ARTICLE IN PRESS

Journal of Magnetism and Magnetic Materials xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Magnetic fluid bridge in a non-uniform magnetic field

D.A. Pelevina*, V.A. Naletova, V.A. Turkov

Lomonosov Moscow State University, Leninskiye gory, Moscow 119991, Russia

ARTICLE INFO

Keywords:
Magnetic fluid
Fluid free surface
Non-uniform magnetic field
Magnetic fluid bridge

ABSTRACT

The shape of a magnetic fluid bridge between a horizontal ferrite rod of circular cross-section and a horizontal plate above the rod in a vertical applied uniform magnetic field is studied. Various static shapes of the bridges are obtained theoretically and experimentally for the same magnetic field value. Abrupt changes and the hysteresis of the bridge shape in alternating magnetic fields are observed experimentally.

1. Introduction

A magnetic fluid (MF) is a colloidal solution of nano-size ferromagnetic particles in a nonmagnetic carrier fluid. The non-uniform magnetic field can change the MF surface shape and move the MF volume. This property of the MF is used in the design of technical devices. MF bridges and valves are investigated in several studies. In [1] the breaking process of the MF bridge between poles of an electromagnet and formation of a small droplet during this process are studied experimentally. The surface shape of the MF between coaxial cylinders with a line conductor is investigated theoretically in [2]. In [3] theoretical study of a MF volume between two horizontal planes in the magnetic field of a line conductor located on the upper plane is made. Various ways to create pistons and valves in narrow channels filled with liquid using a MF are proposed in [4].

In this paper the possibility to create a MF bridge between a horizontal ferrite rod of circular cross-section and a horizontal plate above the rod in a uniform vertical applied magnetic field is investigated experimentally and theoretically.

2. Experiment

Water-based MF with magnetite nano-size particles and transformer oil are chosen for the experiment. The properties of the fluids are the following: the MF initial susceptibility $\chi_0 = 0.14$, the MF saturation magnetization $M_{fs} = 5.218$ kA/m, the MF density $\rho_f = 1410$ kg/m^3, the oil density $\rho_s = 960$ kg/m^3, the surface tension between MF–oil $\sigma = 0.2$ N/m. In the experiment different MF volumes V_f and a fixed oil volume V_s=0.8 cm^3 are investigated. Fluids are placed in a rectangular plexiglas vessel (the length $L = 2R_V = 4.5$ cm, the depth $\delta_V = 0.5$ cm). The horizontal ferrite rod of circular cross-section with the radius $R_b = 0.4$ cm is placed in the center on the bottom of the vessel. The horizontal plate is located above the rod (the distance between the rod and the plate d=4 mm). The rod is sufficiently long to avoid magnetic end effects. The uniform vertical applied magnetic field $\mathbf{H}_\infty$ is created by a pair of Helmholtz electromagnetic coils, see Fig. 1. The current in the coils is controlled by the LabView virtual instrument. The coils can create the magnetic field up to 37.2 kA/m. The permanent and alternating vertical magnetic fields are considered.

Experimental results in a permanent magnetic field. Various stable MF shapes consisting of one, two or three volumes in a permanent magnetic field are observed. At certain values of the magnetic field, the MF can bridge the gap between the rod and the plate. There are various shapes of the MF bridge for the same magnetic field value, e.g. for V=1.7 cm^3 and $H_\infty = 27.8$ kA/m MF shapes are shown in Fig. 2. The dependencies of the minimal bridge volume on the applied magnetic field value for different types of bridges forms are measured experimentally, see Figs. 5, 7 and 9. The existence of different static shapes can cause the MF shape hysteresis in alternating magnetic fields.

