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Effect of Magnetized Ferro Fluids in Heat Exchanging- A Review

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Abstract- Ferro fluids are colloidal suspensions of magnetic nano particles stabilized by surfactants coating. Fe3O4 magnetic nanoparticles can be prepared by co-precipitation of Fe2+ and Fe3+ using ammonium hydroxide as precipitating agent. The particle size is around 10 nm. The size and ingredients of the particles are vital factors affecting the magnetic properties. Patterns can be obtained by magnetizing the ferro particles. Peaks or spikes are formed when ferrofluid is magnetized and this increases heat carrying capacity. When magnetic filed act on fluid increases beyond critical value, patterns appears in the form of squares, rolls or hexagons. The stability of ferrofluid when magnetized, depends upon magnetic permeability. The thermal conductivity of suspended ferro particles varies based on carrier liquid.

Keywords:Ferrofluid, magnetism, spikes, patterns, thermal conductivity .

I. INTRODUCTION

Ferrofluids are synthezised using colloidal mixtures of non magnetic carrier liquid generally water[1-4]. These fluids are stabilized by coating surfactants. The stability of fluid greatly depends on the balance between repulsive and attractive interactions among magnetic nano fluids. The size and content of the particles are important factors influencing the magnetic properties of the fluids[5-6]. Usually the particle size varies from 1 nm to 100 nm in diameter[7]. Different kinds of ferrofluids such as water based or organic compound based have been used abundantly in dynamic loud speakers, computer hardware, dynamic sealing, mechanical engineering, aerospace and bio engineering.

The particle content, magnetic saturation, suspension viscosity and surfactants for stabilizing the ferrofluid are important and dominate the process performances[9]. The normal field surface instability in magnetic fluids promotes rise to pattern formation. When the magnetic field applied to the surface of a magnetic fluid increases beyond critical value, the patterns will change in the form of rolls, squares or hexagons. The critical value of normal magnetic field for the appearance of rolls depends on the magnitude of horizontal component of the field as well as its orientation in the horizontal plane, whereas for the onset of squares and hexagons are independent of the orientation. The instability in pattern formation occurs when the strength of a uniform magnetic field applied perpendicularly to the flat interface between a ferrofluid pool and a non magnetic fluid (e.g. air) reaches a threshold, a critical value. If the ferrofluid pool is laterally unbounded, each patterned state of the ferrofluid / nonmagnetic fluid system bifurcates from the ' flat' state.[11-12]

The thermal conductivity of a suspension differs from the thermal conductivity of its carrier liquid due to high thermal conductivity of the colloidal particle fraction. In ferro fluids, the inter particle interaction has important impact on the fluid properties, since the magnetic dipole interaction forces active agglomeration of the particles, which can be regulated by applied magnetic fields. To avoid irreversible particle agglomeration due to van der Waals interaction in fluids, the magnetic particles are synthesized with a surfactant. Hence the particles are suspended colloidally and homogeneously in the liquid in absence of a magnetic field[15]. Strek and Jopek simulated heat transfer through a ferrofluid under the influence of magnetic dipole. Wrobel et al. studied thermo magnetic convective flow of paramagnetic fluid in an annular enclosure with a round rod core and a cylindrical outer wall numerically and experimentally. Their results show that magnetizing force affects the heat transfer rate and a strong magnetic field can control the magnetic convection of paramagnetic fluid[13-14].

II. CHARACTERIZATION OF FERRO FLUID

Research and development on the preparation, characterization and application of ferro fluids have been very active since the inception of ferrofluids in the mid 1960s [4]. Different types of ferro fluids such as water-based ferro fluids or organic compound based ferro fluids have been obtained and widely used in dynamic loudspeakers, computer hardware, dynamic sealing [16], electronic packing, mechanical engineering, aerospace, and bioengineering [17]. The application of aqueous ferrofluids is influenced greatly in biological and medical diagnosis and therapy, in pharmacy, and in biosensors[18-20]. According to a report in 2005 [21] that a new type of tilt inductive sensor using four magnets and a ferrofluid was invented to detect the tilt of a body against horizontal and vertical plane. Ferrofluids prepared by dispersing magnetic particles in silicone was proved to be useful as internal tamponades in eye surgery[22]. The particle content, saturation magnetization, suspension viscosity and surfactants for stabilizing the ferrofluids [23] are vital and dominate the process performances [24].

