International Journal of Thermophysics, Vol. 27, No. 1, January 2006 (© 2006)
DOI: 10.1007/s10765-006-0015-8

Measurement of the Viscosity of Dilute Magnetic Fluids[1]

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The capillary tube viscometer is used to measure the viscosity of aqueous magnetic fluids under the influence of parallel and perpendicular magnetic fields. The effects of the volume fraction of the suspended magnetic particles, the concentration of surfactants, and the external magnetic field strength, as well as the orientation, on the viscosity of the magnetic fluid are analyzed. The experimental results show that the viscosity of the sample magnetic fluids increases with increases in the concentrations of suspended magnetic particles and surfactants. The external magnetic field is also an important factor that affects the viscosity of the magnetic fluid. The viscosity first increases with the magnetic field and finally approaches a constant as the magnetization attains a saturation state. For the same magnetic fluid, the viscosity in a perpendicular magnetic field is larger than that in a parallel magnetic field for the same magnetic field.

KEY WORDS: magnetic effect; magnetic fluid; viscosity.

1. INTRODUCTION

A magnetic fluid is a colloidal suspension consisting of magnetic nanoparticles and a carrier liquid. Due to some of its unique characteristics, the magnetic fluid behaves as a smart or functional fluid and has been finding more and more applications in a variety of fields such as electronic packaging, mechanical engineering, aerospace, and thermal engineering [1–3]. In some cases, the viscosity of the magnetic fluid is a vital

[1] Paper presented at the Seventh Asian Thermophysical Properties Conference, August 23–28, 2004, Hefei and Huangshan, Anhui, P. R. China.

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parameter that determines application performance. A quantitative understanding of the viscosity is essential to describe the flow characteristics of the magnetic fluid as the applications of magnetic fluids expand into thermal engineering. Generally speaking, the viscosity is mainly dependent upon the properties, concentration, dimensions, and distribution morphology of the suspended nanoparticles as well as the relevant properties of the carrier liquid. If an external magnetic field is applied, this field exerts a strong effect on the transport properties of the magnetic fluid, i.e., the field strength and direction will alter the viscosity of the fluid.

To date there is no sophisticated and widely accepted theory for accurate predictions of the viscosity of magnetic fluids. An experimental approach is necessary to determine such a property. By taking the magnetic field into account, some investigations [4–10] were focused on measurements of the viscosities of magnetic fluids. Experimental results revealed that the viscosity of the magnetic fluid is greater than that of the original carrier liquid independent of the presence of a magnetic field. Both the strength and direction of the magnetic field play important roles in the viscosity of the magnetic fluid. The viscosity increases with an increase in the strength of the magnetic field applied in either the parallel or perpendicular directions of the flow, finally reaching a constant upon saturation of the magnetization. Furthermore, existing experimental data indicated that the viscosity behavior for magnetic fields parallel and perpendicular to the flow direction is controvertible. For example, the measured results of McTague [4] showed that the viscosity increase in a parallel field is nearly double that corresponding to a perpendicular field. In his paper, this phenomenon was explained by a hindrance of the suspended particle rotation due to the action of the magnetic field. According to his experimental data, however, Hamedani [6] pointed out that the magneto-viscosity effect of magnetic fluids in the perpendicular field is higher than that in the parallel field, and the magneto-viscosity effect is almost negligible for a magnetic field parallel to the flow direction. This may give an impression about a paradox in the effect of the magnetic field direction on the viscosity of the magnetic fluid. Thus, there are a number of questions that remain unresolved and need to be investigated based on measurements of transport properties.

To obtain evenly distributed and stabilized colloidal suspensions, some auxiliary surfactants (activators or dispersants) are necessary. By means of a schematic sketch, Odenbach [3] perceivably explained the interactions among the surfactant, magnetic particles, and carrier liquid. The addition of a surfactant will affect the distribution of the particles and furthermore affect the transport properties of the magnetic fluids. Therefore, the viscosity of a magnetic fluid also depends upon the properties and concentration of the surfactants in addition to the above-mentioned factors. To our knowledge, there are few references involved in describing the effect of the surfactants on the viscosity of the magnetic fluid.

As mentioned above, this paper involves an experimental investigation of the viscosity of magnetic fluids. Since magnetic fluids with higher volume fractions of magnetic nanoparticles may be limited in practical applications in thermal engineering, experimental measurements of dilute magnetic fluids are carried out to analyze the effects of the volume fraction of the suspended magnetic nanoparticles, surfactant concentration, and the magnetic field strength as well as the orientation on the viscosity of the fluid.

