HEFAT2007
5th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
Sun City, South Africa
Paper number: CC2

MODES OF FERRODROPLET BREAKUP IN A NARROW PASSAGE

Chen Chen-Hua [1,2], Chen Ching-Yao[1,*] and Hong C.-Y.[3]
[1]Department of Mechanical Engineering, National Yunlin University of Science and Technology, Taiwan, R.O.C.
[2]Department of Automation Engineering, Nan-Kai Institute of Technology, Taiwan, R.O.C.
[3] Department of Mechanical Engineering, Nan-Kai Institute of Technology, Taiwan, R.O.C.

*Author for correspondence
E-mail:chingyao@yuntech.edu.tw

ABSTRACT

The motion of a magnetic drop through a narrow passage under an applied magnetic field is investigated experimentally. The influences of two control parameters: the strength of applied magnetic field and the width of passage, are investigated. Many interesting phenomena in the processes of the motions are observed, such as drop deformation, necking down, pinch-off, separation, and the formation of a satellite drop. From the results, different motions of a drop through the passage are categorized into four modes which strongly depend on the control parameters. Moreover, effects of the control parameter on the time of a magnetic drop passing through a narrow passage are evaluated as well. The weaker strength of applied magnetic field and a smaller diameter of the passage result in the difficulty to pass through the passage and longer time to complete the whole process.

INTRODUCTION

Magnetic fluids or ferrofluids, which are colloidal suspensions of single-domain magnetic nano-particles coated by a layer of surfactants in a carrier liquid such as water or oil, contain both flow and magnetic properties [1]. They have been first developed in the 1960s as bearing seals for space applications. The products like multistage rotary seals, inertial dampers and loudspeakers are now well-established goods in the industry [2]. New applications are implemented in the domain of lab-on-a-chip developed for biotechnological purposes [3]. A future application is to produce medical solution in a form of magnetic fluid. With guidance by an external magnetic field, the medication can reach and remain at the target spot [4,5], which is hard to achieve for the traditional human circulation. In order to contribute to the development of such applications, experimentally study the transportation and fluid dynamics of a magnetic drop in a tube under the influence of an applied magnetic field is presented. For the applications of such a problem, Greivell and Hannaford [6] designed a ferrofluid magnetic pipette to sample liquid volumes smaller than 0.2 μl. They used a series of electromagnets to generate a magnetic field gradient that moves the ferrofluid to pump the liquid in a capillary tube. Hartshorne et al. [3] used magnetically actuated plugs of ferrofluid in micro-channels to design microfluidic valves and pumps. Ganguly et al. [5] analyzed the ferrofluid transport for magnetic drug targeting (MDT). They experimentally and numerically investigated the magnetically induced accumulation of ferrofluid at target location and its subsequent dispersion in a steady host fluid flow. In the study of the fundamental problem about the topics, a number of researchers [7-10] calculated the static shape of a magnetic fluid drop in a homogeneous magnetic field by different theoretical approaches. They studied the stretched shape [7,9,10] or the breakup [8] of a magnetic fluid drop under the influence of an applied magnetic field. Sudo et al. [11] experimentally studied the interactions and deflections of two magnetic functional fluid drops in a magnetic field. Chen et al. [4] numerically explored the displacements of miscible magnetic fluids in a capillary tube under a moving ring-shaped magnetic field. Recently, Lin et al. [12] numerically simulated the dynamics of a miscible magnetic droplet in a capillary tube under the influence of an applied magnetic field. They found the interesting evolution of droplet patterns. In this experimental study, the motion of a magnetic drop through a narrow passage under the effects of an applied magnetic field is investigated regarding how magnetically induced motions may lead to interesting dynamical and morphological effects.

EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic of experimental apparatus is shown in Fig. 1. A magnetic drop is first placed into a quartz tube and then attracted through an acrylic orifice by an external magnetic field. The quartz tube of 6.0 mm inner-diameter and 8.0 mm outer-diameter is horizontally supported by a coil with an 8.1 mm-diameter central hole. Each end of the tube was connected to a flexible tube with open end to keep the same level of the free surface. A short tube type acrylic orifice with length of 3.0mm, outer diameter of 5.96 mm, and inner diameter d = 1.0, 1.3, 1.5, 1.8 or 2.0 mm, is fixed firmly in the quartz tube. The magnetic fluid used is a commercial light mineral oil-based ferrofluid (APG830) produced by Ferrotec Corp., with a saturation magnetization Ms=220 gauss, a viscosity 101 cp at 27℃ and a specific gravity 1.04 at 25℃. The tube was filled with distilled water-glycerol mixture with specific gravity 1.04 to closely match the one of ferrofluid. In order to avoid the adhesion of ferrofluid drop to the solid, Tween-80 is used to lubricate the surface of the quartz tube and the acrylic orifice. A positive-displacement microliter system, which consists of a medical syringe with nominal capacity of 0.5 ml and a micrometer, is used to inject magnetic drops into the tube in range of weight from 10~20mg. Moreover, the system is calibrated by an electronic balance (PRECISA 205A with an accuracy of 0.1 mg) and bears an accuracy of ± 0.5 mg in drop weight. A coil of electromagnet with 1500 turns of 0.6 mm-diameter wire, an outer diameter of 63.0 mm, and a width of 41.0 mm in the Helmholtz configuration, is used to magnetize the magnetic drop. The strength of the magnetic field is changed with the electric current I provided by a programmable power source. The motion and deflection of drops are observed with the photographic recording method and a CCD or a high-speed video camera system.

The experimental procedure is as follows. A 15 μl magnetic drop is first injected into the quartz tube through a medical syringe. The coil is fixed at l = 12 mm downstream of the orifice and the magnetic drop is drawn by a permanent magnet to 15 mm upstream of the orifice. When the magnetic field is triggered, the magnetic drop is attracted and moves through the orifice. With the video camera, the whole process is recorded from the beginning, and the images are subsequently analyzed on a PC.

RESULTS AND DISCUSSIONS

The motion-mode of a magnetic drop through a narrow passage is dominated by the competition of three different mechanisms: surface tension, drag of orifice and magnetic force. When a bigger drop runs through the narrow passage of orifice, it will first be blocked up and jammed into entrance of the orifice. In this transient equilibrium, the drop can be balanced with an increase in the curvature of surface and extends along the field. If the field strength is high enough, the drop will elongate into a prolate shape or pinch-off into two small drops to run through the orifice. In this study, the effects of the width of passage (inner diameter of orifice d) and the strength of the magnetic field (applied electric current I) are investigated by observing the motion and deformation of the drop in a magnetic field.

Reference case

To begin with, the observation for a magnetic drop with volume of 15 μl (initial drop diameter about $D_o \approx$ 3.06mm) passing through a d = 1.8mm orifice under the magnetic field of an applied electric current I= 1.5A is described first, as shown in Fig.2. Fig.2 shows the sequential snapshots recorded by a high speed CCD-camera. At the start, the magnetic drop is drawn to 15 mm upstream of the orifice and stays at the bottom of the quartz tube as shown in Fig.2(a). When the magnetic field is triggered, an instant force attracts the magnetized drop. The drop deforms slightly and moves ahead until it runs into the leading edge of the orifice as shown in Fig. 2(b) and (c). In the fraction of a second, the drop blocks up the orifice and jammed into it. When the drop stretches forward, part of the drop passing through the orifice extends forward and forms a rounded leading edge and begins to neck. In Fig.2(g), the drop necks down so that the part of the drop passing through the orifice turns into a new drop attached to original drop by a thread. Fig. 2(h) shows that the diameter of the thread decreases rapidly until the pinch-off occurs. The new drop is separated and sucked forward, and the left part of the drop with conical end springs back to almost a round shape because the larger curvature of the surface induces stronger cohesive force. In Fig. 2(j)~(m), the process that the left part of the drop prolongs to pass through the orifice and then turns into a prolate drop is observed. In this study, the observed phenomena that the original drop pinch-off and residual drop passes the orifice at last, are referred as the state of “mode-II” motion herein.

