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

The Influence of magnetic field on the separation of droplets from ferrofluid jet

M. Fabian[a,*], P. Burda[b], M. Šviková[b], R. Huňady[a]

[a] The Faculty of Mechanical Engineering, Technical University of Košice, Letná 9, 04200 Košice, Slovakia
[b] The High School of St. Thomas Aquinas, Zbrojničná 3, 04001 Košice, Slovakia

ARTICLE INFO

Keywords:
Drop formation
Magnetic fluid
Self-similarity

ABSTRACT

The influence of parallel and perpendicular homogenous magnetic field on the ferrofluid drop formation in dripping regime is studied experimentally. Experimental images are obtained using high-speed video camera with frame rate up to 25,000 fps. The detachment of a drop from the nozzle occurs via the formation of a neck which quickly narrows down until the drop pinches off. The formation of micro-thread from the primary neck is observed before the drop separation. Details of the shape and dynamics of the liquid neck are studied with regard to magnetic field. It is shown that near the detachment point scaled profiles exhibit self-similarity which is not affected by applied magnetic field.

1. Introduction

Flow of the fluids with the free surface and sudden disintegration into a string of drops is broadly studied scientific area because of many practical applications and number of interesting unresolved physical questions (for review see [1,2]). A liquid jet flowing through the nozzle is unstable and breaks into the drops. At low flow rates the emerging liquid drips from the orifice under its own weight. The hanging drops detach when the gravitational force exceeds surface tension forces. At high flow rates, the liquid is ejected from the nozzle as a jet that subsequently breaks up into small drops in a larger distance from the nozzle. This phenomenon is described by well known Rayleigh instability [1]. These two regimes of drop formation are referred to as a dripping regime and the jetting regime, respectively [3]. In the both cases, near breakup where nonlinear effects are essential, the process of droplet separation has common characteristics with highly asymmetric self-similar profiles [4–6].

In the magnetic fluids the influence of the parallel and perpendicular magnetic field on the intact jet length was studied in a jetting regime [7]. The influence of the homogeneous magnetic field on the volume and shape of the drops in a dripping regime was analyzed in [8]. The ferrofluid droplet formation and breakup dynamics in the microfluidic device was studied in [9]. Recent study of the pinch-off dynamics of the ferrofluid drops at a nozzle in the air and inhomogeneous magnetic field has verified universal scaling law near the point of detachment [10].

This paper presents the study of the pinch-off process of the pendant drop of the magnetic fluid that fall from an orifice under the action of the gravity and the influence of the parallel and perpendicular homogenous magnetic field on the dynamics of the process.

2. Experimental

Our experiments were performed using an oil-based ferrofluid prepared at the Institute of Experimental Physics SAS. The characteristics of the ferrofluid are as follows: density ρ=1.56×10^3 kg/m^3, surface tension $\sigma \sim 0.45\sigma_0$, σ_0 is surface tension of water, viscosity η=60 mPa/s at 20 °C and magnetization M=2.9×10^4 A/m (360 Gauss) at magnetic field 27 mT. For strength of the magnetic field used in our experiment the magnetization of the ferrofluid is linear function of magnetic field strength H: $M=\chi H$, with magnetic susceptibility χ=0.78.

Fig. 1 shows the scheme of the experimental arrangement. The magnetic fluid drips vertically from a cylindrical nozzle at the bottom of a plastic cylindrical syringe (a). The inner and outer diameters of the nozzle were 2 mm and 4 mm respectively. To create parallel or perpendicular magnetic field to the jet Helmholtz coils (b) with a diameter of 140 mm were used which produced homogeneous magnetic field with strength from 5 to 50 mT.

The experiment was recorded using high-speed camera (c) Phantom v12.1 with 1280×800 CMOS sensor and frame rate 6242 fps at full resolution, up to 680,000 fps at lower resolutions. To achieve optimal speed-image resolution ratio, two recording speeds, depending on visualized phenomena were used. The whole evolution of a drop was recorded at 10,000 fps and smaller area of pinch-off at

---

* Corresponding author.
E-mail addresses: fabian.michal@gmail.com (M. Fabian), peterburda2@gmail.com (P. Burda), svikova@gmail.com (M. Šviková), robert.hunady@tuke.sk (R. Huňady).

http://dx.doi.org/10.1016/j.jmmm.2016.09.052
Received 14 July 2016; Accepted 11 September 2016

Please cite this article as: Fabian, M., Journal of Magnetism and Magnetic Materials (2016), http://dx.doi.org/10.1016/j.jmmm.2016.09.052

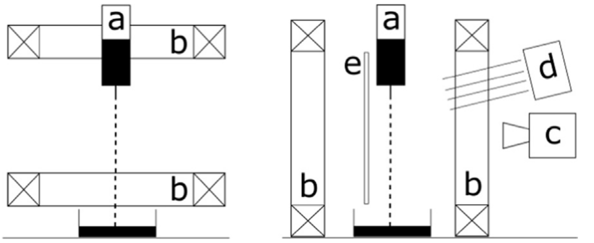

Fig. 1. Experimental arrangement: cylindrical syringe (a), Helmholtz coils (b) for parallel MF (left) and perpendicular MF (right), high-speed camera (c), xenon spotlight (d), diffusive background (e).

25,000 fps. In both cases, the camera was coupled with Nikon Micro Nikkor 60 mm f/2.8 D lens. For the most detailed images of detachment process, extension rings and close-up lenses were attached. As only small central region of the sensor and optical system is used, the distortion present mainly at its edges is negligible. Necessary contrast in frames was achieved by using light reflected from diffusive background (e). Experiment was illuminated by xenon spotlight (d) only for a short period of time during the recording in order to eliminate thermal effect on the experiment.