2. EXPERIMENTAL

In this experiment, two types of aqueous magnetic fluids are involved. One is an Fe_3O_4–water magnetic fluid prepared by chemical precipitation, in which oleic acid is added as an activator. Its saturation magnetization is 421.3×10^{-4} T and the density is $1253\,\mathrm{kg \cdot m^{-3}}$. In this case, the average particle diameter for Fe_3O_4 is 20 nm and the particle volume fraction is about 2.8%. For this Fe_3O_4–water magnetic fluid, samples with different particle volume fractions are prepared by dilution of the initial sample in the carrier liquid. Another magnetic fluid is an Fe–water magnetic fluid that is prepared by a direct mixing method. In this case Fe nanoparticles of 26 nm diameter are mixed with deionized water by volume percentage over the range from 1 to 4%. To stabilize the suspension, sodium dodecylbenzenesulfonate is selected as the activator to coat the nanoparticles. The amount of sodium dodecylbenzenesulfonate is calculated based on weight percentages of the suspension of Fe nanoparticles and water. In addition, the sample magnetic fluid is vibrated for some hours in an ultrasonic vibrator. It is shown that for the case that an appropriate amount of sodium dodecylbenzenesulfonate is added, stabilization of the suspension can take from about several hours to one week in the stationary state.

The capillary tube viscometer is used to measure the viscosity of the aqueous magnetic fluid. As shown schematically in Fig. 1, the capillary tube viscometer consists of a capillary tube with an inner diameter of 2 mm and a length of 45 mm connected to a container. In order to eliminate the heating effect caused by an electromagnet coil and to determine the temperature of the magnetic fluid, the capillary tube is cooled by a water reservoir, in which the cooling water comes from a thermostatic bath. Thus, the temperature of the magnetic fluid can be controlled. The viscosity of the magnetic fluid is measured at a temperature of 293 K. Such a viscometer can also be exposed to a parallel magnetic field

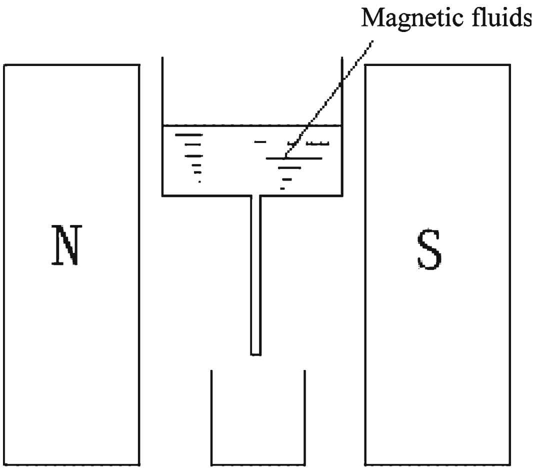

Fig. 1. Schematic diagram of the capillary tube viscometer (perpendicular field).

produced by a solenoid or a perpendicular magnetic field produced by a permanent magnet. The dependence of the strength and the uniformity of the magnetic field over the dimensions of the capillary tube is measured by using a gaussmeter, which demonstrates that the maximum non-uniformity of the field strength over the dimensions of the capillary tube is less than 3.7%. The magnetophoretic forces exerted by the field on the particles can be neglected.

The fundamental equation of the capillary tube viscometer is introduced as follows:

$$\eta = \frac{\pi r^4 t \Delta P}{8VL} = \frac{\pi r^4 t \rho g h}{8VL} = \frac{\pi r^4 t m g h}{8V^2 L} \tag{1}$$

where η is the viscosity, r is the radius of the capillary tube, t is the measuring time, ΔP is the pressure drop induced by the height difference between the upper surface of the magnetic fluid in the container and the outlet of the capillary tube, ρ is the density of the sample fluid, h is the height difference between the upper surface of the magnetic fluid in the container and the outlet of the capillary tube, L is the length of the capillary tube, and V is the volume of the flowing magnetic fluid during time t as well as m is the mass of the magnetic fluid during time t. If the volume, mass, and time for a magnetic fluid flowing through the capillary tube are known, the viscosity of the magnetic fluid in the absence or in the presence of an external magnetic field can be determined. Before measuring the viscosity of magnetic fluids, the capillary tube viscometer is calibrated by measuring water and ethylene glycol with no external field, which demonstrates that the experimental error of the system is less than 4.5%. The uncertainty of the viscosity is derived from mainly the measuring errors of parameters such as dimension and time. From Eq. (1), it can be estimated as

