ER유체의 채널유동에 대한 직접수치해석

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Direct Numerical Simulation of an Electro-Rheological Channel Flow

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Introduction

Electro-Rheological (ER) materials are concentrated suspension of micron-sized particles in a continuous fluid phase. In the presence of strong electric field, these particles become polarized. The interactions of these polarized particles with one another and with the suspending medium give rise to qualitative changes in the flow.

ER fluid's fast response and low power requirement provide the possibility of rapid response coupling between mechanical devices and electronic control. Some useful applications are ER engine mounts, shock absorbers, ER clutches, and other viscous damping devices. Since some devices have planar or concentric cylindrical electrodes, the analysis of shear (Couette) and pressure-driven (Poiseuille) flows in channel geometry is important.

Under steady flow conditions, the viscosity data for ER fluids are often fitted to an empirical equation for Bingham visco-plastic fluid of the form,

$$\sigma = \eta\dot{\gamma} = \sigma_y + \eta_\infty\dot{\gamma} \quad (\text{for } \sigma > \sigma_y) \qquad (1)$$

where $\dot{\gamma} = 0$ for $\sigma < \sigma_y$. Here σ is the shear stress, η is the viscosity function, $\dot{\gamma}$ is the shear rate, σ_y is called the dynamic yield stress, and η_∞ is the high shear limiting viscosity, also called the plastic viscosity.

The Bingham model is valuable for describing steady flow motion of an ER fluid from macroscopic point of view, but the model is highly oversimplified. The phenomenological constitutive theories refered to eq. (1) assume that an ER fluid can be modeled as a homogeneous, single-phase fluid.

However, ER fluid is non-homogeneous fluid with solid particles and suspending medium. ER fluids have been reported to possess essentially instantaneous response but this characteristic is not reflected in Bingham model.

Another approach to describe the features of the microscopic phenomena of an ER fluid has been studied (D.J. Klingenberg et. al, 1989, 1998). These models are associated with tracking the time-evolved motion of individual particles under the action of hydrodynamic forces and electrically induced polarization forces in the basic level. These particle level models consider suspensions consisting of hard, neutrally buoyant, dispersed spheres immersed in a Newtonian fluid. But the local fluid motion for this model system is governed by the Stokes's equations and the formation of chain-like particulate structures on a suspension of randomly dispersed particles has been simulated. The particle motion is driven by point-dipole forces and resisted by Stokes drag, ignoring all hydrodynamic interactions between the spheres and the fluid.

In this study, to overcome these drawbacks, hydrodynamic interactions between the spheres are accurately accounted for using the Navier-Stokes equations, and the multi-body electrostatic interaction is solved simultaneously at the particle-dipole level for the analysis of an ER fluid. The present DNS method provides not only the macroscopic behavior but also the microscopic structure of an ER fluid, so that we can explain the ER fluid mechanics more clearly such as the accurate measure of the effective viscosity.

Governing Equations

This study shows the flow of an ER fluid in the 2D electrode periodic channel.

Hydrodynamic interactions between the spheres are accurately calculated by using the Navier-Stokes equations. The governing equations for unsteady, laminar, incompressible flow are,

$$\nabla \cdot \mathbf{u} = 0, \qquad (2)$$
$$\rho_f \frac{D\mathbf{u}}{Dt} = \nabla \cdot \tilde{\sigma} \quad (\tilde{\sigma} = -p\tilde{I} + \tilde{\tau})$$

The multi-body electrostatic interaction is solved at the particle-dipole level (Klingenberg et. al, 1989, 1998). The electrostatic polarization force between two dipoles is,

$$F^{el}_{i,j}(R_{i,j}, \theta_{i,j}) = F_0\left(\frac{d}{R_{i,j}}\right)^4 [\,[3\cos^2\theta_{i,j} - 1]e_r + \sin 2\theta_{i,j}\, e_\theta] \qquad (3)$$

$$F_0 = \frac{3}{16}\pi\varepsilon_0\varepsilon_c d^2\beta^2 E_0^2\ , \qquad (4)$$
$$\beta = (\alpha-1)/(\alpha+2), \quad \alpha = \varepsilon_p/\varepsilon_c$$

where ε_0, ε_c, ε_p, and d are the permittivity of vacuum, the dielectric constant of the base fluid, the dielectric constant of the particle, and the diameter of the particle, respectively, R and θ are position vectors, and E_0 is the electric field.

The electrostatic forces are the sum of electrostatic interactions with the particles and electrostatic interactions with the electrode and repulsive forces between the particles.

$$\sum(F^{el}) = \sum F^{el}_{i,j} + \sum F^{el}_{i,wall} + R_p \qquad (5)$$

Then, the particle motion is determined by the fluid and electrostatic forces.

$$M\frac{dU_p}{dt} = F_p + E_p \qquad (6)$$
$$= \sum_{j\in\partial\Gamma_p} a_{ij}(u_h)_j + \sum_{j\in\partial\Gamma_p} b_{ij}(p_h)_j + \sum(F^{el})$$

This is the combined formulation which does not necessarily calculate the fluid force on the surface of the particles explicitly.

