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Topological instability of a semi-bounded magnetic fluid drop under influence of magnetic and ultrasound fields

V. Bashtovoi[a,*], A. Reks[a], A. Baev[b], Al-Jhaish Taha Malik Mansoor[a]

[a] Belarussian National Technical University, 65 Nezavisimosti Ave., Minsk 220013, Belarus
[b] Institute of Applied Physics of NAS of Belarus, 16 Akademicheskaya str., Minsk 220072, Belarus

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ABSTRACT

Theoretical and experimental results on deformation and disintegration on parts (topological instability) of semi-bounded magnetic fluid drop placed on horizontal plate in the presence of gravity and vertical external uniform magnetic field, and the influence of acoustic wave on these processes, as well as an experimental results of acoustic fountain on free surface of magnetic fluid are presented. The role of individual mechanisms leading to disintegration is analyzed, and analytical relationships and experimental dependences for critical parameters are established.

1. Introduction

Interest to investigation of behaviour of a magnetic fluid drop in magnetic and acoustic fields [1–4] is caused, in particular, by existing proposals on their practical use in such technical devices as a guided acoustic contact in systems of ultrasonic non-destructive test [5], and also for creation of thermal and electric contacts [6,7]. Besides, such drop finds out also a number of such interesting from the scientific point of view features as its lengthening along a direction of a uniform magnetic field [8] and topological instability appearing as a destruction of initial volume of a fluid and its disintegration on separate parts [9–11].

2. Theory

2.1. Deformation of drop

First of all is of interest to establish the analytical relations describing process of deformation of a drop under the influence of magnetic, gravitational and acoustic fields. In this connection the semibounded drop of magnetic fluid placed on a horizontal plane surface is considered.

Uniform magnetic field H and gravity acceleration g are directed perpendicularly to a surface as it is represented on Fig. 1. An acoustic wave I enters into a drop in vertical direction and creates pressure p_{ac} on its basis. It is supposed that the drop has the form of semi-ellipsoid of revolution with the large semi-axis h and small semi-axis R. The wetting angle of a drop with a solid surface is supposed equal 90°. The magnetic field in a drop is supposed, as well as the external field, uniform.

Capillary pressure jump, as well as the magnetic pressure jump determined by a square of normal to a surface component of fluid magnetisation M_n take place at each point on a drop free surface.

Following [12], equilibrium of a drop is determined by a balance of pressure at the top point h and bottom lateral point R:

$$\sigma\left(\frac{1}{R_1^h}+\frac{1}{R_2^h}\right)-\sigma\left(\frac{1}{R_1^R}+\frac{1}{R_2^R}\right)+\rho gh-\frac{1}{2}\mu_0 M^2-p_{ac}=0. \tag{1}$$

where σ is the surface tension coefficient, R_1 и R_2 are the main radii of surface curvature at corresponding points, M=$M(H)$ is the fluid magnetization, μ_0 is the magnetic susceptibility of vacuum.

In top h a magnetic field is perpendicular to the drop surface and M_n=M, and at bottom point R a field is tangential to the surface and M_n=0.

Using well-known relationships between geometrical parameters of ellipsoid it is possible to get from (1)

$$\sigma\left(\frac{2h}{R^2}-\frac{R}{h^2}-\frac{1}{R}\right)+\rho gh-\frac{1}{2}\mu_0 M^2-p_{ac}=0. \tag{2}$$

At a large lengthening of a drop when $(h/R)>>1$ relationship (2) gives

$$\sigma\frac{2h}{R^2}+\rho gh-\frac{1}{2}\mu_0 M^2-p_{ac}=0. \tag{3}$$

Since in the process of drop deformation its volume V remains constant it is possible to take as the characteristic dimension R_0 a

* Corresponding author.
E-mail address: bashv@rambler.ru (V. Bashtovoi).

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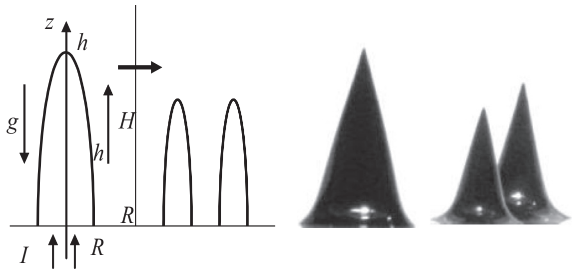

Fig. 1. Scheme and picture of drop deformation and topological instability.

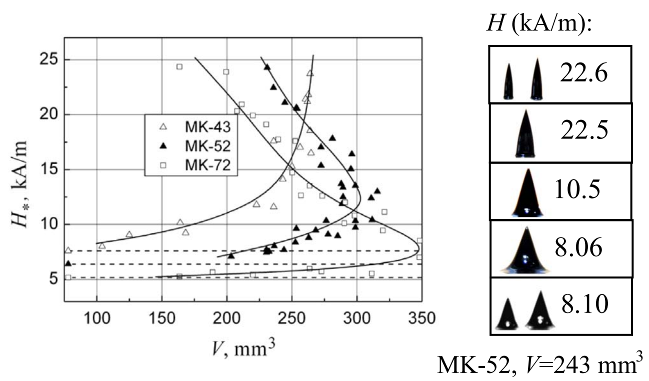

Fig. 2. Neutral curves of stability of magnetic fluid drops with different magnetization of saturation.