$$\left(\frac{\delta\eta}{\eta}\right)=\sqrt{16\left(\frac{\Delta r}{r}\right)^2+\left(\frac{\Delta t}{t}\right)^2+\left(\frac{\Delta t}{t}\right)^2+\left(\frac{\Delta h}{h}\right)^2+\left(\frac{\Delta m}{m}\right)^2+4\left(\frac{\Delta V}{V}\right)^2+\left(\frac{\Delta L}{L}\right)^2} \tag{2}$$

where the error terms $\left(\frac{\Delta r}{r}\right)$, $\left(\frac{\Delta h}{h}\right)$, $\left(\frac{\Delta V}{V}\right)$, and $\left(\frac{\Delta L}{L}\right)$ arise from errors of the dimensions whose measurement uncertainties are all less than 1%. The time measuring precision is 1%. The mass measuring precision is 0.5%. Therefore, the maximum uncertainty of the viscosity is 4.8%.

3. RESULTS AND DISCUSSION

3.1. Effects of the Particle Volume Fraction

Figure 2 shows the effects of the particle volume fraction on the viscosity for Fe–water magnetic fluids in the absence and presence of an applied parallel magnetic field. The experimental results show that the suspended Fe nanoparticles give an increase in the viscosity of the fluid, and the Fe–water magnetic fluid has a larger viscosity than that of the pure carrier liquid, whether the external field is applied or not. The viscosity of an Fe–water magnetic fluid increases with an increase in the volume fraction of Fe nanoparticles. It is one of the main factors affecting the viscosity of the magnetic fluid. For example, the viscosity of the Fe–water magnetic fluid varies from 6.14 to 9.25 mPa · s with no external field if the volume fraction of the nanoparticles increases from 2% to 4%. The reason is that an increase of energy dissipation occurs during viscous flow due to the presence of suspended particles. This situation is the same as that for a nanofluid consisting of nonmagnetic solid particles [11] or a liquid–solid mixture [12].

3.2. Effects of the Surfactant Concentration

Other than the magnetic nanoparticles and base liquid, surfactants are involved in the preparation of a magnetic fluid. The surfactant concentration will affect the distribution of the suspended particles and thus affect the viscosity of the magnetic fluid. Therefore, the effect of the surfactant concentration on the viscosity is investigated in this study. Figure 3 reveals the viscosity of the Fe–water magnetic fluid with a particle volume fraction of 2.0 vol% at different activator concentrations in the

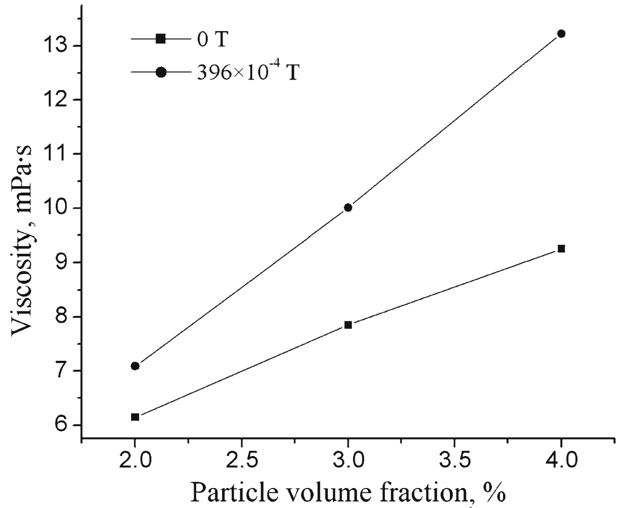

Fig. 2. Dependence of the viscosity of the Fe–water magnetic fluid on the particle volume fraction.

absence of an external magnetic field, for which the activator concentration refers to the mass ratio of the activator to the sum of the Fe nanoparticles and the water. The experimental results indicate that the viscosity of the Fe–water magnetic fluid increases significantly with an increase in the concentration of the added activator. Obviously, the activator concentration is an important factor affecting the viscosity of the magnetic fluid. This fact is explained by the fact that although the activator coats the surface of the magnetic nanoparticles, the interaction between the magnetic nanoparticles and the liquid molecules is intensified. Consequently, the viscosity of the magnetic fluid is increased. In addition, from Fig. 3, it is also found that the viscosity increases smoothly at low activator concentrations. If the activator concentration exceeds 4%, however, the viscosity of the Fe–water magnetic fluid increases sharply. The reason may be that the over-saturation phenomenon of the activator inside the magnetic fluid occurs when the superfluous activator is added to the magnetic fluid. The excessive activators will aggregate with each other. The interactions and collisions among the magnetic particles, fluid, and activator are increased. Thus, the viscosity of the magnetic fluid increases sharply.