Effects of the strength of the field

Secondly, the effects of the strength of the magnetic field are studied. In the studies have been done [7-11], they reported [7,9,10] that the aspect ratio on the static shape of a magnetic drop strongly depends on the field strength under a homogeneous field. For small-applied field strength, the drop deforms into a prolate shape, while the highly deformed shape forms conical end above critical field strength. In Fig.3, the strength of the magnetic field is increased by changing the electric current to I =2.5A**.** As expected, the stronger magnetic force attracts the drop to quickly pass through the orifice. Fig.3(g)~(k) show the process that the drop deforms into two blobs connected by a thread and quickly pass the narrow passage without pitch-off. The total process of motion only takes 0.635 second. In this situation, the stronger magnetic force and a wider passage lead to the drop’s quick deformation and passing through the passage with ease. Compared with the case of Fig.2, Fig.3(g) clearly shows the larger curvature at the trailing edge of the drop. The phenomena that the stronger strength of the field induces a larger curvature at lateral surface of the drop is consistent with the findings in static studies [7,9,10]. The processes that drop passes through the orifice without pitch-off are referred as the mode-I motion. By contrast, the drop is subjected to a weaker field and jams in the orifice all along if the strength of the magnetic field is decreased to I =1.0A. This stable case is referred as the mode-IV motion.

Effects of the width of passage

Next, investigation is turned to the role played by the width of passage. As shown in Fig.2, the strength of the magnetic field is kept at I =1.5A, but decrease the inner diameter of orifice to d =1.5mm. For the same drop, the larger friction drag will be generated in a smaller passage. In Fig.4, it is observed that the drop is more difficult to pass such a small passage. Like the case of Fig.2, the pinch-off of the drop also occurs and the new drop passes through the passage; however, the similar process waste more time in this case. Besides, the residual drop finally remains in the orifice during the application of the field. Since the residual drop is smaller, it undertakes a smaller magnetic force in the same field. When the magnetic force isn’t larger than the drag of orifice, static equilibrium occurs and the drop remains in the orifice**.** The case, in which residue eventually remains in the orifice even though the drop undergoes one or several times of pitch-off, is referred to mode-III motion.

If the strength of the magnetic field is increased to I =2.5A, shown in Fig.5, it is obviously observed that the drop undergoes several times of pinch-off. When the drop first extends out of the orifice, a rapid necking and pinch-off occurs as shown in Fig.5(c)~(e). Under such strong magnetic force and large friction drug, pinch-off keeps on occurring until the residual drop is slim enough to pass through the passage. In this case, the residual drop finally passes the orifice at t=12.9 second. Besides, it is worth noting that the drop with conic end at the trailing edge is quite obvious. Another interesting feature observed is the formation of a satellite drop. Fig.5(e) and (f) clearly show the process of pinch-off. When the thread breaks off the drop, the front part of the thread moves forward slowly and the bottom part bounces back rapidly until the two ends join and form a primary satellite drop. This phenomenon was also observed in the breakup of jets by Kowalewski[13] and the pinch-off of a pendant drop by Henderson et al.[14]. To sum up, the case where the drop undergoes several times of pinch-off and the residual drop eventually passes through the orifice, is also referred to mode-II motion.

Distribution of the motion-mode

The results can be concluded by plotting the distribution of motion-mode as a function of the applied field strength (electric current I) and diameter of orifice d in Fig. 6. The plot clearly shows the motion-modes of a magnetic drop passing through the orifice depend on the diameter of orifice and the field strength. Fig. 6 shows that Mode-I always appears at a wider passage (d=1.8mm, or d=2.0mm). Mode III occurs either at the stronger field strength and a smaller passage or at the weaker field strength and a wider passage. The condition of Mode II is between Mode I and Mode III. Mode IV is a stable case, in which the drop maintains the static equilibrium of the drag of orifice and magnetic force under a very weak field. From the results of Mode IV, it is found that the condition for a drop to run through a smaller passage is the stronger field strength. It is worth noting that the lubricated condition on the passage strongly affects the motion modes in the transitional region (a wider passage and the weaker field strength like d=2.0mm and I=1.25A). The motion mode may become mode-I, mode-II, or mod-III shown in Fig. 6, when the friction drag of the orifice is slightly changed.

