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THE INFLUENCE OF MAGNETIC FIELD ON FREE SURFACE FERROFLUID FLOW

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This paper experimentally investigates the influence of magnetic field on the breakup of ferrofluid flow. In dripping regime, with increasing parallel magnetic field strength, the drop elongation coefficient increases, while the drop volume decreases. The simple quasi static model is suggested for interpretation of decrease of the droplets volume. The shape is discussed using theory based on minimizing the sum of surface and magnetic energy of ellipsoidal drop. At a little bit larger velocity at the nozzle, applying magnetic field induces dripping to jetting transition, while in jetting regime significantly smaller drops arise.

1. Introduction. Problems of breakup of liquid jet and formation of droplets are very fundamental topics in the field of fluid dynamics and they play a role in many industrial processes: fuel injection, fibre spinning, ink-jet printing, etc. [1,2]. However, there are less studies devoted to these attractive phenomena in magnetic fluids (MF) exposed to the external magnetic field [3-6]. The accepted mechanism of jet breakup involves flow from regions of the liquid column with smaller radii, where Laplace pressure is larger; to crest regions with lower pressure, until pinch-off occurs. For the flow of MF a new parameter emerges: magnetic pressure acting on the boundary of ferrofluid and air [3]. In [4] the influence of magnetic field on the intact jet length was studied. The main concern of this paper is the shape and volume of arising drops.

2. Experimental. In our experiments we observed ferrofluid leaving a cylindrical nozzle of 2 mm in diameter at the bottom of a cylindrical syringe with diameter of 21 mm filled up to the height of 65 mm above the nozzle (Fig.1). The MF used in this experiment was oil-based ferrofluid with these characteristics: density $\rho = 1.56\text{x}10^3$ kg/m^3, surface tension $\sigma \sim 0.45\sigma_0$, where σ_0 is surface tension of water, viscosity η = 60 mPa/s and magnetization 360 Gauss at magnetic field 27 mT.

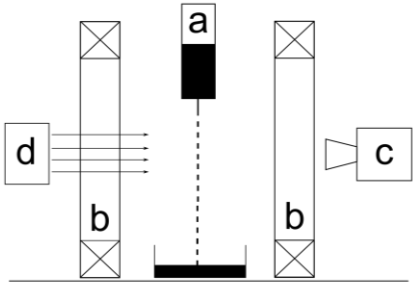

Fig.1. Schematic diagram of the experimental apparatus. a- syrringe with ferrofluid, b- Helmholtz coils, c- high-speed camera, d- stroboscope

The entire experiment was recorded by high-speed camera with frame rate 1200fps.

3. Results and discussion. We can recognize two regimes of flowing in dependence on fluid velocity: dripping and jetting regimes

[1,2]. In our experiment, the velocity at which fluid is released from the nozzle is driven by the amount of ferrofluid above the nozzle and decreases continuously over time. In dripping regime, fluid is released very slowly from the nozzle, so that at first surface tension forces are in balance with the gravitational and surface magnetic force. Instability will set in as the drop becomes heavier and the gravity combined with surface magnetic force overcomes the surface tension.

High-speed image sequences in dripping regime in zero magnetic field and in magnetic field parallel and perpendicular to the jet are depicted in Fig.2.

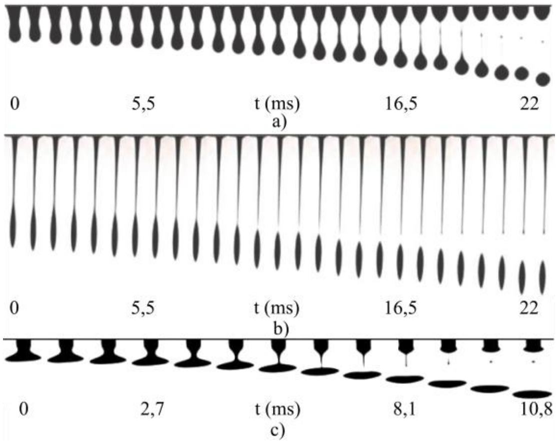

Fig.2. High-speed sequences in dripping regime a) without magnetic field; b) parallel magnetic field of 27 mT; c) perpendicular magnetic field of 13 mT.