To solve these equations finite element method (FEM) is used which consists of a four-step fractional-step method used with P2P1 mixed finite element and the second order accurate fully implicit Crank-Nicolson timemarching scheme (Choi, 2000).

Results and Discussions

We have simulated the 2-dimensional channel flow of an ER fluid. The geometry and boundary conditions of the flow field are shown in Fig. 1. The uniform pressure gradient is applied in the flow field and the electric potential is applied on the electrode wall. The periodic condition is used for the computational domain.

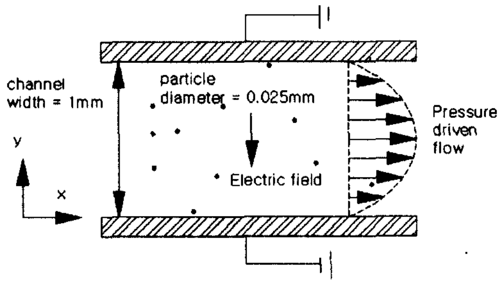
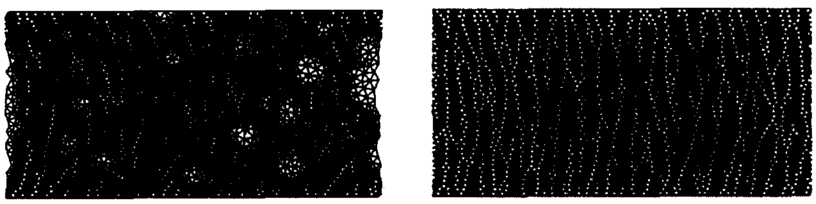


Fig. 1 Computational domain and flow conditions.

To verify the FEM code, equilibrium height of a particle in the Poiseuille flow is calculated. When the pressure gradient is applied, the particle begins to slide and to roll in the bottom of the channel. After a few seconds, the particle begins to be fluidized by the lift force. When the lift force makes a counterbalance for the gravity force, the particle drifts at a constant height from the bottom. This simulation result has the height 1.2 of the particle diameter at the Reynolds number 16.2. This result is in good agreement with the previous study (Patankar et. al, 2001).

For an ER fluid flow simulation, the dielectric constants, $\varepsilon_0 = 8.8542X10^{-12} F/m$, $\varepsilon_c = 7.3$, $\varepsilon_p = 23.4$ are chosen. The channel is 1 *mm* height, where the diameter of a particle is $d = 0.025mm$. The viscosity of the suspending medium is 100 *mPas*.

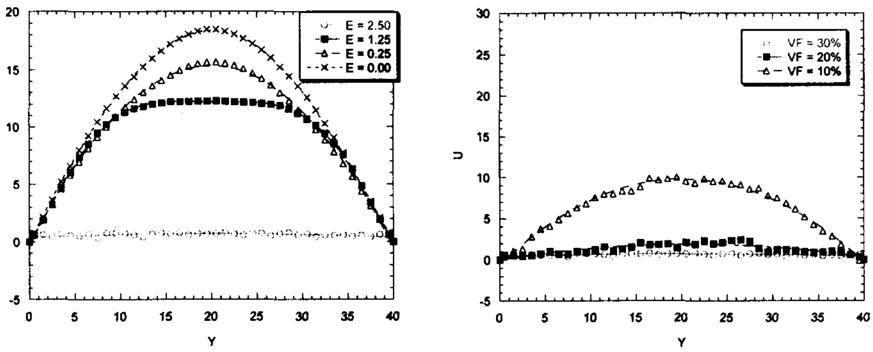


(a) (b)

Fig. 2 Snapshots of particles in an ER fluid when electric field and pressure gradient are applied. (a) 10% volume fraction, (b) 30% volume fraction.

At first, particles have random positions without an electric field. When electric potential is applied on the electrode, the particles have the formation of chain-like structures in the fluid medium. The images of these structures are seen in Fig. 2. This figure describes the formation of the chains of ER particles, and how the particles resist the fluid flow and increase the fluid viscosity. The fluid of 10% volume fraction has short chains. However, as the volume fraction becomes higher, the particles form longer chains and columns through the electrodes. The images of the chains describe that why the volume fraction is an important factor to resist the fluid flow, as shown in Fig. 3.

The intensity of the electric field has an influence on the formation of the chains, which results in fluid velocity change. In Fig. 3, the relation of the electric field and the velocity of the ER fluid is shown. This is the same trend as given by previous experiments (Jdayil & Brunn, 1996). The flat pattern of the velocity in the center of the channel is significant when the electric field is large.



(a) (b)

Fig. 3 Velocity profiles across the channel: (a) for various electric fields (volume fraction = 30%), (b) for various volume fraction fluids (electric field E=2.5).

Conclusions

The flow of an ER fluid in the 2D electrode periodic channel is studied by using FEM. The hydrodynamic interactions between the spheres and fluid are calculated using the Navier-Stokes equations, and the multi-body electrostatic interaction is solved at the particle-dipole level.

The motion of the particles in the ER fluid is described and the mechanisms of the flow resistence and the viscosity increase are explained. The ER effects have been studied by considering the electric field and volume fraction. These parameters have an influence on the formation of the chains resulting in changes of the fluid velocity and the effective viscosity.

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