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Casson fluid flow in a microchannel containing a flow disturbing rib

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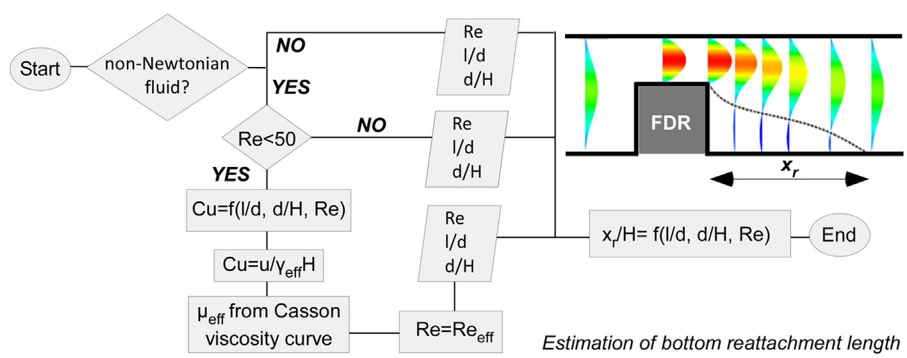
HIGHLIGHTS

- Casson-fluid flow in a μ-channel with a flow-disturbing rib (*FDR*) was studied.
- A validated *CFD* code is used to assess the effect of key design parameters.
- The blockage ratio and the *Re* greatly affect the formation of recirculation zones.
- An algorithm is proposed to predict the length of the bottom recirculation zone.
- Two new correlations facilitate the optimal design of μ-devices with *FDRs*.

GRAPHICAL ABSTRACT



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ABSTRACT

This work numerically studies the flow of a *Casson* liquid over a flow-disturbing rib in a rectangular μ-channel. The aim is to investigate, using a previously validated *CFD* code, the effect of the non-Newtonian behavior on the fluid flow characteristics, i.e. the size of the *reattachment length* at the bottom of the channel and downstream from the rib, in a μ-channel equipped with a Flow Disturbing Rib (*FDR*). The effect of the type of fluid, the *Re* number and key geometrical parameters on the size of the bottom *reattachment length* of the primary recirculation zone is investigated by performing a parametric study based on the *Design of Experiments* and the *Response Surface Methodology*. The results show that the reattachment length is mainly affected by the *Re* value and the rib height. It was also found that for $Re < 50$ the reattachment length decreases up to 35% for the non-Newtonian fluid compared to a Newtonian one, whose viscosity is equal to the asymptotic value of the non-Newtonian fluid. Based on the results two new and properly validated correlations are proposed, which can serve as a useful tool for designing microfluidic devices.

1. Introduction

The investigation of flow in a microchannel (μ-channel) is important for various applications, e.g. μ-heat exchangers, μ-reactors etc. As, due to the small characteristic length, the flow in such conduits is laminar, molecular diffusion is the major transport mechanism. Thus, it is common to enhance heat and mass transfer rates by introducing sudden changes in flow geometry, such as a Backward, a Forward Facing Step (*BFS*, *FFS*) or a Flow Disturbing Rib (*FDR*) that cause flow separation and subsequent reattachment. For example, Stogiannis et al. (2013) reported that

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Nomenclature

a_{ij}	coefficient of the polynomials [dimensionless]
Cu	Carreau number [dimensionless]
d	rib height [m]
H	channel height [m]
l	rib length [m]
p_i	variable in *RSM* methodology
Re	Reynolds number [dimensionless]
Re_{eff}	effective Reynolds number ($\mu = \mu_{eff}$) [dimensionless]
U	mean liquid velocity based on the channel cross section [m/s]
WSS	Wall Shear Stress [Pa]
x_r	bottom recirculation length [m]

Greek letters

γ	shear rate [s^{-1}]
μ	dynamic viscosity [Pa s]
μ_{eff}	effective dynamic viscosity [Pa s]
μ_∞	dynamic viscosity at infinite shear rate [Pa s]
ρ	liquid density [kg/m^3]
τ_y	yield stress [Pa]

the existence of an *FDR* on the conduit wall results to heat transfer enhancement. Heat transfer enhancement in simplified standard geometries like *BFS* (Kondoh et al., 1993; Vogel and Eaton, 1985) or *FFS* (Abu-Mulaweh, 2003) has been extensively studied in the macroscale, where the flow over a *BFS* is considered a benchmark and it has been investigated either experimentally (Armaly et al., 1983; Lee and Mateescu, 1998; Wengle et al., 2001) or numerically (Kaiktsis and Monkewitz, 2003; Le et al., 1997). However, to the authors' best knowledge, there is only limited information considering this type of flow in the microscale. Kherbeet et al. (2014), who studied a *BFS* in a μ-channel, reported that the basic features observed (like velocity profiles and recirculation areas) remain practically the same as in the macroscale.