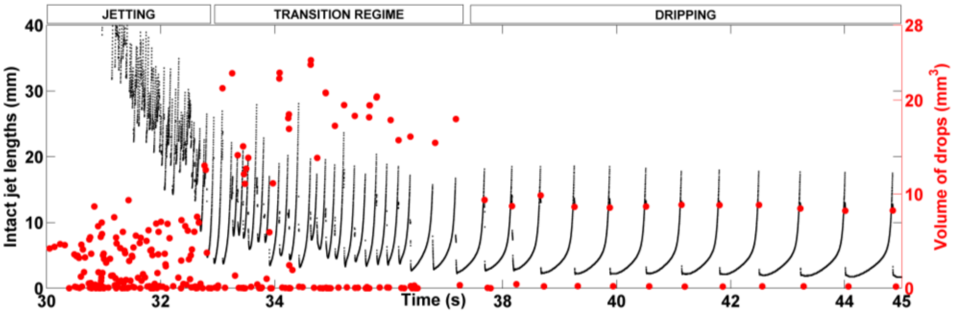

Fig. 3. Intact lengths and volumes of drops vs. time in parallel 10mT magnetic field.

The dynamics of drop formation process could be manifested in the time evolution of intact jet length *l*. For parallel magnetic field of 10mT it is depicted in Fig.3. We can notice clearly distinguished jetting where *l* rapidly oscillates around mean value due to the jet breakup governed by capillary instability known as Rayleigh regime [1] and dripping regime where droplet falling from the nozzle creates an elongated neck, which finally breaks up and the main drop is separated. From retractig neck the small satelite drop is formed. In transition region the both mechanisms play the role.

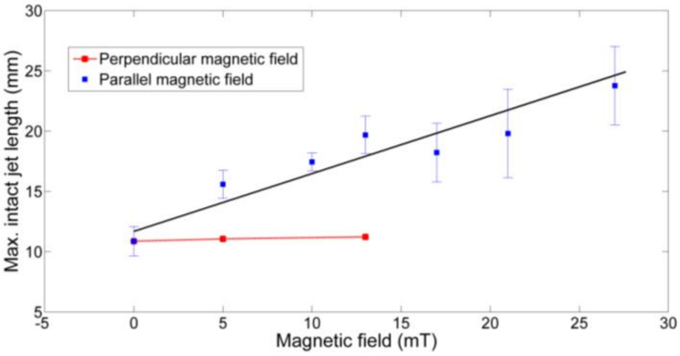

Fig. 4. Dependence of peak neck length on magnetic field in dripping regime.

In the dripping regime magnetic field influences the process of drop formation and drop shape. Increasing the parallel magnetic field strength we observe longer neck and drop separation at a larger distance from the nozzle than in the case without a magnetic field (Fig.2,4). This resembles the behaviour of fluids with increasing viscosity [1,2]. In a perpendicular magnetic field we do not observe similar tendency. There is a neck with the maximum intact length *l* almost independent on the magnetic field strength.

A large part of our results is devoted to analysis of volumes and shapes of drops. As it was mentioned, the magnetic field causes elongation of the drop in the direction of magnetic field due to the magnetic pressure acting on its surface [3].

In the dripping regime there are two types of drops– main and satellite ones [1,2] with different volumes that can be clearly distinguished in Fig.3. Between dripping and jetting regimes there is also a transition region (Fig.3) in which drops larger than the main drops in subsequent dripping regime may appear. In the jetting regime the size of drops is smaller and a frequency of drop formation is large.

The mean volume of main drops in dripping regime as a function of parallel magnetic field is in Fig.5. The solid line in Fig.5 represents theoretical prediction in the frame of a simple quasi-static model, where surface tension force $F_\sigma = 2\pi r_1 \sigma$ (r_1 is jet radius) is in a quasi-static balance with gravity force $F_g = V.\rho.g$ (V is volume of a drop, and g is gravitational acceleration) and magnetic force $F_m = S.p_m = \pi.b^2.\mu_0\chi^2 H^2/2$ (p_m is magnetic pressure acting on the boundary of ferrofluid and air for the case of nonzero normal component of magnetization at the surface, S is mean surface area on which magnetic pressure acts, χ is magnetic susceptibility and $H = B/\mu_0$ is magnetic field strength).

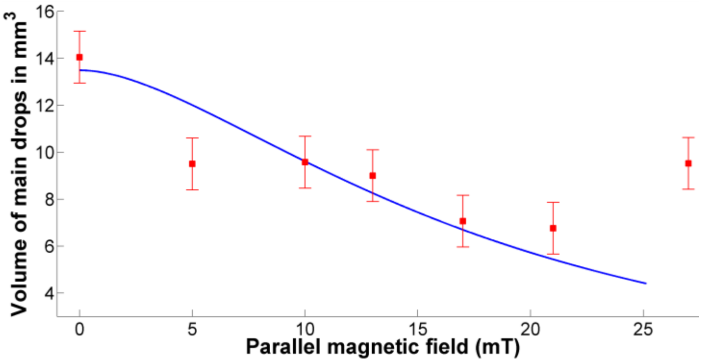

Fig. 5. Mean volume of the main drop as a function of parallel magnetic field.

