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Effects of magnetized walls on the particle structure and the yield stress of magnetorheological fluids

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ABSTRACT

In this work, we investigate the quasi-static shear deformation of magnetic particles (MPs) in a Couette flow of magnetorheological (MR) fluids through Stokesian dynamic simulations. The magnetized walls are modeled by a congregation of magnetic dipoles and their effects on the MPs are considered. The simple shear flow of the base fluid with linear velocity distribution is used to generate the shear deformation of the MP structure and the yield stresses under different shear rates are obtained. Comparing with the relatively long chains forming in base fluid without the effect of magnetized walls, the initial structure of MPs is mainly in the form of short chains due to the attractive force of walls. At the beginning of the shear deformation of the MP structure, the concentration of MPs near the walls is found. As the shear deformation develops, however, the chains concentrate at the center of the simulation domain and the MPs near wall boundaries are attracted to the center. The yield stress depends on the initial structure of MPs which is affected by the magnetized walls. It is revealed that the larger shear rate of base fluid results in the larger yield stress, and the effects of the magnetization intensity of the walls and their space distance on the yield stress are also investigated.

1. Introduction

Magnetorheological (MR) fluids are suspensions of magnetizable particles (e.g. magnetite particles) in nonmagnetizable base fluids, such as water or oil. MR fluids exhibit special properties under an external magnetic field due to the formation of chains and clusters of magnetic particles (MPs). The MPs interact through the induced magnetic dipole moments and can attract or repel each another depending on their relative positions and the dipole moment vectors. MR fluids behave like Bingham fluids, whose viscosity and yield stress can be changed dramatically by the magnetic field. These properties have made MR fluids of great interest in many industrial applications. However, the complex behaviors of MR fluids pose challenges for the systematic characterization of the fluid properties.

The characterization of yield stress for MR fluids has attracted great interest recently due to the complicating role of the yield stress in application and the measurement of other rheological properties [1]. MR fluids are known to exhibit a very high yield stress caused by structural changes of MPs and they are able to flow (i.e., deform indefinitely) only if they are submitted to a stress above some critical value [2]. The nonequilibrium magnetization and magnetoviscosity of MR fluids can be enhanced due to the dipolar interactions among MPs [3]. It was revealed that the maximum shear strength of MR fluids varies as the square of the saturation magnetization of the MPs [4], and the effective viscosity of MR fluids depends on the strength of the magnetic field in the direction perpendicular to the MR fluid flow [5,6]. The microstructural model for the determination of the static and dynamic (Bingham) yield stresses of electrorheological (ER) fluids [7] can be employed to evaluate the yield stress of MR fluids. The physical properties of the particles in ER fluid have no effect on the adhesive force of the pearl chains of a congealed ER fluid [8], but for MR fluids, there exists strong interactive effect among MPs. The magnetically induced yield stress of MR fluids depends on the induced solid structure of MPs [9] and it is associated with formation of a field-oriented structure, the strength of which depends on the degree of particles magnetization [10]. Theoretical analyses show that the microscopic mechanism of the transition from elastic to viscous behavior of MR fluids is mainly associated with the breakup of the particle cluster into two separate drops as the shear strain exceeds a critical value [11].

It has been shown that true yield stress materials indeed exist and the shear banding is generically observed in yield stress fluids [12]. Experiments show that the yield stress of MR fluids depends on the magnetic field strength as well as the interparticle

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interaction and particle size distribution [13]. Although some progress has been made in understanding the remarkable properties of MR fluids in the past decades, it is still challenging for the systematic investigation of the roles of different factors in affecting the viscosity and yield stress of MR fluids through experiments. This might be due to the fact that the limited available MR fluids do not reflect all the factors and experiments are usually time-consuming and costly.

Numerical methods, such as the Monte Carlo, Molecular Dynamics and lattice Boltzmann methods, have been used to study the microstructural transformation of MR fluids [14–17]. To obtain the detailed information of MP distribution and structural change, the most accurate approach might be the molecular dynamics (MD) simulations, where the particle–particle and particle–fluid interactions are considered at the molecular scale. However, MD simulations may not be suitable for MR fluids because of the scale difference between MP and base fluid. A feasible strategy for dealing with the MR fluid interactions is to use the Stokesian dynamics (SD) simulation method, where the drag force on MPs is evaluated using the Stokes's law [18]. SD simulations, in which both enough particles and the hydrodynamic effects can be treated, have been used in the literature to study the rheology, diffusion and structure in a concentrated colloidal dispersion of Brownian hard spheres [19,20]. To reduce the computation time of SD simulation, the accelerated SD simulation method [21] as well as the cluster-based SD simulation method were proposed and used [22,23].

However, most of the previous work is about bulk MR fluids and the properties of MR fluids under confinements are unclear. Since the simulation cell is only a very small part of MR fluid, the SD simulation domain is usually a cube with three pairs of periodic boundaries. In application of MR fluid as lubricant, it always touches the magnetized solid walls which will affect the structure formation and evolution of MPs. In this work, we study structural changes of MPs and the yield stress of MR fluids in Couette flow, where MR fluids are confined by two parallel walls, based on the additivity of forces model of SD simulation [24]. On objective is to gain a better understanding of how the magnetized walls affect the conformational changes of MPs and the properties of MR fluids under quasi-static shear deformations. The structure evolution of MPs and the variation of shear stress caused by the shear flow of base fluid are investigated. In addition, the yield stresses are obtained in different situations.

2. Model and algorithm

The schematic of the Couette flow model is illustrated in Fig.1. A MR fluid is confined between two parallel magnetizable walls, which move with a constant velocity, U, but in opposite directions. The direction of magnetic field aligns with the y axis. The magnetite spherical particles of same diameter are chosen to be the MPs. X, Y and Z are the side lengths of the simulation domain, and $\boldsymbol{H}$ is the vector of magnetic field, as shown in Fig. 1.

