MAGNETOHYDRODYNAMICS Vol. 49 (2013), No. 3-4, pp. 402–406

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

1. Introduction. The problems of liquid jet breakup and droplet formation are very fundamental topics in the field of fluid dynamics and they play a role in many industrial processes, such as 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 recognized mechanism of jet breakup involves flow from regions of the liquid column with smaller radii, where Laplace pressure is larger, to crest regions with a lower pressure until a pinch-off occurs. For the MF flow, a new parameter emerges – a magnetic pressure acting at 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 a ferrofluid leaving a cylindrical nozzle of 2 mm in diameter at the bottom of a cylindrical syringe with a diameter of 21 mm filled up to a height of 65 mm above the nozzle (Fig. 1). The MF used in this experiment was an oil-based ferrofluid with the following characteristics: density $\rho = 1.56 \cdot 10^3\,\mathrm{kg/m^3}$, surface tension $\sigma \sim 0.45\sigma_0$, where σ_0 is the surface tension of water, viscosity $\eta = 60\,\mathrm{mPa/s}$, and magnetization 360 Gauss under the magnetic field 27 mT.

The whole experiment was recorded by a high-speed camera with the frame rate 1200 fps.

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

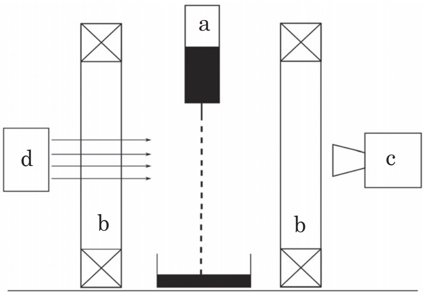

Fig. 1. Schematic diagram of the experimental apparatus: a – syringe with ferrofluid, b – Helmholtz coils, c – high-speed camera, d – stroboscope.

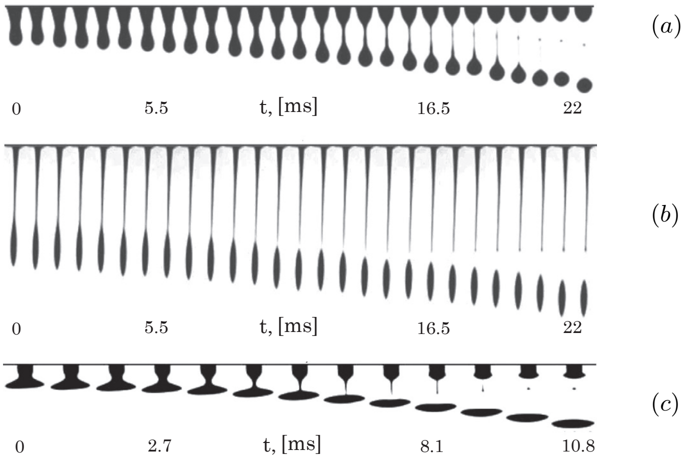

Fig. 2. High-speed sequences in dripping regime: (*a*) without magnetic field; (*b*) a parallel magnetic field of 27 mT; (*c*) a perpendicular magnetic field of 13 mT.

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

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

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

Most of our results are devoted to analysis of volumes and shapes of drops. As mentioned above, the magnetic field causes elongation of the drop in the direction of the 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

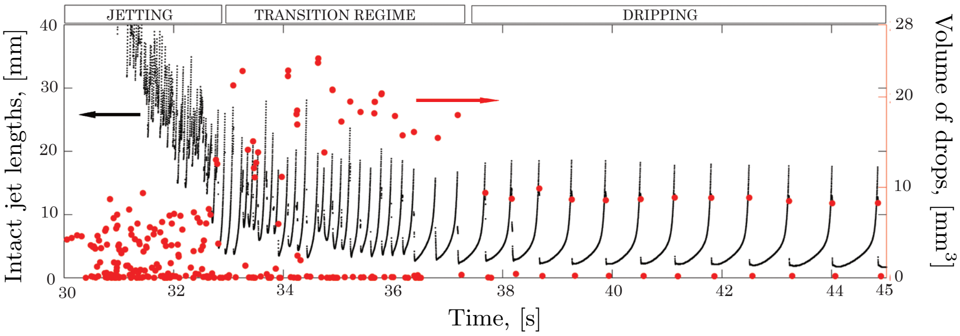

Fig. 3. Intact lengths and volumes of drops vs. time in the parallel 10 mT magnetic field.

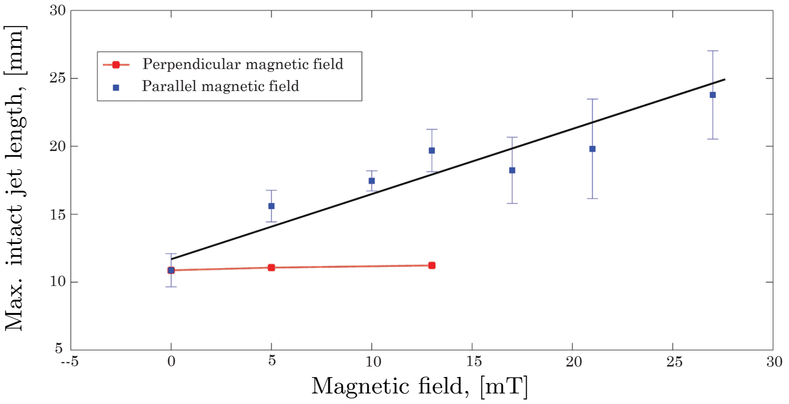

Fig. 4. Dependence of the peak neck length on the magnetic field in the dripping regime.