Sample no.	1	2	3	4	5	6	7	8
Oleate sodium (g)	2.00	3.00	4.00	5.00	3.00	3.00	3.00	4.00
PEG-4000 (g)	3.00	3.00	3.00	3.00	2.00	4.00	5.00	2.00
Solid content (g/ml)	0.048	0.106	0.200	0.068	0.042	0.052	0.056	0.040

Table:1 The amounts of oleate sodium and PEG-4000 during ordinary agitating

Among these parameters, rheological properties [25] are of crucial importance. In the present investigation, the oleate sodium and PEG-4000 were used as the primary and the secondary layers. Effect of their dosages on the solid content of ferrofluids was analyzed and found that the saturation magnetization and solid content of the ferrofluids prepared in the present investigation were much higher than those of Arkadiusz [26].

2.1. Preparation of Ferrofluid

Ferric chloride (FeCl36H2O), ferrous sulfate (FeSO47H2O), polyvinylalcohol (PVA) and ammonium hydroxide (NH4OH) used are all analytic grade. Oleate sodium and polyethylene glycol 4000 (PEG-4000) are chemical grade. De-ionized water was used throughout the experiments.

2.1.1. Ordinary agitating

The Fe3O4 precipitate was washed and 4.06 g MNPs was used to prepare each ferrofluid. De-ionized water of 60 ml was added to MNPs in a flask. To reduce aggregation of MNPs, the mixture was kept under ultrasonic vibration with a power of 120W and a frequency of 40 kHz for 1 h. The ferrofluids were then prepared by two - step additions of the primary and the secondary surfactants, respectively. The mixture of water and Fe3O4 particles stirred vigorously for 30 min under Ar protection, the solution was heated to 70°C, and then a solution of 25 ml oleate sodium was added to the mixture with slow agitation. The surface modification procedure was allowed to proceed for additional 30 min. The suspension was subsequently cooled slowly to 45° C with constant stirring. The PEG-4000 solution was then added to the suspension. Then, the mixture was kept at 45°C under vigorous stirring and Ar protection for 1hour. Then, it was cooled down to room temperature. Finally the mixture was centrifugated at 6000 rpm to remove large particles/aggregates and a stable ferrofluid was obtained. To study the influence of surfactant concentrations on the solid content, various dosages of oleate sodium and PEG-4000 were fitted together, as listed in Table 1. Oleate sodium and PEG-4000 were always dissolved in 25 ml and 10 ml de-ionized water, respectively. There were no other modifications throughout the preparation procedure. As shown in Table 1, Sample 3 with 4g oleate sodium and 3g PEG-4000 has the highest solid content of 0.200 g/ml.

Sample no.	9	10	11	12
Oleate sodium (g)	4.00	5.00	6.00	6.50
PEG-4000 (g)	3.00	3.75	4.50	4.90
Solid content (g/ml)	0.210	0.280	0.366	—

Table:2 The amounts of oleate sodium and PEG-4000 during ball milling

2.1.2. Ball milling

Based on the types and dosages of surfactants during the preparation by ordinary agitating, high solid content ferrofluids were prepared by ball milling. In this method, the synthesized Fe3O4 MNPs were collected by magnetic field separation and washed 4 times with de-ionized water. 4.06 g Fe3O4 MNPs, 4g oleate sodium powder and 10 ml water were added to the mill pot A and B, respectively, then 3 g PEG-4000 was added into pot A.

