INTERFACE EVOLUTION BETWEEN BINARY IMMISCIBLE FLUIDS UNDER WEAK MAGNETIC FIELD

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Abstract: In order to investigate the interface evolution between liquid metal and magnetic fluid under weak magnetic field, the distributions of magnetic flux and magnetic force were simulated by using the ANSYS software, and the experiments of interface evolution were also conducted. Both the simulation and experimental results suggested that interface evolution under weak magnetic field was controlled by the distributions of magnetic flux and magnetic force. Finally, a circuit breaker which based on the principle of interface evolution between liquid metal and magnetic fluid is presented.

Keywords: Weak magnetic field, Magnetic fluid, Liquid metal, Binary immiscible fluids, Interface evolution.

1. Introduction

Binary immiscible fluids system is ubiquitously existed in nature. For this system, the interface evolution has already been utilized in many technologies due to its practical significance. For example, the interface evolution plays a significant role in the processes of electro-spraying[1], ink-jet printing[2] and surface-relief patterning[3]. Thus, how to effectively control the interface evolution becomes an important issue. Sugawara et al reported that the interface between water (diamagnetic) and air descends obviously in the presence of high magnetic field, and this is the so-called "Moses effect"[4, 5]. Similarly, the interface between air and saturated $CuSO_4$ aqueous solution (paramagnetic) rises under high magnetic field, and this is the "Reversed Moses effect"[4]. Correspondingly, for the binary fluids system which consists of weak magnetic fluids, once the difference of densities of fluids is negligible, the interface evolution is significant under high magnetic field, and this is the "Enhanced Moses effect"[6-8]. Thus, by adjusting the parameters of high magnetic field, the interface evolution between binary fluids can be effectively controlled. However, although the interface evolution can be controlled by high magnetic field, the high magnetic field itself is not industrial applicable. Since weak magnetic fields are widely available, therefore controlling the interface evolution by weak magnetic field is much more practical. Nevertheless, as the magnetic force of weak magnetic fluid is always negligible under weak magnetic field, it is unlikely to control the motion of this fluid by weak magnetic field. On the contrary, magnetic fluid (a kind of colloid which is uniformly distributed with nanoscale ferromagnetic particles)[9] is super-paramagnetic and has extremely high saturate magnetization[10]. Thus, for the magnetic fluid, quite significant magnetic force can be produced by weak magnetic field. Therefore, when considering the binary fluids system which consists of magnetic fluid and other fluid, it is expected that the interface evolution can be effectively controlled by weak magnetic field.

In this work, the interface evolution between liquid metal and magnetic fluid under weak magnetic field was investigated. The distributions of magnetic flux and magnetic force were simulated by the ANSYS software, and the experiments of interface evolution were also conducted. Finally, a circuit breaker which based on the principle of interface evolution between liquid metal and magnetic fluid is presented

2. Numerical simulations and experiments

Numerical simulations were conducted by the ANSYS software. Since the magnetic field can be imposed either under the side of bottom of container or under the middle of bottom of container, therefore two simulation models are named as Side type model and Middle type model, respectively. The free meshing method is used for both models, and the length of mesh is 2 mm. After the boundary conditions are given, the distributions of magnetic flux and magnetic force are simulated.

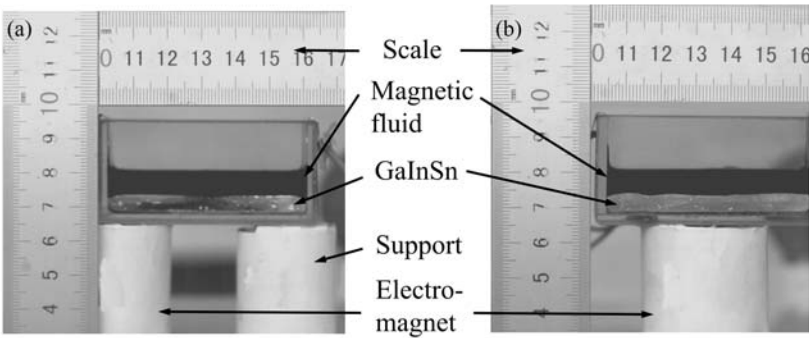

Figure 1: The experimental setups, (a) Side type setup, (b) Middle type setup.