Experimental results in an alternating magnetic field. The stepwise alternating vertical applied magnetic field is considered: the magnetic field is constant during 20 s, then the field is changed by ΔH A/m, so the field increases from 0 to 35.8–36.6 kA/m, then the magnetic field decreases in the same way to 0. The value of ΔH is varied in experiments. When $H_\infty = 0$, the initial MF shape is symmetric with respect to the axis z. In these experiments for the small enough MF volume ($V \leq 1.6$ cm^3) the MF bridge does not exist for any field. In the increasing magnetic field, the MF with a sufficiently large volume ($V > 1.6$ cm^3) rises above the rod and can lock the gap between the rod and the plate. The MF can abruptly change its shape in an alternating magnetic field (the number of MF volumes changes). The bridge appears at some value of the increasing magnetic field and disappears at another smaller magnetic field value when the magnetic field decreases. For example, for $\Delta H = 1.6$ kA/m the bridge appears at

* Corresponding author.
E-mail address: pelevina.daria@gmail.com (D.A. Pelevina).

http://dx.doi.org/10.1016/j.jmmm.2016.09.059
Received 27 June 2016; Accepted 11 September 2016
Available online xxxx

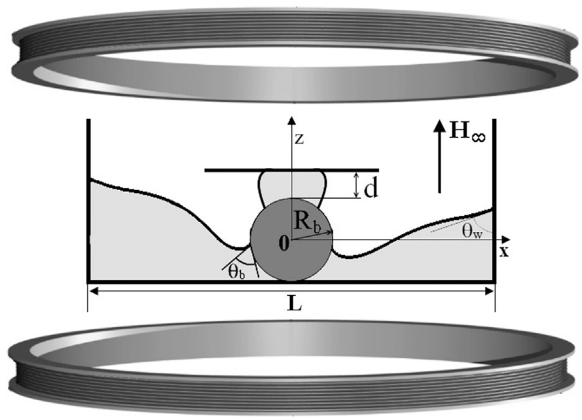

Fig. 1. The experimental setup scheme.

$H_\infty = 25.5$ kA/m and disappears at $H_\infty = 22.3$ kA/m. Thus, the hysteresis is observed, the MF shape in increasing magnetic field differs from the MF shape at the same value of decreasing field, see Fig. 3.

3. Theory

Hereinafter the parameters related to the rod, the MF and the oil are marked by b, f and s, respectively. The pressure p_s in the oil is constant. The magnetization of the oil is zero, M_s=0. The MF magnetization M_f depends on the magnetic field by the Langevin law: $M_f = M_{fs} L(\xi)$, where $L(\xi) = \coth(\xi) - 1/\xi$, $\xi = mH/kT$. Here T is the MF temperature, and k is the Boltzmann constant, m is the magnetic moment of the ferromagnetic particle. The magnetization of the ferrite depends linearly on the magnetic field intensity $M_b = \chi_b H$, where $\chi_b = \text{const}$. We assume that the magnetization of the body material is much higher than the fluid magnetization $M_b \gg M_f$. The absolute value of the magnetic field H in the non-inductive approximation, when $H \gg 4\pi M_f$, can be calculated as follows [5] ($A = -R_b^2$): $H = |\nabla\varphi|$, $\varphi = H_\infty z + AH_\infty z/(x^2 + z^2)$.

The fluid static equation and the dynamic boundary condition at $z = h(x)$ in the non-inductive approximation are the following ($[A]_f^s = A_s - A_f$):

$$-\nabla p_j + M_j \nabla H_j + \rho_j \mathbf{g} = 0 \quad j = f,\, s,\, z = h(x){:}\;\; [-p]_f^s = \pm 2\sigma K. \tag{1}$$

Here $K = h''/(1 + h'^2)^{3/2}$ is the mean curvature. Using (1), we obtain the following equation at the MF surface $z = h(x)$ (C=*const*):

$$C + (\rho_s - \rho_f)gh + P(H) = \pm 2\sigma K, \quad P = \int_0^H M_f(H)dH,$$
$$H = H(x,\, h). \tag{2}$$

Taking into account the expression for the mean curvature, the Eq. (2) is a nonlinear second order differential equation for h. The boundary conditions are the following: on the vessel walls and on the rod the wetting angles θ_w and θ_b are given (for the experiment $\theta_w = 132.5°$, $\theta_b = 142.2°$). The volume V_f of the MF is constant. Various numerical solutions of this equation will be further obtained.