To avoid the aggregation of particles, MPs are covered by layers of activating agent. Hence, there exist both the attractive force caused by the magnetic potential of dipoles and the repulsive force induced by the active layers. Each MP is regarded as a magnetic dipole and the forces exerted on each MP may arise from the interacting potential of dipoles, u^m, the magnetic field potential, u^h, the repulsive potential caused by the active layers, u^r, and the van der Waals potential, u^v. In this work, the gradient of magnetic field along the y axis is assumed to be zero, then the effect of u^h is neglected. u^v, as well as the Brownian force, has very small contribution to the resultant force on MP comparing with u^m and u^r, hence their effects can also be ignored [24]. u^m [24] and u^r [25] are

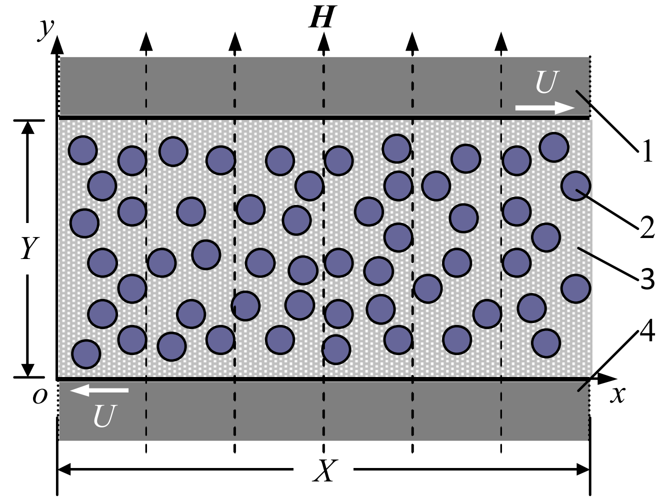

Fig. 1. Couette flow model of a MR fluid. 1 – Upper wall; 2 – Free MP; 3 – Base fluid; 4 – Lower wall.

given by

$$u_{ij}^{m}=\frac{\mu_0 m^2}{4\pi d_p^3}\left(\frac{d_p}{r_{ij}}\right)^3\left[\boldsymbol{n}_i\cdot\boldsymbol{n}_j-3(\boldsymbol{n}_i\cdot\boldsymbol{t}_{ij})(\boldsymbol{n}_j\cdot\boldsymbol{t}_{ij})\right] \tag{1}$$

$$u_{ij}^{r}=\frac{\pi d_p^2 n_s kT}{2}\left[2-\frac{r_{ij}}{\delta}\ln\left(\frac{d}{r_{ij}}\right)-\frac{r_{ij}-d_p}{\delta}\right] \tag{2}$$

where the subscripts i and j denote two interacting MPs, μ_0 is the vacuum permeability, r_{ij} is the distance between the two particles, d_p is the diameter of MP, δ is the thickness of the active layers, $d=d_p+2\delta$ is the particle diameter including the active layers, ξ is the number of activating agent molecules per unit area, $\boldsymbol{n}_i$ is the unit vector of magnetic moment, $\boldsymbol{n}_i=\boldsymbol{m}_i/m_i$ with $\boldsymbol{m}_i$ being the vector of the magnetic moment of MP, $m_i=|\boldsymbol{m}_i|$, $\boldsymbol{t}_{ij}=\boldsymbol{r}_{ij}/r_{ij}$, where $\boldsymbol{r}_{ij}=\boldsymbol{r}_i-\boldsymbol{r}_j$, $r_{ij}=|\boldsymbol{r}_{ij}|$. The dipole–dipole force between two MPs, $\boldsymbol{F}^m$, and the repulsive force, $\boldsymbol{F}^r$, can be obtained as the special derivatives of the potentials in Eqs. (1) and (2). The moments generated by the magnetic dipole potential and magnetic field, $\boldsymbol{T}^m$ and $\boldsymbol{T}^h$, are calculated using

$$\boldsymbol{T}_{ij}^{m}=-\frac{\mu_0 m^2}{4\pi d_p^3}\left(\frac{d_p}{r_{ij}}\right)^3\left[\boldsymbol{n}_i\times\boldsymbol{n}_j-3(\boldsymbol{n}_j\cdot\boldsymbol{t}_{ij})\boldsymbol{n}_i\times\boldsymbol{t}_{ij}\right] \tag{3}$$

$$\boldsymbol{T}_i^h=\mu_0 mH\boldsymbol{n}_i\times h=\mu_0 m\boldsymbol{n}_i\times H=\mu_0\boldsymbol{m}\times\boldsymbol{H} \tag{4}$$

The SD simulation method in detailed can be seen in [24]. In non-dilute colloidal dispersions, multibody hydrodynamic interactions are a main factor for governing the particle motion. For a simple shear flow, Satoh gave the translational velocity and angular velocity equation of particles on the level of the approximation of the additivity of forces [26]. At the beginning of simulations, MPs are randomly dispersed in the control volume. The unit vector of each magnetic dipole is randomly initialized and the initial velocity is set to be zero. Periodic boundaries are employed in the x and z directions. The MP–wall interactions are considered so that MPs cannot penetrate the boundaries at $y=0$ and $y=Y$. The cut-off distance for the interactions is $10d$ and the time step is 20 ns. The values of the major parameters are set as $\mu_0=4\pi\times10^{-7}$ N A^{-2}, $d_p=10$ nm, $\xi=10^{18}$ m^{-2}, $\delta=1.5$ nm, $\mu=0.01$ s, $H=5\times10^5$ A m^{-1}, and $m=1\times10^{-19}$ A m^2.