Finally, the effects of the control parameter on the time of a drop passing through a passage are studied, shown in Fig.7. We define t is the interval of the drop from the time starting moving to the time either running through the passage for mode-I or first pinching off for mode II and mode III. The results show that d has a less influence on t in the stronger field strength (I>2.5A). However, under the weaker field strength, d has a stronger influence on t. The weaker strength of applied magnetic field and a smaller diameter of the passage lead to the difficulty to pass through the passage. As a result, it takes more time to complete the whole process.

CONCLUSION

The experiments have shown the process of a magnetic drop passing through a narrow passage under an applied magnetic field. The common characteristics are observed, such as drop deformation, necking down, pinch-off, separation, and the formation of a satellite drop. From the results, the different motions of the drop passing through the passage are referred as four modes that strongly depend on the control parameters: the strength of applied magnetic field and the diameter of passage. From the distribution of motion-mode, all kinds of conditions for a drop to pass through the narrow passage are observed. Moreover, the effects of the control parameters on the time of a magnetic drop passing through a narrow passage are studied as well. The weaker strength of applied magnetic field and a smaller diameter of the passage result in the difficulty to pass through the passage and more time to complete the whole process.

ACKNOWLEDGEMENT

C.-Y. Chen thanks the National Science Council of the Republic of China for financial support of this research through grant NSC 94 -2212-E-224-011.

REFERENCES

1. R. E. Rosensweig, *Ferrohydrodynamics*, Cambridge Univ. Press, New York; 1985.
2. K. Raj, B. Moskowitz and R. Casciari, “Advances in Ferrofluid technology,” *J. Magn. Magn. Mater*, vol. 149, pp. 174-180, 1995.
3. H. Hartshorne, C. J. Backhouse and W. E. Lee, “Ferrofluid-Based Microchip Pump and Valve,” *Sensors and Actuators B*, vol. 99, pp. 592-600, 2004.
4. C.-Y. Chen, C.-Y. Hong and L.-M. Chang, “Displacements of Miscible Magnetic Fluids in a Capillary Tube,” *Fluid Dyn. Res.*, Vol. 32, pp. 85-98, 2003.
5. R. Ganguly, A. P. Gaind, S. Sen and I. K. Puri, “Analyzing Ferrofluid Transport for Magnetic Drug Targeting,” *J. Magn. Magn. Mater*, vol. 289, pp. 331-334, 2005.
6. N. E. Greivell and B. Hannaford, “The Design of A Ferrofluid Magnetic Pipette,” *IEEE Trans. On Biomedical Eng.*, Vol. 44, No. 3, pp. 129-135, 1997.
7. V. I. Arkhipenko, Yu. D. Barkov, and V. G. Bashtovoi, “ Shape of A Drop of Magnetized Fluid in A Homogeneous Magnetic Field,” *Magneto- hydrodynamics*, vol. 14, No. 3, pp. 131- 134, 1978.
8. J. D. Sherwood, “Breakup of Fluid Droplets in Electric and Magnetic Field,” *J. Fluid Mech.* vol. 188, pp. 133- 146, 1988.
9. O. E. Sero-Guillaume, D. Zouaoui, D. Bernardin, and J. P. Brancher, “The Shape of a Magnetic Liquid Drop”, *J. Fluid Mech.* vol. 241, pp. 215- 232, 1992.
10. H. A. Stone, J. R. Lister and M. P. Brenner, “Drops with Conical End in Electric and Magnetic Fields,” *Proc. R. Soc. Lond. A*, vol. 455, pp. 329- 347, 1999.
11. S. Sudo, A. Nakagawa, K. Shimada and H. Nishiyama, “ Interactions of Two Functional Fluid Drops in Magnetic Field,” *Magnetohydrodynamics*, vol. 39, No. 3, pp. 361-

368, 2003.

12. S.-Y. Lin, C.-Y. Chen, W.-K. Tsai and B.-Y. Wu, “Motion of A Miscible Magnetic Drop in A Capillary Tube,” *Proc. of the 22th (ROC) National Conference on Mechanical Engineering, CSME,* Chungli, Nov. 25~26, A2-018, pp.1~6, 2005.
13. T. A. Kowalewski, “On the Separation of Droplets from a Liquid Jet,” *Fluid Dyn. Res*., vol. 17, pp.121-145, 1996.
14. D. M. Henderson, W. G. Pritchard, and L. B. Smolka, “ On the Pinch-Off of a Pendant Drop of Viscous Fluid,” *Phys. Fluids*, vol. 9, No. 11, pp.3188-3200, 1997.