4. Comparison of theoretical and experimental results

The calculations are made for the parameters, corresponding to the experiment with the permanent magnetic field. The MF volume can consist of one, two or three volumes (with a droplet), depending on the MF amount and the magnetic field. Various stable MF shapes of a fixed volume for fixed magnetic field are found numerically (see Fig. 2 theory). From Fig. 2 we can see that experimental and theoretical results coincide with each other.

For permanent magnetic field up to 35.8 kA/m, minimal bridge volumes are found for the following cases: the case 1 — symmetric volume, connecting the vessel bottom and the plate (see Fig. 4); the case 2 — asymmetrical volume, connecting the vessel bottom and the plate (see Fig. 6); the case 3 — the MF droplet on the rod (see Fig. 8). The dependencies of the minimal bridge volume on the applied magnetic field are shown in Figs. 5, 7 and 9. It was found that the bridge in case 1 cannot be formed for any magnetic field if $V < 1.5$ cm^3. Also the bridge in case 2 cannot be formed for any magnetic field if $V \leq 0.7$ cm^3. It was obtained that the bridge in the case 3 cannot be formed for the applied magnetic field $H_\infty < 11.9$ kA/m. In Figs. 5, 7 and 9 a good agreement of theoretical and experimental results is observed.

5. Conclusion

The shape of a magnetic fluid bridge between a horizontal ferrite rod of circular cross-section and a horizontal plate above the rod in a vertical applied permanent uniform magnetic field is studied experimentally and theoretically. It was found experimentally and theoretically that the MF bridge can have different shapes: symmetrical or asymmetrical volume, connecting the vessel bottom and the plate, and the droplet on the rod at the same applied magnetic field. For different MF bridge shapes the dependencies of the minimal bridge volume on the value of the applied magnetic field are found experimentally and theoretically. A good agreement between experimental and theoretical results is obtained. Abrupt changes and the hysteresis of the MF shape

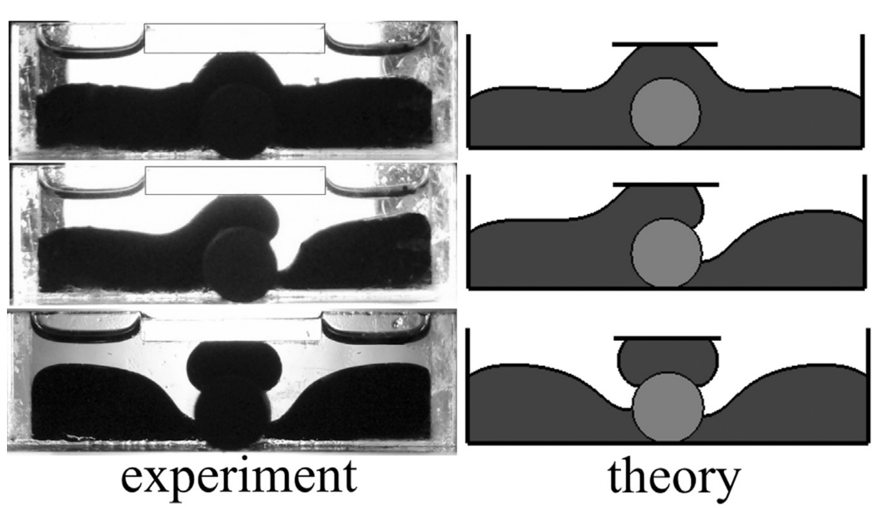

Fig. 2. Various shapes of the MF bridge (V=1.7 cm^3) for $H_\infty = 27.8$ kA/m.