The decrease of volume of detached drop while increasing the magnetic field induced by larger magnetic pressure acting on the boundary of ferrofluid and air is in a good agreement with our measurements except for the volume at the largest field strength. However for this value of magnetic field rotational ellipsoid may not be valuable approximation of a drop shape [6]. In perpendicular magnetic field, the volume of main drop increases with increasing strength of the magnetic field. It is consistent with approximately two times larger radius on which the drop is connected with the rest of fluid in the perpendicular field compared to the parallel field case (Fig.2).

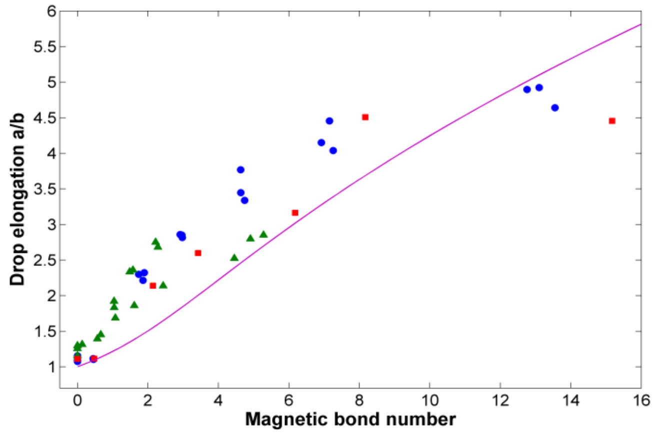

Fig. 6. Elongation a/b as a function of magnetic Bond number; (●)-main drops, (▲)-satellite drops (■)-large drops from transition region.

The equilibrium shape of magnetic fluid drop depends on the balance of magnetic force and surface tension force. Their ratio is described by dimensionless magnetic Bond number $B_m = (\mu_0 V^{1/3}\chi H^2)/2\sigma$. In Fig.6 there is elongation a/b (a and b are major and minor semi axes of prolate ellipsoid) of main drops, satellite drops and also large drops in the transition regime measured at various strengths of parallel magnetic field depicted as a function of magnetic Bond number. Results of all measurements seem to follow the same universal function. The equilibrium shape of ferrofluid drop was studied theoretically by minimizing the surface and magnetic energy under assumption of ellipsoidal drop shapes by Bacri and Salin [7]. Result of such solution for χ = 1.2 is shown in Fig.6 by solid line.

When MF is leaving the nozzle in dripping regime and container contains sufficient volume of fluid, transition from dripping to jetting regime may occur applying the parallel magnetic field (Fig.7). On the other hand we can notice drop formation without magnetic field in dripping regime. The magnetic field was suddenly switched on after the neck separation. Ensuing drop is elongated in the direction of magnetic field. After the drop separates, the neck is not detached at the nozzle and a non-zero intact jet length oscillating around mean value is formed. Significantly smaller drops arise.

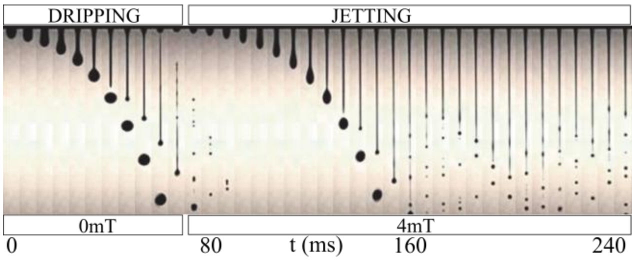

Fig. 7. High speed sequence during dripping-jetting transition induced by magnetic field.

3. Conclusions .

At this work we study the influence of magnetic field on the breakup of ferrofluid jet. In dripping regime magnetic field substantially changes the shape and volume of the drops and the dynamics of the detachment process. With increasing parallel magnetic field we observe elongation of a neck so that drop separates at a larger distance from the nozzle while in perpendicular magnetic field there is a neck length almost independent on magnetic field strength. The decrease of volume of the main drops observed in parallel magnetic field is consistent with the increase of magnetic pressure acting on the free surface of MF. The elongation coefficient of main, satelite and large drops in the transition regime depicted as a function of magnetic Bond number seem to follow the same increasing function for all measurements in various parallel magnetic fields. Increasing velocity at the nozzle applying of magnetic field induce dripping to jetting transition, where the drop size becomes significantly smaller.

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