CHART ARRANGEMENT

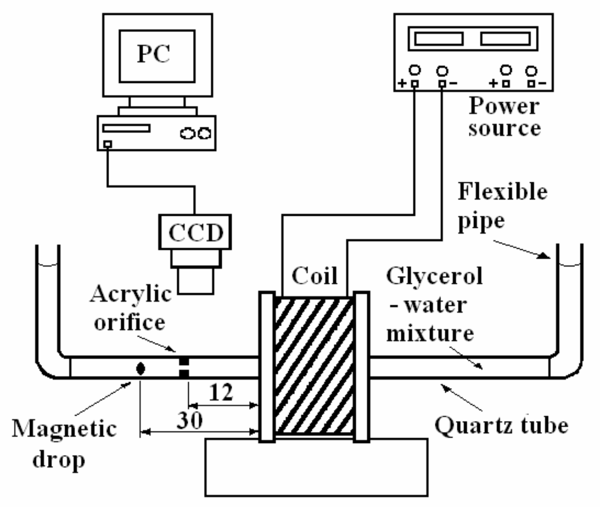

Fig.1 Schematic presentation of the experimental apparatus. [unit: mm]

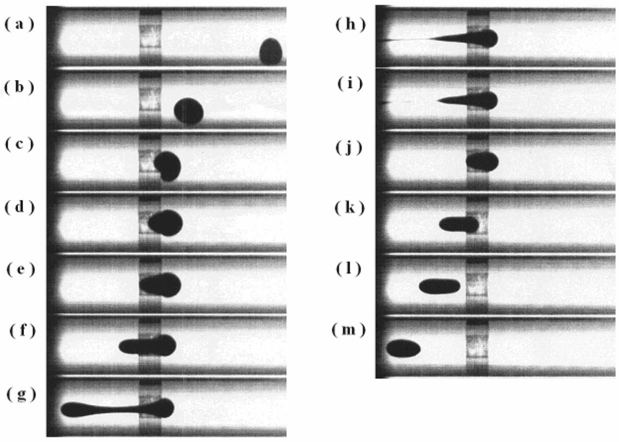

Fig.2 Evolution of magnetic drops through the orifice recorded with a high speed CCD-camera. The relative time of each image are at t= (a) 0 s, (b) 0.500 s, (c) 0.580 s, (d) 0.730 s, (e) 1.980 s, (f) 3.500 s, (g) 3.658 s, (h) 3.825 s, (i) 3.840 s, (j) 4.100 s, (k) 4.860 s, (l) 4.910s, (m) 4.940 s for d=1.8 mm, I=1.5A. A Mode-II motion, which original drop is pinch-off and residual drop passes the orifice at last, is observed.

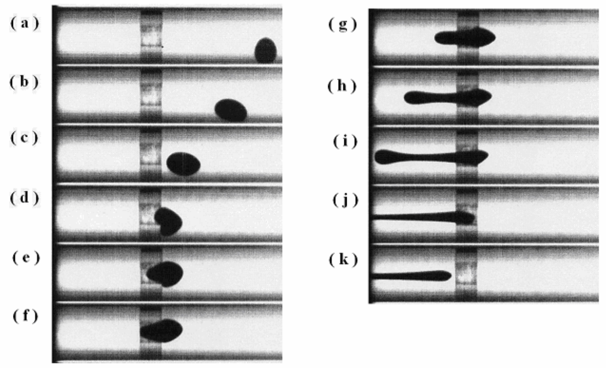

Fig.3 Evolution of a magnetic drop through the orifice. The relative time of each image are at t= (a) 0.000 s, (b) 0.175 s, (c) 0.255 s, (d) 0.275 s, (e) 0.330 s, (f) 0.375 s, (g) 0.525 s, (h) 0.565 s, (i) 0.583 s, (j) 0.615 s, (k) 0.635 s for d=1.8 mm, I=2.5A. A Mode-I motion, which drop passes through the orifice without pitch-off, is observed.