In a recent work conducted in our Lab Stogiannis et al. (2014) have studied both experimentally (by employing *μ-PIV* and *electrodiffusion* techniques) and numerically (by using a validated *CFD* code) the flow of a Newtonian fluid (i.e. water) over an *FDR* in a rectangular *μ-channel* and they have investigated the effect of key design parameters (i.e. the rib *height* and *length* as well as the *Reynolds* (*Re*) number) on the size of the *reattachment length* of the recirculation zone observed at the bottom of the channel, downstream from the rib. These parameters are identified as important in microfluidic applications (e.g. fluid mixing, heat transfer enhancement and biomedical engineering). It is also known that in the macroscale the reattachment length depends primarily on the geometrical characteristics of the channel as well as the fluid *Re* (Tihon et al., 2001).

Casson fluids are *shear-thinning non-Newtonian* fluids that appear in industrial applications and bio-fluid dynamics. Many foodstuffs (e.g. yoghurt, tomato purée, molten chocolate), aqueous bentonite and silicon suspensions are among the fluids that follow the Casson fluid model (Chhabra and Richardson, 2008; Dash et al., 1996). Blood is also a dispersion that follows the *Casson* viscosity model (Merrill, 1969) and its flow in μ-conduits equipped with an *FDR* is important in the field of hemodynamics, since the non-Newtonian character of blood might become prominent in flow regions where the local shear rate is low, as for example in flow recirculation zones created downstream from a flow disturbance obstacle. Experimental and numerical studies (Anastasiou et al., 2012) suggest that although the non-Newtonian behavior may have a relatively small impact on the overall flow field, its effect on Wall Shear Stress (*WSS*) may become significant.

The flow of a shear-thinning non-Newtonian fluid over a flow disturbing obstacle in a μ-channel has recently attracted interest in biomedical applications, since an *FDR* can be regarded as a simplification of a stenosis in a human artery. In medical applications and particularly in hemodynamics the *WSS* profiles have been also identified as a major parameter that influences the formation of the atherosclerotic plaque in arteries, since it is reported (Caro, 1978; Nerem, 1992) that the progression of atherosclerotic lesions for specific sites in the arterial tree can be attributed to low and oscillating *WSS*. It is known (Malek et al., 1999) that the *WSS* values in a healthy human artery are in the range of 1–7 Pa and that the endothelial cells respond differently to different types of shear stress; for example the chronic exposure of the endothelial surface to *WSS* values greater than 7 Pa could lead to thrombosis and damage of the endothelium, while *WSS* values lower than 0.4 Pa promote the development of atherosclerosis (Chatzizisis and Giannoglou, 2006). Choi and Barakat (2005) also suggest that in order to approximate *in vitro* the physiological flow conditions in an atherosclerotic environment, conduits that induce flow disturbance can be used. There are also studies concerning the blood flow modification in channels with a *BFS* configuration (Choi and Barakat, 2005; Gijsen et al., 1998).

However and to the authors' best knowledge limited research have been published on the flow of non-Newtonian fluids in a μ-conduit that encompasses an *FDR*. Motivated by the above, the purpose of this study is to investigate the flow of a non-Newtonian shear thinning liquid, which follows the *Casson* viscosity model, in the aforementioned geometry. As reliable experiments in the microscale are difficult to perform, it is common practice to replace expensive and time-consuming experiments with reliable *Computational Fluid Dynamics* (*CFD*) simulations. As a result, in this study a *CFD* code is used to assess the effect of various design parameters of the μ-channels on the flow field characteristics.

Thus the *scope* of this work is to extend our previous work (Stogiannis et al., 2014) by investigating, using the previously validated *CFD* code, the effect of the non-Newtonian behavior on the fluid flow characteristics, i.e. the size of the *reattachment length* at the bottom of the channel and downstream from the rib, in a μ-channel equipped with an *FDR*. Finally, a parametric study based on *Design of Experiments* (*DOE*) and *Response Surface Methodology* (*RSM*) techniques will be performed in order to predict the mean shear rate and the length of the bottom recirculation zone as a function of the geometrical characteristics of the rib and the liquid flow rate.

2. Numerical methodology

The velocity field was visualized using a *CFD* code (*ANSYS CFX® 15.0*) while the computational geometry and the mesh were designed using the parametric features of *ANSYS Workbench®* package. The μ-channel was modeled as a *3D* computational domain as in similar geometries (Chhabra and Richardson, 2008; Kaiktsis et al., 1991). Computational simulations were conducted in the same rectangular channel that was used by Stogiannis et al. (2014), i.e. 0.925 mm in height (*H*), 10 mm in width (*W*) and 100 mm in length with a rib located at a distance of 60 mm downstream from the channel inlet (Fig. 1a).