3.3. Effects of the Magnetic Field Strength

The dependences of the relative viscosity of the magnetic fluid upon the magnetic field strength are shown in Figs. 4 and 5. The relative

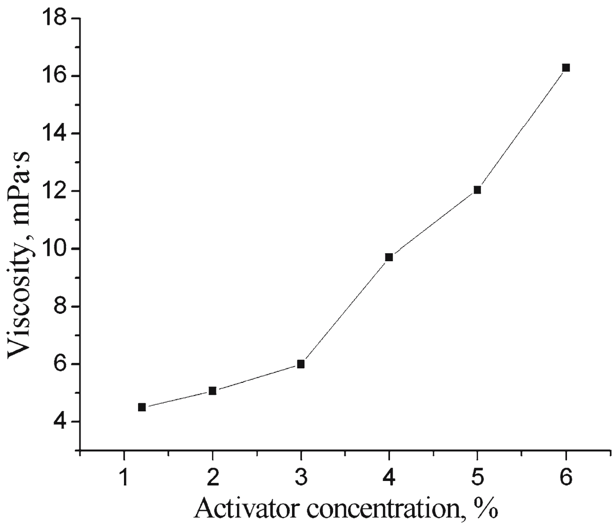

Fig. 3. Viscosity of the Fe–water magnetic fluid as a function of the activator concentration.

viscosity refers to the ratio of the viscosity of a magnetic fluid in the presence of an external magnetic field to that of a magnetic fluid with no external magnetic field present. Figure 4 shows the relative viscosity of the Fe_3O_4–water magnetic fluid with an activator concentration of 5% in a perpendicular field, and Fig. 5 gives the relative viscosity of the Fe–water magnetic fluid with an activator concentration of 3% in a parallel field. From these experimental results, it can be seen that the viscosity increases with an increase in the strength of the applied magnetic field in either the parallel or perpendicular directions of the flow. The field strength is one of the important factors affecting the viscosity of the magnetic fluid. The viscosity increase of the magnetic fluid in the external magnetic field also depends on the concentration of the magnetic particles. The effect of the magnetic field on the viscosity is reinforced with an increase in the volume fraction of the magnetic particles. Obviously, a magnetic force acts on the magnetic particles when the magnetic fluid is exposed to a magnetic field. The magnetic particles in the fluid tend to align with the direction of the external field. The distribution morphology of the suspended nanoparticles with the external field is different from that of the suspended nanoparticles with no external field present. Therefore, it is expected that the viscous dissipation in the magnetic fluid induces an increase of the viscosity of the magnetic fluid as a whole.

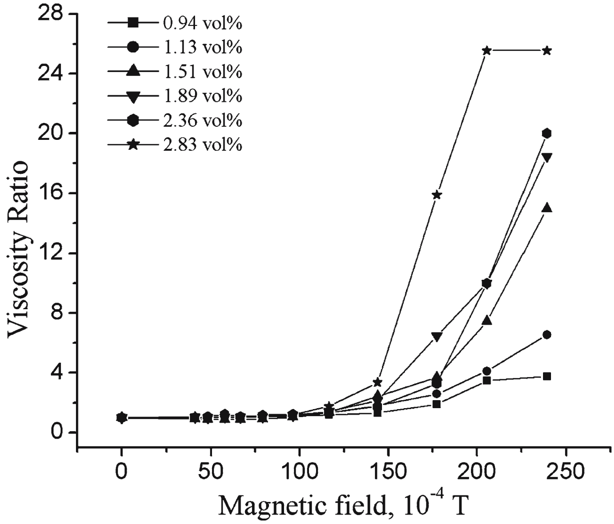

Fig. 4. Relative viscosity of the Fe_3O_4–water magnetic fluid as a function of the perpendicular magnetic field strength.

