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Numerical simulation of laminar flow of water-based magneto-rheological fluids in microtubes with wall roughness effect☆

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Abstract

Fully developed laminar flows of water-based magneto-rheological (MR) fluids in microtubes at various Reynolds and Hedsrom numbers have been numerically simulated using finite difference method. The Bingham plastic constitutive model has been used to represent the flow behavior of MR fluids. The combined effects of wall roughness and shear yield stress on the flow characteristics of MR fluids, which are considered to be homogeneous by assuming the small particles with low concentration in the water, through microtubes have been numerically investigated. The effect of wall roughness on the flow behavior has been taken into account by incorporating a roughness–viscosity model based on the variation of the MR fluid apparent viscosity across the tube. Significant departures from the conventional laminar flow theory have been acquired for the microtube flows considered.

Keywords: Microchannel; Microtube; MR fluid; ER fluid; Bingham plastic; Wall roughness; Laminar flow

1. Introduction

Magneto-rheological (MR) fluids are dispersions of fine (~0.05–10 μm) magnetically soft, multi-domain particles [1]. The field-induced transition of these smart fluids from the liquid to a geleous state

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is fast and reversible, i.e. after switching on the field the stiffening of the fluid occurs within a couple of milliseconds and after removal of the field, the material returns to its original fluid state. The degree of the stiffness depends on the kind of material and on the strength of the electric or magnetic field, respectively, and can therefore be regulated by the field. Correspondingly, electro-rheological (ER) fluids are colloidal suspensions, which exhibit dramatic reversible changes in properties when acted upon by an electric field. Both MR and ER fluids develop significant increases in shear yield stress and viscosity when they subjected to the electric field. They also behave like Newtonian fluids under zero field condition. With the field applied, these fluids become like non-Newtonian fluids for which the shearing stress can be represented by either Bingham plastic or Herschel–Bulkley constitutive model. This means that these fluids exhibit a finite yield stress with the shear stress depending upon the shear rate. These outstanding properties of such smart fluids give them a large potential for a variety of technical applications from which interesting perspectives.

MR fluid devices are being used and developed for shock absorbers, clutches, brakes, actuators, exercise equipment, and seismic dampers [2–6]. For such fluids, water, some hydrocarbons, glycol and silicone oil are generally employed as the carrier liquid depending upon the requirements of the application considered. Interest in such controllable fluids derives from their ability to provide simple, quiet, rapid-response interfaces between electronic controls and mechanical systems. These controllable fluids have the potential to radically change the way electromechanical devices that are designed and operated have long been recognized [7]. In the future, they also may play an important role in the "chemistry laboratory on a chip" systems currently under development [8]. However, before such microfluidic applications can be designed, researchers need more information about how MR fluids behave at the microscopic level.

A detailed literature review would reveal that the understanding of flow behavior of both Newtonian and particularly non-Newtonian fluids through microchannels is far from complete and inconclusive. The present work is a preliminary study of the flow behavior of water-based MR fluid through microtubes using Bingham plastic constitutive model. This study focuses on the effects of the wall roughness and yield stress on the flow behavior. The analytical solution of the laminar Bingham plastic fluid flow is first introduced, and a roughness–viscosity model proposed by Mala [9] is adapted to account for variation of apparent viscosity of the MR fluid across a microtube. The governing differential equation describing the flow in the microtubes is solved numerically using finite difference method (FDM).

2. Flow analysis of MR fluid in a round tube using Bingham plastic model

For one-dimensional steady flow in a circular tube, the streamlines are parallel to the wall, so that velocity can be assumed to vary in the radial direction only, i.e., $u=u(r)$. For this case, z-component of the momentum equation with the gravity neglected in cylindrical coordinates for steady-state conditions reduces to:

$$\tau_{rz} - \frac{1}{2} r \frac{dp}{dz} \tag{1}$$

The Bingham plastic constitutive model has shown to be applicable to represent the flow behavior of rheological materials such as MR and ER fluids. According to this model, the flow is generally divided into pre-yield and post-yield regions, depending on whether the material is stressed below or above a