The interface evolution processes were recorded by the high-speed camera. Figure 1 shows the experimental setups. The high-speed camera is Photron FASTCAM-APX 120K, and the speed is 500 frames per second. The weak magnetic field is produced by a DC electromagnet. The core of electromagnet is electrical pure iron, the total turns of electromagnet is 5654. Besides, the resistance is 408 Ω and the current is 0.52 A (dc). Similarly, the two setups are named as Side type setup and Middle type setup, respectively. The solution of magnetic fluid is engine oil, the density and saturate magnetization of magnetic fluid is 1320 kg/m^3 and 450±50 GS, respectively. Liquid metal is GaInSn, its melting point is 283.5K, and the density is 6620 kg/m^3. In all the experiments, both volume of the magnetic fluid and liquid metal are 3.6 ml.

3. Results and discussion

Figure 2 (a) shows the distributions of magnetic flux along the interface. For the Side type model, there are two peaks in the distribution of magnetic flux. The strongest peak is around the side wall, it corresponds to the very place where the fastest fall of the interface is. And the second peak lies at the right side of the strongest peak. For the Middle type model, there are two symmetrical peaks in the distribution of magnetic flux. Figure 2 (b) and 2 (c) shows the distributions of magnetic force. It is clear that magnetic force mainly concentrates on the position which corresponds to that of the DC electromagnet. Moreover, magnetic fluids are subjected to significant magnetic forces under weak magnetic field. Since magnetic force can drive the interface evolution, therefore, the simulation results show that it is possible to induce interface evolution by weak magnetic field.

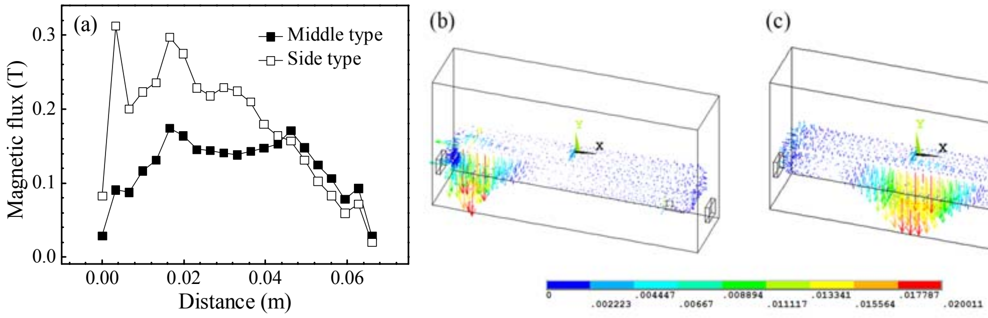

Figure 2: (a) Distributions of magnetic flux along the interface. Distributions of magnetic force, (b) Side type model, (c) Middle type model.

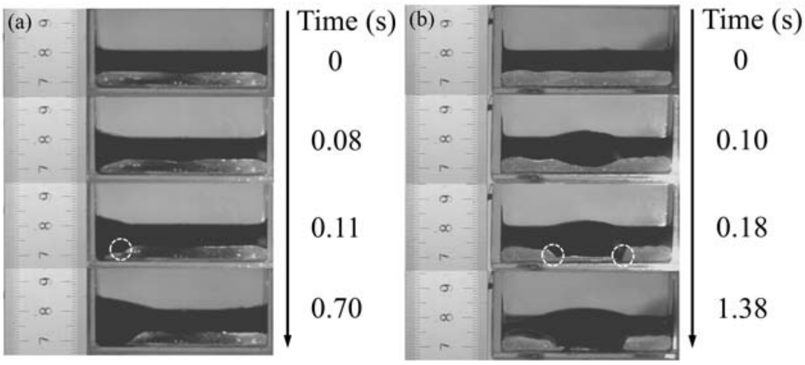

Figure 3: Interface evolution processes under weak magnetic field, (a) Side type setup, (b) Middle type setup.