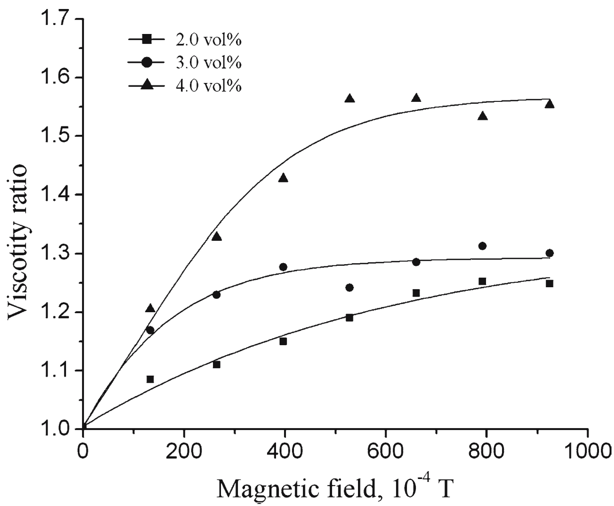

Fig. 5. Relative viscosity of the Fe–water magnetic fluid as a function of the parallel magnetic field strength.

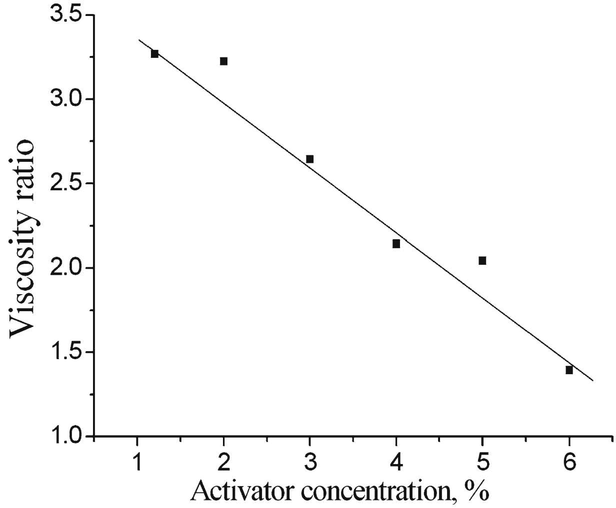

Fig. 6. Relative viscosity of the Fe–water magnetic fluid as a function of the surfactant concentration at a constant parallel magnetic field strength.

In addition, the experimental results also show that the magnetic effect on the viscosity of the magnetic fluid is remarkably dependent upon the surfactant concentration for a given external magnetic field strength. Figure 6 shows the relative viscosity of the Fe–water magnetic fluid at a particle volume fraction of 3.0 vol% at different activator concentrations with an external parallel magnetic field strength of 10^{-2} T. As shown in Fig. 6, the relative viscosity of the magnetic fluid decreases as the surfactant concentration increases at a constant magnetic field strength. For example, the relative viscosity of the magnetic fluids decreases from 3.33 to 1.45 as the surfactant concentration increases from 1.2 to 6.0%. As mentioned above, the superfluous activators will aggregate with each other and larger clusters may be formed inside the magnetic fluid. When an external magnetic field is applied, the movement of the particle ensembles occur based on the magnetic force. Obviously, the mobility of larger clusters is weaker than that of smaller clusters. The larger is the surfactant concentration, the weaker is the action effect of the magnetic force. Therefore, the relative viscosity of the magnetic fluid is reduced as the surfactant concentration is increased. It may be instructive to point out that a proper selection of the surfactant concentration is important for controlling the magneto-rheological properties of a magnetic fluid.

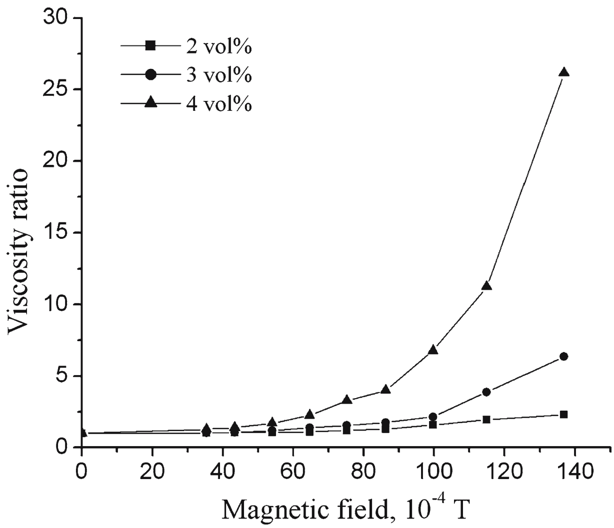

Fig. 7. Relative viscosity of the Fe–water magnetic fluid as a function of the perpendicular magnetic field strength at different particle volume fractions.