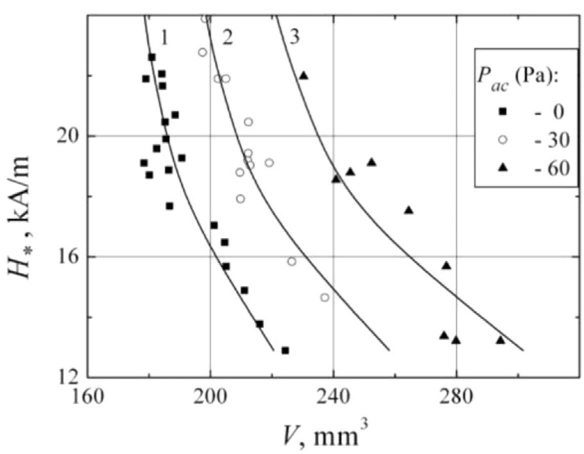

Fig. 3. Neutral curves of stability of magnetic fluid drop under influence of ultrasound with frequency 1 MHz.

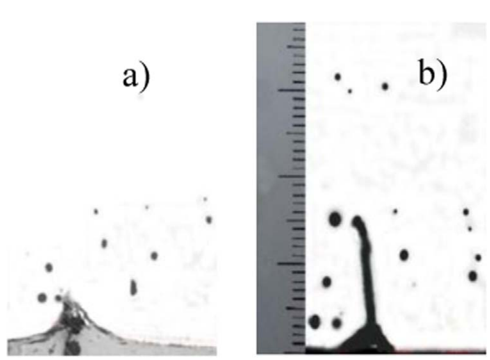

Fig. 4. Ultrasound fountain on magnetic fluid: (a) no magnetic field, (b) in vertical magnetic field.

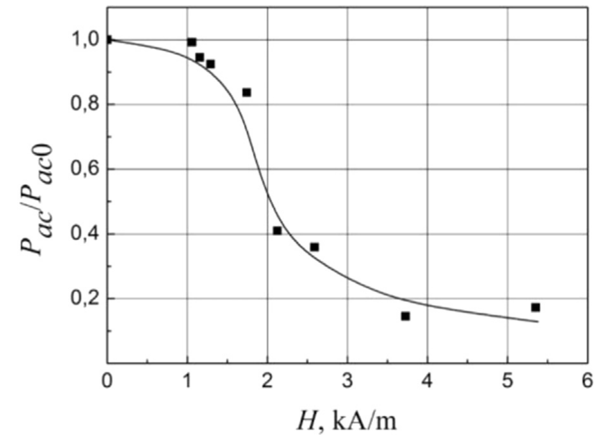

Fig. 5. Dependence of critical ultrasound pressure for begining of fountain on vertical magnetic field intensity for magnetic fluid MK-72.

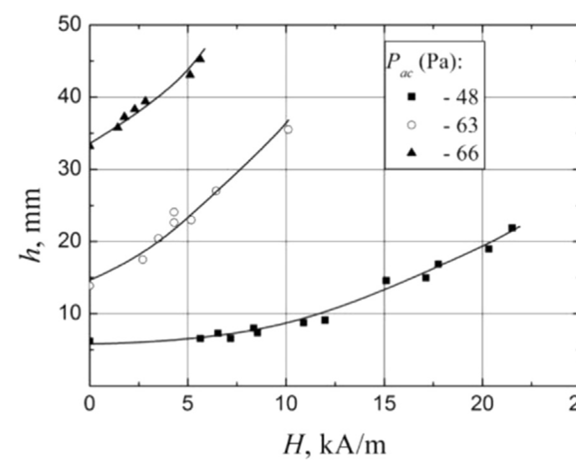

Fig. 6. Dependence of jet height on vertical magnetic field intensity for magnetic fluid MK-72 at different ultrasound intensity.

radius of a hemispherical drop of the same volume. Then $V = (2/3)\pi R_0^3$, $hR^2 = R_0^3$, and the following quadratic equation for the large semi-axis of a drop turns out from (3):

$$h^2 + \frac{\rho g R_0^3}{2\sigma}h - \frac{\mu_0 M^2 R_0^3}{4\sigma} - \frac{P_{зв} R_0^3}{2\sigma} = 0,$$

which has a solution

$$\frac{h}{R_0} = -\frac{\rho g R_0^2}{4\sigma} + \sqrt{\left(\frac{\rho g R_0^2}{4\sigma}\right)^2 + \frac{\mu_0 M^2 R_0}{4\sigma} + \frac{P_{зв} R_0}{2\sigma}}. \tag{4}$$

This expression can be written with use of known dimensionless criteria [8]: magnetic criterion $S=\mu_0 M^2 R_0/\sigma$, Bond number $Bo=\rho g R_0^2/\sigma$, and also acoustic criterion $Ac=p_{ac}R_0/\sigma$, representing the relation of sound pressure to capillary one

$$\frac{a}{R_0} = -\frac{Bo}{4} + \sqrt{\frac{Bo^2}{16} + \frac{S}{4} + \frac{Ac}{2}}. \tag{5}$$

It is seen from this expression that the acoustic field described by criterion Ac facilitates drop lengthening, increasing its height h at constant values of other parametres.

2.2. Topological instability of a drop

From the energy balance point of view topological instability of drop, leading to its disintegration on two drops, is caused by that at certain values of fields acting on the drop a total energy of two drops becomes less than energy of the initial single drop and this state is