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Theoretical analysis on the orientational characteristics and rheological properties of a rod-like hematite particle suspension in a simple shear flow

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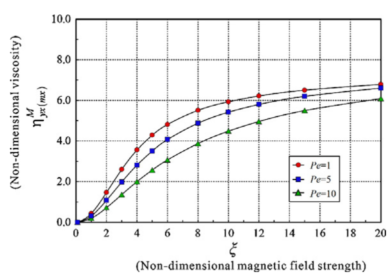
HIGHLIGHTS

- We have clarified the particle orientational and rheological properties.
- We have derived the basic equation of the orientational distribution function.
- The effect of the spin rotational Brownian motion has been clarified.

GRAPHICAL ABSTRACT



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ABSTRACT

We have theoretically investigated the particle orientational and rheological properties of a dilute suspension composed of spindle-like hematite particles under a simple shear flow. In the present study, we have derived the basic equation of the orientational distribution function by taking into account the spin Brownian motion about the particle axis. The basic equation has been solved numerically in order to investigate the influence of the shear rate, the magnetic field strength, and the rotational Brownian motion on the orientational distribution and rheological properties. For a very strong magnetic field applied in the shear flow direction, the rotational motion of the particle is restricted in a plane normal to the shearing plane due to the spin rotational Brownian motion. Although the negative viscosity was observed in the previous study, in the present case the orientational properties of the particle give rise to positive viscosity. The viscosity becomes large with increasing magnetic field strength. The viscosity due to magnetic properties does not occur in the situation of a magnetic field applied in the direction of the angular velocity vector of a simple shear flow.

1. Introduction

A colloidal dispersion that is obtained by dispersing functional particles (mainly responding to an applied magnetic or electrical field) in a base liquid can exhibit characteristic functional features in certain situations. Representative functional fluids are magnetic fluids and magneto-rheological (MR) suspensions [1,2]. Since these fluids and suspensions exhibit the magneto-rheological effect and characteristic aggregation phenomena in an applied magnetic field as well as a flow field, numerous numbers of studies have being conducted on the target of engineering applications to dampers, actuators and magnetic recording materials [3–5]. Up to the present time, spherical iron oxide particles have mainly been focused on as ferromagnetic fine particles that are ordinarily used for synthesizing magnetic fluids and MR suspensions. In addition to these particles, Fe-Pt particles [6,7] and cobalt ferrite

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particles [8,9] have recently been addressed because these particles have high coercive force. Non-spherical magnetic particles [10,11] instead of spherical ones may be expected to lead to a highly functionalization of new functional fluids or functional materials. Moreover, Carbon-encapsulated magnetic nano-particles [12–14] may be another hopeful functional particle for developing new magneto-rheological fluids.

To generate magnetic particles with various shapes, hematite particles may be a hopeful fine particle. Depending on the synthesis method, hematite particles result into rod-like [15–17], disk-like [18–20] and cubic-like particles [21,22]. In particular, rod-like hematite particles are expected to exhibit a characteristic magneto-rheological effect. This is partially because rod-like hematite particles have a magnetic moment normal to the particle axis direction at the particle center [15,23]. Comparing with ferromagnetic particles such as magnetite [10,11], hematite particles have a significantly weak magnetization [23,24], so that coarse spindle-like particles are not difficult to be handled for obtaining a stable dispersion due to only an electrical double layer without using a special technique such as surfactant molecules. These characteristics clearly say that a stable dispersion composed of spindle-like hematite particles is obtained without serious difficulty and this dispersion exhibits characteristic orientational features due to the particle magnetized in the minor axis direction.

From this background, several research groups have been conducting various studies mainly on rheological properties of a hematite particle suspension [25,26]. The previous theoretical study [27,28] predicted the appearance of the negative magneto-rheological effect for the case of an external magnetic field applied in the direction normal to the shear flow direction. Moreover, quite recently, careful experiments using a cone-plate-type rheometer have succeeded in verifying that the negative magneto-rheological effect can also be observed experimentally in an applied magnetic field [29]. On the other hand, for the case of an external magnetic field applied in the different directions, the previous theory without taking account of spin Brownian motion clarified that the magneto-rheological effect exhibited different features from those for the above case. That is, application of an external magnetic field in the shear flow direction (or in the same direction of the angular velocity vector of a shear flow) gives rise to a usual positive increase in the viscosity or zero viscosity, respectively [30,31]. These complex characteristics of the magneto-rheological effect have a strong relationship with the particle orientational distribution that are significantly dependent on the situations of a simple shear flow and an applied magnetic field (i.e. their direction and strength). Hence, for considering the application of a hematite particle suspension in engineering fields, further studies are necessitated to be conducted in order to investigate the influence of an applied magnetic field and a shear flow on the particle orientational distribution and rheological properties.