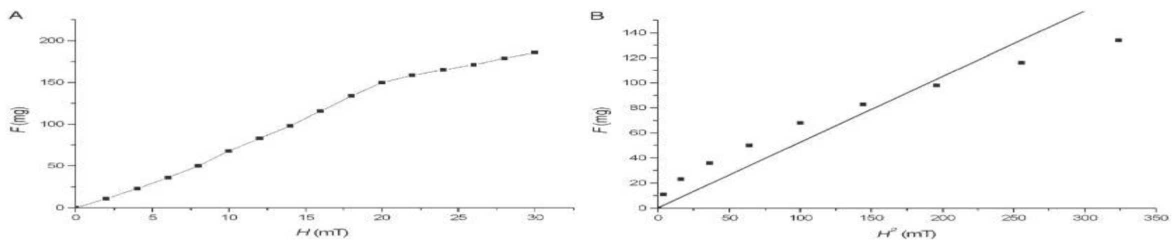
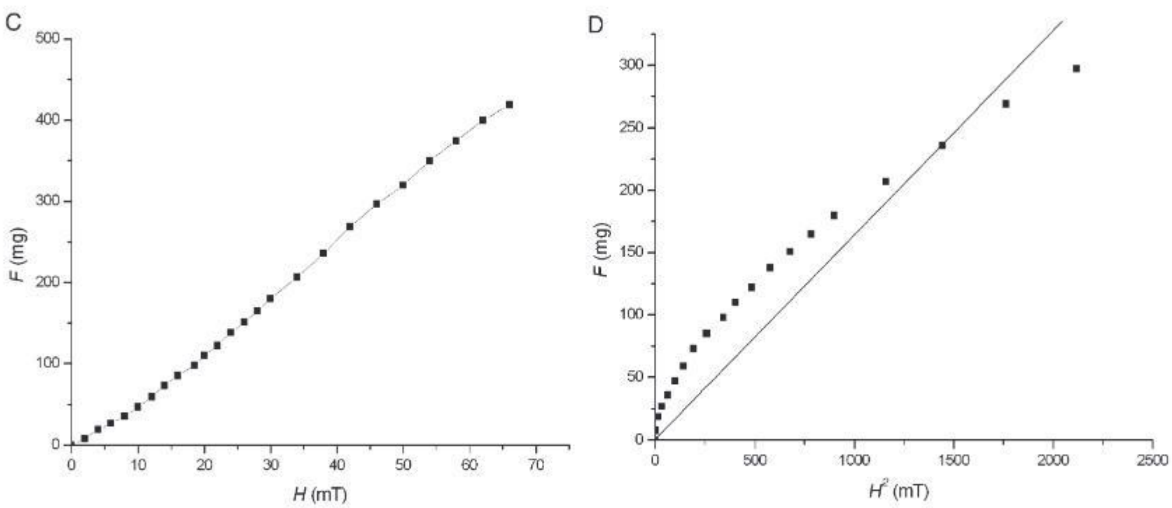


Figure:1 Relationship between magnetic weight and magnetic field intensity.

The mill pot and balls were made of carnelian and the volume of each pot was 50 ml. The milling operation was carried out in a QM-1SP4 planetary ball milling (Scientific Instrument Factory of Nanjing Univ., China) under Ar protection at room temperature for 1h. The milling speed was set at 40 rpm. Afterwards, 3g PEG-4000 was added to pot B, and the milling operation continued for another 30 min. The obtained mixture was centrifuged at 6000 rpm. It was found that the two solid contents were nearly the same whether PEG-4000 was added together with oleate sodium or not. Table 2 shows a series of oleate sodium and PEG-4000 with various dosages fitted together. For all the samples prepared by ball milling, PEG was added initially. According to the test results listed in Table 2, the highest solid content obtained was 0.366 g/ml of Sample 11, and ferrofluid cannot be obtained from Sample 12 because of the excessive surfactants. In the following analyses, Samples 3 and 11 were used. A series of measurements were carried out to characterize their properties [27].

2.2. Particle size and magnetic property of Ferro fluid

The size distribution of Fe3O4 MNPs dispersed in ferrofluids is shown in Fig. 2. The value of d (0.98)num of Sample 3 indicates that the median size of 98% Fe3O4 particles in volume is 48.4 nm, while d (0.99)num of Sample 11 is 31.8 nm. The size reduction is probably related to the existence of the carrier phase that tends to homogenize the spatial distribution of the granular solid at the initial stage of ball milling. This homogenization in turn allows a more homogeneous collision rate between particles and balls within the milling pots [18]. However, the core size of MNPs calculated from XRD data was about 10nm,smaller than that measured by the laser particle-size analyzer. This result may be explained that the MNPs in ferrofluid tend to aggregate to reduce their huge surface energy since the nanoparticles have large specific surface areas (ratio of surface area to volume). The magnetic dipole attractions among MNPs also enhanced the trend of aggregation, which could not be prevented completely only by coating surfactants on the particle surface.