Figure 3 shows the interface evolution processes under weak magnetic field. For the Side type setup, when t = 0 s, the interface is horizontal. When t = 0.08 s, the interface at the left side descends significantly, and the magnetic fluid rises. When t = 0.11 s, a sharp point occurs in the interface, and magnetic fluid is converged at the side wall of container. Finally, when t = 0.7 s, the interface descends to the lowest position. Similarly, for the Middle type setup, when t = 0 s, the interface is also horizontal. When t = 0.10 s, the interface descends, and the maximum fall occurs in the middle of interface. Besides, the magnetic fluid is also converged. When t = 0.18 s, there are two symmetrical sharp points occur in the interface. Then the interface descends gradually. Finally, when t = 1.38 s, the magnetic fluid was attracted to the bottom of the container, and the liquid metal is driven away to both sides of the container.

For the side type setup, when t = 0.08 s, the magnetic fluid rises. This is because that magnetic force is exerted on the magnetic fluid. When t = 0.11 s, a sharp point occurs in the interface. And the position of the sharp points is identical to that of the peak of simulated magnetic flux. Then the interface descends gradually. Finally, when t = 0.7 s, the interface descends to lowest position, and the liquid metal is entirely detached from the side wall of the container. Besides, by comparing the distribution of magnetic force and the interface evolution process, it also shows that the trend of interface evolution is in a good agreement with the distribution of magnetic force.

Similarly, for the Middle type setup, when t = 0.10 s, magnetic fluid is converged in the middle of the container. When $t = 0.18$ s, there are two symmetrical sharp points occur in the interface. The positions of the sharp points are also identical to that of the peaks of simulated magnetic flux. Then the interface descends gradually. Finally, when $t = 1.38$ s, the magnetic fluid is attracted to the bottom of the container, and the liquid metal is driven away to both sides of the container. Again, by comparing the distribution of magnetic force and the interface evolution process, it also shows that the trend of interface evolution is in a good agreement with the distribution of magnetic force.

By analyzing the simulation and experimental results, it is clear that significant interface evolution can be induced under weak magnetic field. And the distributions of magnetic flux and magnetic force play critical roles in deciding the interface evolution. Therefore, by adjusting the parameters of weak magnetic field, it is possible to effectively control the interface evolution between liquid metal and magnetic fluid.

4. Design of binary fluids circuit breaker

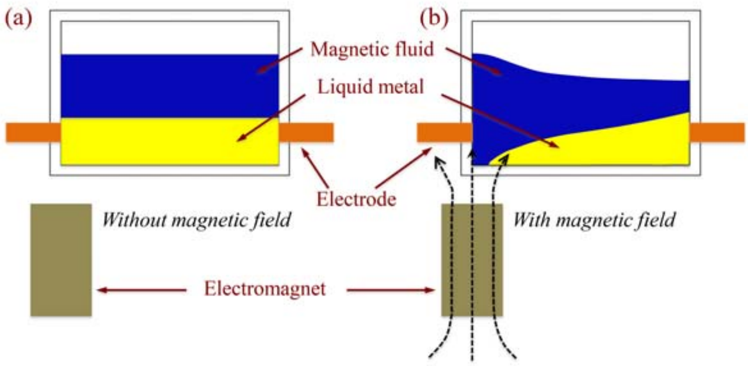

Figure 4. Principle of the binary fluids circuit breaker, (a) The state of interface when the circuit is normal, (b) The state of interface when fault current occurs.

