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Original article

Numerical simulations of wormlike micelles flows in micro-fluidic T-shaped junctions

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Abstract

Numerical simulations of non-Newtonian fluids such as wormlike micellar solutions in confined geometries are of great interest in the oil industry. Their main property called shear-banding is a brutal transition from a very viscous state to a very fluid state above a certain threshold value of shear stress. This feature leads to a very complex behavior in 3D flows.

A modified version of the Johnson–Segalman's model, adapted to our situation (flows with a strong extensional component) is presented. A particular attention is paid to inlet and outlet boundary conditions, and a Poiseuille-like submodel is derived in order to get natural velocity and stress profiles that can be used at the boundaries. A numerical method is then developed, and stability issues are presented.

Our results show the interest of the modified Johnson–Segalman's model performed in this article. A set of 3D numerical simulations are then presented in order to understand the influence of the junction geometry upon the jamming effects observed with this kind of fluids.

Keywords: Rheology; Wormlike micelles; Microfluidics; T-junctions; 3D simulations

1. Introduction

1.1. General context

This paper presents some numerical analysis and simulations on a model used to describe the non-Newtonian behavior of wormlike micelles solutions. Wormlike micelles are polymer-like microscopic structures, that can break and reform permanently (for this reason micelles are often referred as “living polymers”). According to its very singular non-Newtonian properties, wormlike micelles are used in many fields of the industry from food processing to oil recovery [15].

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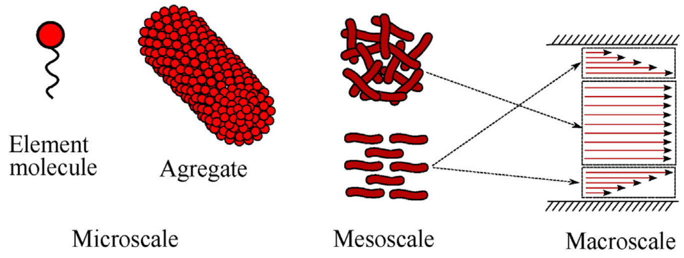

Fig. 1. Flow of a wormlike micellar solution, from the micro-scale to the macro-scale.

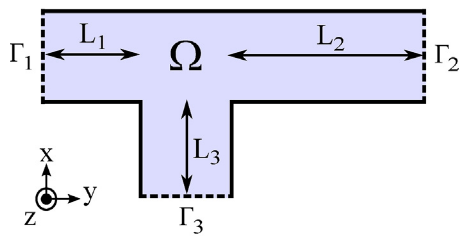

Fig. 2. Schematic view and notations for the T-shaped domain.

Numerical simulations in non-Newtonian fluid dynamics yield many challenging issues (see [22] as a review of numerical problems encountered in this field), the most notable problem being the so-called "high Weissenberg number problem" (see [11,12,24]). Since fluids such as wormlike micelles do not allow situations in which elastic effects are too large (above a critical shear stress the behavior of the fluid becomes close to Newtonian), the high Weissenberg number problem does not occur here. However, many other issues arise in our case, such as extensional instabilities and the choice of appropriate boundary conditions.

Our study will focus on oil recovery applications. Usually, micro-fluidic networks serve as simplified experimental models to understand percolation and drainage in porous media (see [26] for a review of the subject). In the following work, we focus on the case of a T-shaped junction, as an element of a more complex network. The geometry considered here is depicted in Fig. 2. In simulations, the fluid is injected through the boundary $\mathbf{\Gamma_3}$ and exits through $\mathbf{\Gamma_1}$ and $\mathbf{\Gamma_2}$. The walls are denoted $\mathbf{\Gamma_w}$. The expected phenomenon here is the jamming of one branch of the junction for some values of the inlet flow rate (as observed in [19]). This phenomenon can be explained, in some extent, by the particular shear rheology of the fluid.

The main rheological feature of wormlike micelles is "shear-banding", which can be defined as the capacity of a fluid to separate into phases of different viscosities when exposed to a shear stress [20]. For wormlike micelles, the micro-structural interpretation of shear-banding is the following: at rest, the micelles are in an entangled state, but when a sufficiently high shear stress is applied they align quickly in the flow direction. As a consequence, when the applied shear stress is non-homogeneous (like in a pipe flow), high shear rate bands are formed in the area of high shear stress (see Fig. 1), leading to plug flows, as observed also with yield stress fluids. An experimental work that shows this phenomenon can be found in [18].

A particular model has been shown relevant for the description of flows of wormlike micellar solutions: the Johnson–Segalman model introduced in [14] (see [5,6] for a complete review of models for wormlike micelles, and more recently [28]). The originality of this model is that, under a constant shear rate, it allows a non-monotonic relation between the shear rate and the shear stress (Fig. 3). However, in a real hydrodynamic context (shear rate given by a momentum equation) the necessary monotonicity of the shear rate/shear stress relation leads to the selection of a stress plateau. This stress plateau is history-dependent and some hysteresis on this model has been shown in literature [1]. The addition of a diffusion term in the model allows the selection of a unique stress plateau (for physical interpretation of this term see [9]).