Quantitative analysis of the recorded image sequences was carried out in Matlab using self-developed scripts based on the functions from the image processing toolbox. This was to ensure proper binarization of the frames, extract contours of objects and to automatically measure various dimensions and characteristics changing with the time.

3. Results and discussion

In the early stage of dripping, pendant drop goes through sequence of equilibrium shapes characterized by a static balance between surface tension and gravitational force. For magnetic fluid in the presence of homogeneous magnetic field new parameter, so called magnetic pressure [11], $p_m = \mu_0 . (M_n)^2/2$, emerges acting on the boundary of the ferrofluid and the air. Here μ_0 is permeability constant and M_n is normal component of magnetization of the ferrofluid. Fig. 2(a) shows the influence of the magnetic pressure on the shape of the early stage of drop formation. The length of arrows is proportional to magnetic pressure in given direction. The resulting surface magnetic force F_m in parallel magnetic field is in the direction of the gravitational force while it vanishes in the perpendicular magnetic field. Fig. 2(b) depicts the global shapes near to point of the detachment together with an action of the magnetic pressure. The resulting magnetic force acting on the surface of arising drop goes to zero also in parallel magnetic field. In perpendicular magnetic field we can notice that the magnetic pressure has effect on the increase of the width of liquid thread connecting the arising drop with the nozzle.

Using the method described in [12] we evaluated the volume of drops. The influence of the magnetic field on the volume of the main drops is illustrated in Fig. 3. Increasing parallel magnetic field up to 13 mT causes the decrease of droplet volume, in accordance with observation in [8], but further growth of the magnetic field results in the surprising increase of droplet volume. In perpendicular magnetic field volume of droplet increases. Small number of measured points in this case is due to increasing instability of the flow which is illustrated in the sequence in the Fig. 4. It is an analogue of the whipping instability observed in electric field [13].

The equilibrium shape of the ferrofluid drop was studied theoretically in [14]. Fig. 5 shows the comparison of our experimental results with theoretical prediction [14]. The elongation a/b (a and b are length and width of drop) of the drops is depicted against dimensionless Bond number $B_m = (\mu_0\ V^{1/3} \chi H^2)/(2\sigma)$ and supplement measurements of [8] to higher values of Bond number.

The detachment of a drop from the nozzle occurs via the formation of a primary neck which quickly narrows down until the drop pinches off. After the breakup, one or several satellite drops are formed from the neck. Fig. 6(a) shows typical sequences.

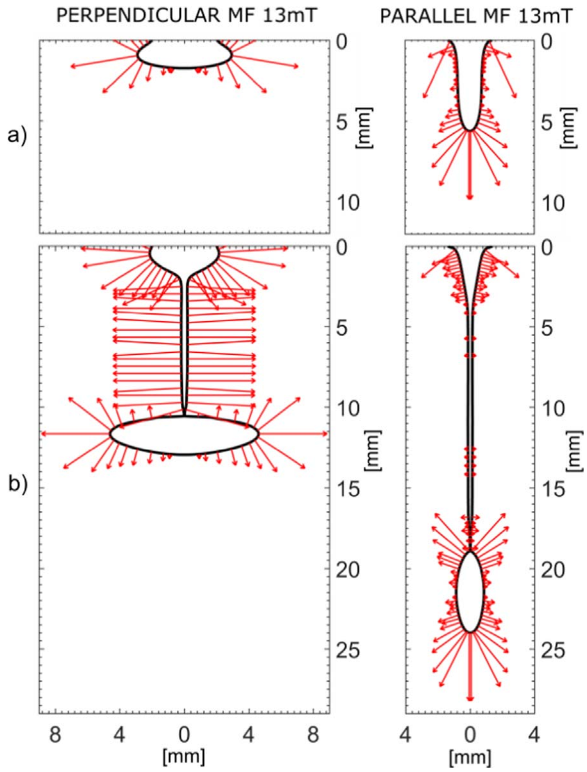

Fig. 2. The influence of magnetic pressure on the shape of the early stage of drop formation (a) and shape near to point of detachment (b). The length of arrows is proportional to magnetic pressure in given direction.

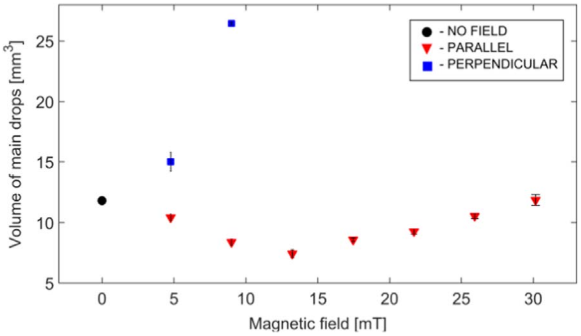

Fig. 3. Volume of main drops in parallel and perpendicular magnetic fields.

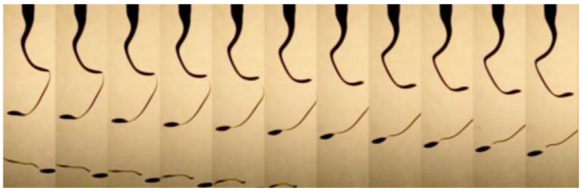

Fig. 4. Jet instability in perpendicular magnetic field.

The enlargement of the breakup region, depicted in Fig. 6(b), clearly shows the formation of new structure, thin micro-thread, from the primary neck. The micro-thread elongation and its breakup leading to the formation of micro satellite drop can be well followed in Fig. 6 (b). This behavior was previously seen in [16–18]. Our study is believed to be the first observation of micro-thread formation in magnetic fluids.