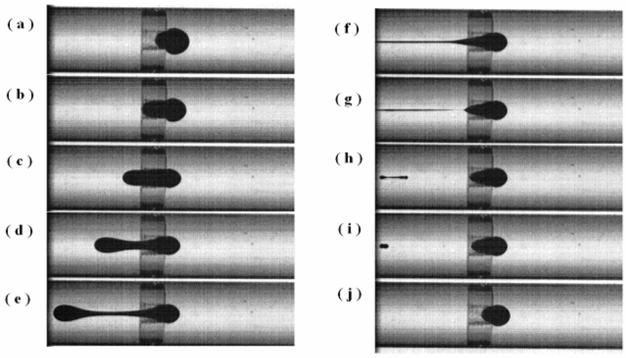

Fig.4 Evolution of magnetic drops through the orifice. The relative time of each image are at t= (a) 0.880, (b) 4.900 s, (c) 8.850 s, (d) 9.130 s, (e) 9.178 s, (f) 09.220, (g) 9.250 s, (h) 9.268, (i) 9.280 s, (j) 14.590 s for d=1.5mm, I=1.5A. A Mode-III motion, which residue eventually remains in the orifice even though the drop undergoes one or several times of pitch-off, is observed.

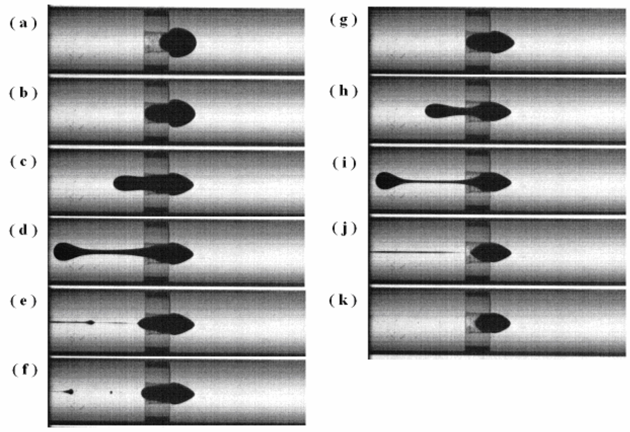

Fig.5 E volution of magnetic drops through the orifice. The relative time of each image are (a) 0.360 s, (b) 1.130 s, (c) 1.730 s, (d) 1.787 s, (e) 1.860 s, (f) 1.870 s, (g) 1.990 s, (h) 3.470 s, (i) 3.505 s, (j) 3.543 s, (k) 13.200 s for d=1.5mm, I=2.5A.

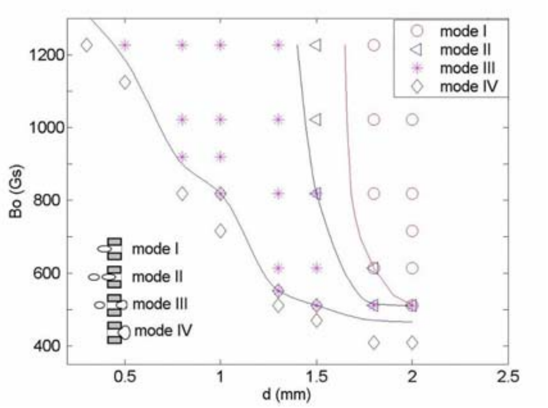

Fig.6 Phase diagram of motion-mode as a function of applied field strength (electric current *I*) and diameter of orifice *d*.

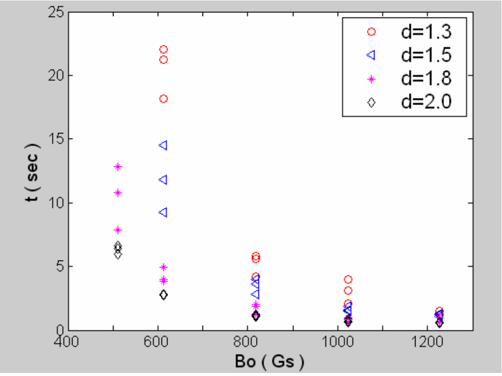

Fig.7 Time of the first drop through the orifice, as a function of field strength for various diameter of orifice *d* .