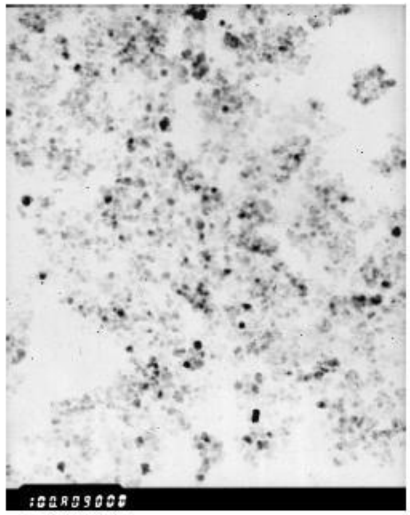


Figure:2 TEM micrograph of bilayer-stabilized ferrofluids

For the ferrofluids prepared by surface coating, the relationship between magnetic weight and applied magnetic field was shown in Fig. 1(A) and (B). The saturation magnetization of Sample 3, was 2.27 x 104 A/m, and the susceptibility 4.93x10 6 calculated using the method presented in the literature [19]. The weight concentration and solid content of Sample 3 were 18.7% and 0.200 g/ml, respectively. For the ferrofluids prepared by ball milling, the same measurements were carried out for Sample 11, as shown in Fig. 1(C) and (D). The saturation magnetization and susceptibility were 1.44x105 A/m and 2.1106, respectively. It is noted that these values are about twenty times higher than those reported in the literature [15]. The solid weight fraction (SWF) and solid content were 37.3% and 0.366 g/ml, respectively. Compared with the ferrofluids prepared by ordinary agitating, the solid content of ferrofluids prepared by ball milling was greatly improved. It is concluded that the saturation magnetization of FFs increases with the increase of solid content [27].

2.3. Stability of Ferro fluid

The absorbance of ferrofluids was found to be steady after sedimentation for 60 days. As the bilayer stabilized ferrofluid was proved to have excellent stability under gravity. The sedimentation velocity of the particles/aggregates in ferrofluid (Sample 11) was about 6.0 mm/month obtained from Stokes law: v = (1-2)gd2/(18), where 1 is the density of solid particles (5.18 g/cm3), 2 is density of carrier fluid (0.998 g/ml), g is the gravitational acceleration (9.81 m/s2),d is the diameter of aggregates and is the viscosity of the carrier fluid (1.00 mPa s). The prepared ferrofluids displayed almost no observable precipitation by naked eyes and exhibited excellent stability over a period of 60 days as evidenced by the UV-vis measurements. An explanation for this result was that PEG-4000 not only acted as an outer secondary surfactant shell but also enhanced the viscosity of the carrierfluid, which led to a notable reduction of sedimentation velocity. The thermal movement of nano particles in ferrofluids also reduced the sedimentation. Moreover, the density of aggregates is much less than that of the magnetite particles. That is to say, the above Stokes equation over-predicted sedimentation rate of aggregates. It is very important to prepare ferrofluids, which are still stable after being diluted. For example, some kinds of ferrofluids could be used as improved MRI diagnostic contrast agents. After being injected into the human vein, the ferrofluid will be quickly diluted by body liquid, hence the dilution-stability of ferrofluids should be examined.

III. PATTERN FORMATION OF MAGNETIZED FERROFLUIDS

The free surface of a laterally unbounded ferrofluid pool at rest is a two-dimensional isotropic system. Moreover, the equations that govern magnetohydrostatic equilibria of the free surface of an unbounded ferrofluid pool[11]admit a simple solution at all values of applied magnetic field strength. This solution consists of a perfectly at interface and a magnetostatic potential that varies linearly in the direction of the applied magnetic field. Such a simple solution is called the flat or base solution. The experimental evidence reveals [10-11] that the flat solution turns unstable to patterned disturbances of interface shape at the onset of the normal field instability, i.e. when the applied field strength passes a critical value. Patterned states of the ferrofluid interface hexagonal patterns or square patterns or axisymmetric (ring-like) patterns [12] multifurcate from the base state and replace it at the onset of the normal field

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instability. The most striking difference between patterned solutions and the at solution is that the latter is invariant under plane rotations and translations, whereas each of the former is invariant under a smaller group of the Euclidean group of plane symmetries. For example, ring-like patterns are invariant under the group of plane rotations alone; hexagonal patterns are invariant under the group of symmetries of the hexagon, i.e. the plane transformations that bring a hexagon into self coincidence. It is noteworthy that the governing equations are themselves invariant under the entire Euclidean group of plane symmetries. Therefore. what happens in the normal field instability is another manifestation of the phenomenon known as 'symmetry breaking' or symmetry reduction. The determination of all multifurcating regularly patterned states is most efficiently done by joining group theoretical methods and bifurcation analysis. With these methods it is possible to construct solutions of the governing equations linearized around the base solution so that each 'carries the symmetry' of a certain regular pattern: that is, each solution is left invariant by symmetry operations that leave a certain pattern invariant. These solutions are described in terms of so-called "symmetry-adapted" or "planform" functions. In two-dimensional isotropic systems the only translationally in-variant patterns that can be admitted are hexagonal, triangular and square patterns. which are all two-dimensional, and roll patterns, which are one-dimensional [30]. Other admissible patterns are ring patterns, which are invariant under any plane rotation about their center, and segmented ring patterns, which are invariant under discrete rotations about their center. The planform functions are as follow (a parameter k appears in each function and is the wave number of the corresponding pattern: x and y are Cartesian coordinates, r is the radial coordinate and is the azimuthal coordinate). Hexagonal patterns:

p p

'= cos (kx) + cos [(k/2)(x+ 3y)]+ cos [(k/2)(x- 3y)].