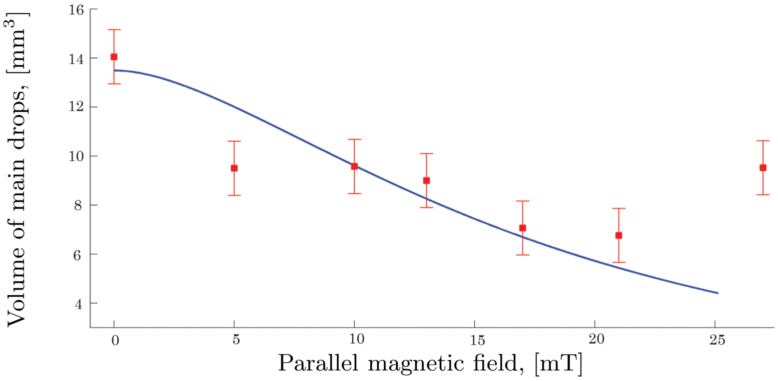

Fig. 5. The mean volume of the main drop as a function of the parallel magnetic field.

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

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

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

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

When the MF is leaving the nozzle in the dripping regime and the vessel still contains a sufficient volume of fluid, the transition from dripping to jetting regime may occur by applying a parallel magnetic field (Fig. 7). On the other hand, we can notice the drop formation with no magnetic field in the dripping regime. The magnetic field was suddenly switched on after the neck separation, ensuring the next drop is elongated in the magnetic field direction. After the drop separates, the neck is not detached at the nozzle and a non-zero intact jet length oscillating around the mean value is formed. Much smaller drops occur.

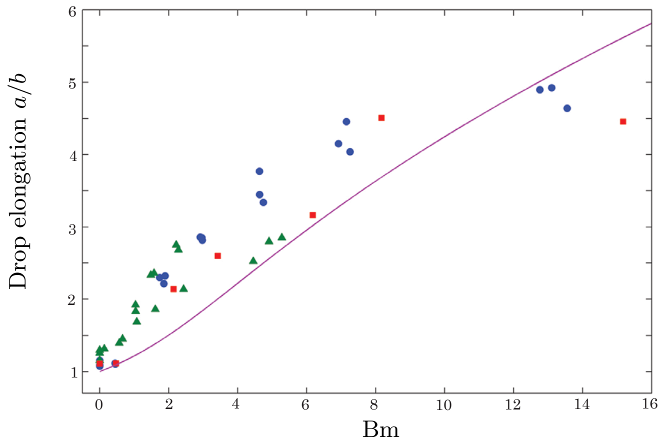

Fig. 6. Elongation a/b as a function of the magnetic Bond number; (●) main drops, (▲) satellite drops, (■) large drops from the transition region.

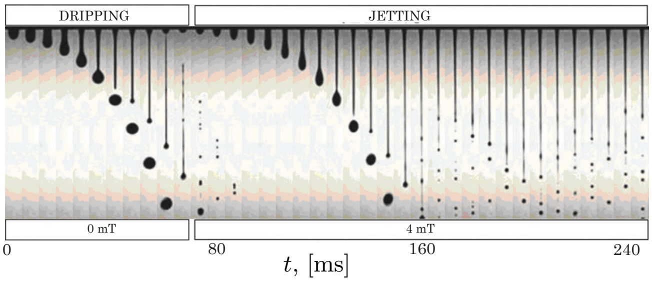

Fig. 7. High-speed sequence during dripping-jetting transition induced by a magnetic field.

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

5. Acknowledgements. We would like to thank Ladislav Tomčo for providing us with Helmholtz coils. The work was done with a support of SUSY (project APVV-LPP-0270-09).

REFERENCES

[1] J. Eggers. Nonlinear dynamics and breakup of free-surface flows. *Rev. Mod. Phys.*, vol. 69 (1997), p. 865.

[2] J. Eggers and E. Villermaux. Physics of liquid jets. *Rep. Prog. Phys.*, vol. 71 (2008), p. 036601.

[3] R.E. Rosensweig. *Ferrohydrodynamics* (Cambridge University press, 1985).

[4] J. Liu, Y.F. Yap and N.T. Nguyen. Numerical study of the formation process of ferrofluid droplets. *Phys. Fluids*, vol. 23 (2011), p. 072008.

[5] M. Sikora, T. Sabados, M. Svikova and M. Timko. Flowing of magnetic fluid with free surface and drop formation. *Physics Procedia*, vol. 9 (2010), p. 194.

[6] O. Lavrova, G. Matthies, T. Mitkova, V. Polevikov and L. Tobiska. Numerical treatment of free surface problems in ferrohydrodynamics. *J. Phys.: Condens. Matter*, vol. 18 (2006), p. S2657.

[7] J. C. Bacri and D. Salin. Instability of ferrofluid magnetic drops under magnetic field. *Phys. Lett.*, vol. 43, pp. 649–54.

Received 10.04.2013