Based upon the above results, a circuit breaker which consists of liquid metal and magnetic fluid is presented [11]. Figure 4 shows the principle of this circuit breaker. When the circuit is normal, the liquid metal is connected with electrodes. When fault current occurs, the magnetic field generator will be activated and produce magnetic field immediately. Therefore, it can attract magnetic fluid and driven away the liquid metal. Finally, the liquid metal is totally detached from the electrode, thus cut off the fault current. It should be noted that since the parameters of magnetic fluid can be adjusted, therefore, various binary fluid systems can be form by magnetic fluid and other fluid. In principle, all the interface evolution of these fluid systems can be effectively controlled by weak magnetic field.

5. Conclusions

The interface evolution between magnetic fluid and liquid metal under weak magnetic field was investigated. Simulation results show that magnetic flux has peak values, and magnetic fluid is subjected to significant magnetic force under weak magnetic field. Experimental results show that interface descends significantly under weak magnetic field. Moreover, sharp points occur during the interface evolution, and the positions of sharp point corresponded to that of the peak magnetic flux. Furthermore, the trends of interface evolution are in good agreement with the distribution of magnetic force. These results suggest that the interface evolution under weak magnetic field is decided by the distributions of magnetic flux and magnetic force. Thus, the interface evolution between magnetic fluid and liquid metal can be effectively controlled by adjusting the parameters of magnetic field. Finally, a circuit breaker which based on the principle of interface evolution between liquid metal and magnetic fluid is presented.

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References

[1] Ganan-Calvo, A. M.; Davila, J.; Barrero, A.: Current and droplet size in the electrospraying of liquids. Scaling laws. J. Aerosol Sci. 28 (1997) 249-275.

[2] Badie, R.; de Lange, D. F.: Mechanism of drop constriction in a drop-on-demand inkjet system. Proc. R. Soc. Lond. A. 28 (1997) 2573-2581.

[3] Schaffer, E.; Thurn-Albrecht, T.; Russell, T. P.; Steiner, U.: Electrically induced structure formation and pattern transfer. Nature. 403 (2000) 874-877.

[4] Hirota, N.; Homma, T.; Sugawara, H.; Kitazawa, K.; Iwasaka, M.; Ueno, S.; Yokoi, H.; Kakudate, Y.; Fujiwara, S.; Kawamura, M.: Rise and fall of surface level of water solutions under high magnetic field. Jpn. J. Appl. Phys., Part 2-Letts. 34 (1995) L991-L993.

[5] Ueno, S.; Iwasaka, M.: Properties of diamagnetic fluid in high gradient magnetic fields. J. Appl. Phys. 75 (1994) 7177-7179.

[6] Kitazawa, K.; Ikezoe, Y.; Uetake, H.; Hirota, N.: Magnetic field effects on water, air and powders. Phys B. 294 (2001) 709-714.

[7] Sugawara, H.; Hirota, N.; Homma, T.; Ohta, M.; Kitazawa, K.; Yokoi, H.; Kakudate, Y.; Fujiwara, S.; Kawamura, M.; Ueno, S.; Iwasaka, M.: Magnetic field effect on interface profile between immiscible nonmagnetic liquids - Enhanced Moses effect. J. Appl. Phys. 79 (1996) 4721-4723.

[8] Zhao, L. J.; You, Y.; Tian, Y. H.; Yang, H. K.; Wang, Q. A.; He, J. C. Interface profile evolution between binary immiscible fluids induced by high magnetic field gradients. Sci China Phys Mech & Astron. 53 (2010) 1319-1324.

[9] Rosensweig, R. E. 1985.: Ferrohydrodynamics. United Kingdom. Cambridge University Press.

[10] Chi, C. Q.; Wang, Z. S.; Zhao, P.Z. 1993.: Ferromagnetic hydrodynamics. Beijing. Publisher of Beihang University.

[11] Wang, Q.; Zhao, L. J.; You, Y.; Yang, H. K.; He, J. C. 2009: Method and device for self-recovery current limiting and circuit breaking by using conductive fluid and magnetic fluid. CRC Patent, CN101651323A.