Triangular patterns:

'= sin (kx) + sin [(k/2)(x+p 3y)]+ sin [(k/2)(x-p 3y)].

Square patterns:

'= cos [(k/p2)(x+y)]+ cos [(k/p 2)(x-y)].

Roll patterns:

'= cos (kx).

Ring patterns

'= J0(kr).

where J0 is the 0th order Bessel function.

Segmented ring patterns:

'= Jm(kr) cos (m) or '= Jm(kr) sin (m).

where Jm is the mth order Bessel function.

IV. THERMODYNAMICS OF THERMAL CONDUCTIVITY MEASUREMENTS

Heat conduction in homogeneous media is described by Fouriers law (Eq.1). Here in thermal conductivity, k occurs as a linear coefficient connecting heat flux

$$\vec{q} = -k\,\mathbf{grad}T \tag{1}$$

To measure thermal conductivity, either the heat flux or the temperature gradient, must be given as a boundary condition and the other has to be measured to calculate thermal conductivity. The temporal and spatial temperature distribution for heat conduction is de-scribed by Fourier's differential equation of temperature distribution. For homogeneous and isotropic media it can be written as:

$$\frac{\partial T(\vec{x},t)}{\partial t} = \frac{k}{\rho c_p}\mathbf{div}(\mathbf{grad}T) \tag{2}$$

where is the density and cp is the specific heat capacity of the medium. Although ferrofluids are inhomogeneous at a mesoscopic scale, they show homogeneous material properties from a macroscopic point of view. For the geometry of a certain measuring device, a specific temperature distribution equation has to be derived from Eqs. (1) and (2) to calculate the thermal conductivity k directly. In practice, two common geometries are used for thermal conductivity measurement devices, a line heat source or a plane heat source. A line heat source is applied in the hot wire technique. It is widely used for liquid specimens. In the most current designs, a thin wire with a diameter between 10 -5 and 10 -4 m is heated

electrically, inducing a radial heat flux through the fluid. Depending on the fluid's thermal conductivity, a characteristic temperature distribution arises within the sample that also affects the wire itself. According to the temperature-dependent ohmic resistance of the wire, the temperature is obtained by measuring the electrical resistance of the wire. The advantage of this technique is that boundary effects can be reduced easily with a large length-to diameter ratio. Main disadvantages are that no parallel alignment of heat flux and magnetic field is possible (Fig. 4a), and that surface effects would be over-represented because the measurement is taken over a very short distance.

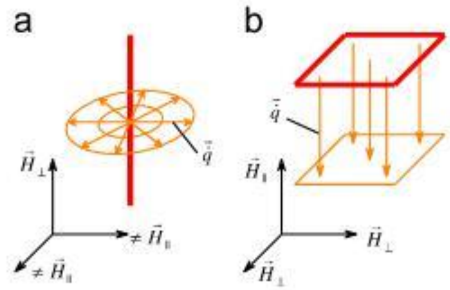

Figure:4 Orientation of heat flux and magnetic field to each other (a) an idealized line heat source and (b) an idealized plane heat source.

Although the hot wire technique is not suitable for anisotropic measurements, it was used for all reported investigations, as far as stated. To align the heat flux and magnetic field parallel to one another, a plane heat source is used here for the hot plate technique. Usually this technique is applied to solid body measurements, for which the specimen is positioned in between two plates. The upper plate is heated, and the lower plate maps the temperature increase. The hot plate technique is characterized by an idealized linear heat flux. So both a parallel and a perpendicular arrangement of heat flux and magnetic field are possible. This is sketched in Fig. 4b. Furthermore the temperature information is obtained over a certain distance x , so potential surface effects between the liquid and the hot plate do not significantly impact on the data [29].

V. CONCLUSION

Ferrofluids posses more heat carrying capacity than conventional fluids used in heat exchangers. Heat carrying property of ferrofluid increases by magnetisation upto a particular magnetic intensity. Beyond that bifurcation takes place and obstruction in flow is observed. The stability of ferrofluids depends upon the balance between repulsive and attractive interactions among magnetic nano fluids. Magnetic particles are to be synthesized with a surfactant to avoid irreversible particle agglomeration due to Vander Wall's interaction of fluids. The main difference between the patterned solution and the at solution is that the at solution is invariant under plane rotations and translational, where as each of the patterned solution is invariant under small group of Euclidean group of plane symmetries. Thermal conductivity of fluid can be measured by giving a boundary condition to either the heat flux or the temperature gradient and the other has to be measured to calculate thermal conductivity.

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