3.4. Effects of the Magnetic Field Direction

As mentioned above, some existing experimental data revealed a discrepancy about the effect of the external magnetic field orientation. The answer of whether the effect of a parallel or perpendicular magnetic field is larger is unknown based on experimental results from several investigations. In order to investigate further the effect of the magnetic field direction on the viscosity of a magnetic fluid, some measurements of the viscosity of the Fe–water magnetic fluid for both magnetic field orientations have been carried out. Figure 7 illustrates the relative viscosity of the Fe–water magnetic fluid corresponding to the perpendicular field. Comparisons between the experimental data shown in both Figs. 5 and 7 show that the relative viscosity of the Fe–water magnetic fluid in the perpendicular field is larger than that in the parallel field. For the Fe–water magnetic fluid with the same particle volume fraction (2%) and the same external magnetic field strength 132×10^{-4} T, for example, an increase of the viscosity of the Fe–water magnetic fluid in the parallel field is expected to be a factor of 1.08, but the increase of the viscosity of the Fe–water magnetic fluid in the perpendicular field is expected to be a factor of 2.31. These are consistent with the experimental results of Hamedani [6]. The reason may be that for the case where the magnetic field is applied perpendicular to the flow direction, the perpendicular chained alignment of the magnetic particles blocks the flow channel of the magnetic fluid and a higher drag against the flow of the magnetic fluid is experienced. But conflicting experimental results were obtained by some other investigators [4, 5]. Therefore, further research is needed.

4. CONCLUSIONS

The capillary tube viscometer is used to measure the viscosity of a magnetic fluid under an applied magnetic field. An experimental investigation has been carried out to analyze the effects of magnetic particle concentration, surfactant fraction, and the applied magnetic strength as well as the orientation of the magnetic field on the viscosity of the magnetic fluid. The experimental results have indicated that the viscosity of the magnetic fluids increases with an increase in the concentration of the suspended magnetic particles and the surfactant. The viscosity increases with an increase in the external magnetic field and will reach a constant as the magnetization of the sample fluid approaches a saturation state. For the same magnetic fluid and the same magnetic field strength, the viscosity in the perpendicular field is larger than that in the parallel field.

ACKNOWLEDGMENTS

This work is sponsored by the National Science Foundation of China (Grant No. 50436020).

REFERENCES

1. Stefan Odenbach, *Ferrofluids* (Springer, Berlin, 2002).
2. R. E. Rosensweig, *Ferrohydrodynamics* (Cambridge University Press, London, 1985).
3. K. Nakatsuka, B. Jeyadevan, S. Neveu, and H. Koganezawa, *J. Magn. Magn. Mater*. **252**:360 (2002).
4. John P. McTague, *J. Chem. Phys*. **51**:133 (1969).
5. W. F. Hall and S. N. Busenberg, *J. Chem. Phys.* **51**:137 (1969).
6. Hooshyar M. Hamedani and Lorin R. Davis, *Proc. Intersociety Energy Conversion Eng. Conf.*, ASME, New York (1988), pp. 359–364.
7. M. Timko, A. Zentko, M. Zentkova, M. Koneracka, and V. Kellnerova, *IEEE Trans. Magn*. **30**:1117 (1994).
8. T. Fujita, B. Jeyadevan, K. Yamaguchi, and H. Nishiyama, *Powder Technol.* **101**:279 (1999).
9. Rajesh Patel, R. V. Upadhyay, and R. V. Mehta, *J. Colloid Interface Sci*. **263**:661 (2003).
10. D. K. Wagh and Ashima Avashia, *J. Magn. Magn. Mater*. **153**:359 (1996).
11. Q. Li and Y. Xuan, in *Heat Transfer Science and Technology 2000*, B. X. Wang, ed. (Higher Education Press, Beijing, 2000), pp. 757–762.
12. D. J. Jeffrey and Andreas Acrivos, *AIChE J.* **22**:417(1976).