The objective of the present study is to address a suspension composed of rod-like hematite particles and theoretically investigate the influence of the spin Brownian motion on the orientational characteristics and the magneto-rheological effect for the two different cases of an external magnetic field applied in the shear flow direction and in the same direction of the angular velocity vector of a simple shear flow. In concrete, we first show the basic equation of the orientational distribution function with the spin Brownian motion, which was neglected in the previous studies [30,31]. Then, in these cases of the two different directions of an applied magnetic field, we solve the basic equation numerically to clarify the dependence of the orientational distribution and the magneto-rheological effect on the magnetic field strength, the shear rate and the rotational Brownian motion.

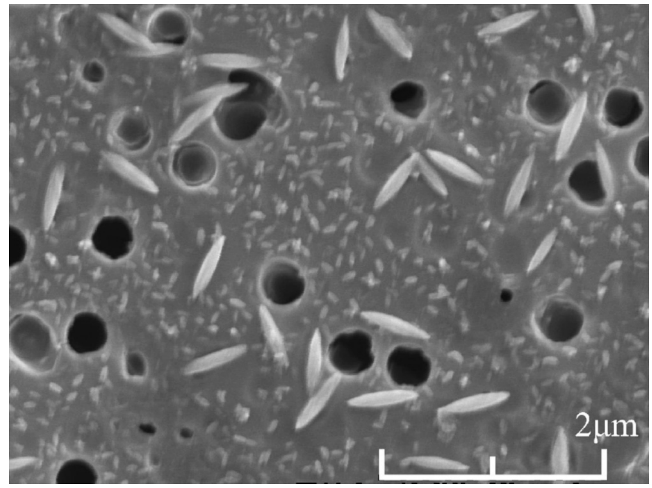

Fig. 1. Electron microscopy image of a hematite particle dispersion ($(2a, 2b) = (0.61 \pm 0.05, 0.09 \pm 0.01)$ μm).

2. Particle model

In the present study, we consider the behavior of the spindle-like particles that are generated experimentally [23] in a simple shear flow with angular velocity Ω and rate-of-strain tensor $\boldsymbol{E}$. As shown in Fig. 1, a normal coordinate system is set at the center of the particle. A simple shear flow $\boldsymbol{U}$ in the x-axis direction is expressed as $\boldsymbol{U} = (\dot{\gamma}y, 0, 0)$ with shear rate $\dot{\gamma}$.

The spindle-like particles are modeled as a prolate spheroidal particle, shown in Fig. 1, and will conduct the rotational Brownian motion in a simple shear flow. The particle is assumed to have a magnetic moment $\boldsymbol{m}$ normal to the particle axis acting at the particle center. With the notation $\boldsymbol{e}$ for the particle direction and $\boldsymbol{m}$ and $\boldsymbol{n}$ for the magnetic moment and its direction ($\boldsymbol{m} = m\boldsymbol{n}$), respectively, the interaction energy U between the magnetic moment and an applied magnetic field $\boldsymbol{H}$ and the torque $\boldsymbol{T}^{(m)}$ acting on the particle are expressed, respectively, as

$$U = -\mu_0 mH\,\boldsymbol{n} \times \boldsymbol{h}, \quad \boldsymbol{T}^{(m)} = \mu_0 mH\boldsymbol{n} \times \boldsymbol{h} \tag{1}$$

in which μ_0 is the permeability of free space, $H = |\boldsymbol{H}|$, and $\boldsymbol{h}$ is the unit vector denoting the magnetic field direction.

Since the rod-like hematite particle has a magnetic moment normal to the particle direction, the orientation of the particle can be described by specifying both the particle direction $\boldsymbol{e}$ and the magnetic moment direction $\boldsymbol{n}$. This implies that we are required to simultaneously take into account both the ordinary Brownian motion about a line normal to the particle axis and the spin Brownian motion about the particle axis. In the previous study [28], we succeeded in developing a theory of the orientational distribution that takes into account the spin Brownian motion for the case of an applied magnetic field normal to the shearing plane. Hence, for the present case of an external magnetic field applied in the two different directions, we here simply outline the development procedure of the basic equations of the orientational distribution function in the following sections.

3. Rotational motion and torques acting on the particle in a simple shear flow

As already mentioned, both the particle direction $\boldsymbol{e}$ and the magnetic moment direction $\boldsymbol{n}$ are necessitated to be specified for describing the orientation of the particle. To do so, as shown in Fig. 2, a normal coordinate system is set at the center of the particle and the particle direction $\boldsymbol{e}$ is described by a zenithal angle θ from