscosity anomaly, finite stress relaxation time, longitudinal viscosity’s dependence on longitudinal deformation rate) and channel shape.

![Streamlines for Newton and viscoelastic fluids](image)

Fig. 2 Streamlines for Newton and viscoelastic fluids, respectively

Comparing the distributions of principal stresses difference in the channel for Newtonian and viscoelastic fluids, it might be seeing that the distribution of these quantities has both a qualitative and a quantitative difference (Fig. 3).

![Isolines of principal stresses difference in the channel](image)

Fig. 3. Isolines of principal stresses difference in the channel

In the left section, the most significant area is \( 0.8 < \gamma < 0.84 \). For a viscoelastic fluid, a flow from the left sleeve will "bump" the flow region, containing partially oriented flexible particles, and flow around it (Fig. 4).
Significant increase of principal stresses difference’s value occurred due to the formation of a long-range order in the arrangement of the flexible particles near the left corner point.

For the center section near the central point of the channel (y = 0.84), the influence of the walls and angular points of the channel is not so significant, so the velocities in this part are greater, and the flexible particles are close to their equilibrium state (Fig. 5). In the upper region, the principal stresses difference decreased due to the fact that at this point a part of the flow is "clamped" between the oriented flexible particles of below and the upper wall of the channel. The maximum value of the principal stresses difference at the point y = 0.823 is explained by the "collision" of two flows. The zigzag change in the velocity of viscoelastic fluid in the interval 0.81<y<0.83 corresponds to the width of the oriented flexible particles.

For the right section in the area of the point y = 0.85, we can suppose that the orientation of the flexible particles is absent (Fig. 6). As we become closer to the upper wall of the channel, the orientation of the flexible particles increases again. Oriented bands appear due to the peculiarities of the channel’s shape, the type of flow and the properties of the fluid, and also due to the mutual influence of oriented macromolecules segments. The velocity distribution shows that the maximum value of the velocity for a viscoelastic fluid is observed near the right corner point.
In the low section, same as for the left section, the increased orientation of the flexible particles (Fig. 7) is observed near the corner points for a viscoelastic fluid. This is a consequence of the flow from below to the right rotation, oriented bands of flexible particles in the central and outlet parts of the channel, symmetry line of the channel in the turning direction.

Fig. 7. Distributions of principal stresses difference and the horizontal velocity component in the low section

4. Conclusions

The peculiarity of this problem is the mutual perpendicular arrangement of the input parts of the channel. Such model configuration cases the following 2 features for the viscoelastic fluid:
1. A band of oriented flexible particles appears in the central part of the channel, along the separation line of the input flows.
2. A stagnant region near the right corner point.

The possible degree of extension of a flexible particle for this case exceeds its length in the equilibrium state by no more than 50 times. Even having such relatively small values, the picture of the stress state in a fluid differs significantly from the Newtonian one, for which the presence of normal stresses in the central part of the channel occurs due to the channel’s shape and the flow’s type. Large stress values in microfluidic devices can adversely affect the components, causing their deformation and, possibly, breaking.

References
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