

FLOW STUDY IN MAGNETIC MICRO-CHANNEL HEAT PIPE

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Abstract

Since the magnetic field can provide an alternative driving force to help the condensed liquid traveling to the evaporating side of heat pipe, we can take advantage of this to enhance the performance of heat pipe. In order to enhance the performance of our next generation magnetic ferro-fluid heat pipe and further investigate the fluid motion in micro channels, experiments of a magnetic drop through a narrow passage are carried under various control parameters. The magnetic ferro-fluids we used are commercial light mineral oil-based ferro-fluids (EMG905) produced by Ferrotec Corp. The experiments have shown the process of a ferro-fluid drop passing through narrow passages with different sizes (diameters = 0.3mm, 0.5 mm and 0.8mm) under various applied magnetic field strengths. The common characteristics are recorded in details, such as drop deformation, necking down, pinch-off, separation, and the formation of a satellite drop. Although the capillary driving force drops as the size of micro-channel increases, it is easier and faster for magnetic fluid to pass through larger size of micro-channel. Therefore, an optimized size or maybe several mixed-size micro-channels of magnetic heat pipe should be adopted for better performance. In addition, initial location of the magnetic field source (a coil of electromagnet) is also an important factor to be considered when a magnetic micro-channel heat pipe is designed. Last but not least, applying magnetic field to enhance the performance of heat pipe is now possible and practical. The magnetic flow motion is interesting and should be further studied with various thermal conditions. More theoretical analysis and simulations of the new idea is currently under development and some preliminary results with experimental data will be presented.

KEY WORDS: Magnetic Heat Pipe, Ferro-fluid, Nano-fluid, Micro-channels.

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Nomenclature

- G_l = driving force term in liquid phase (gravity, capillary force, and...etc)
 M_l = driving force term in liquid phase (magnetic force)
 H = intensity of magnetic field
 E = intensity of electric field
 J = current density
 μ = magnetic permeability (usually taken as unity)
 M_s = saturation intensity of magnetic field
 ρ_l = density of liquid (function of temperature)
 μ_l = liquid viscosity (function of temperature and intensity of magnetic field)
 R_{th} = thermal resistance
 Q_{max} = maximum allowable heat flux of heat pipe (dry-out, sonic limit, or ...etc)
 L = distances between narrow passage and coil
 ΔL = extended length of the magnetic ferro-fluid drop

Introduction

Magnetic ferro-fluid is composed of nanometer-scale magnetic particles, surfactant, and carrier fluid. Basically the key manufacturing processes include coating the nanometer-scale magnetic particles with surfactant through artificial synthesis to prevent the agglomeration and scattering of these nanometer-scale magnetic particles in the carrier fluid, usually an organic solvent or water. Since it is a colloidal mixture comprising extremely small magnetic particles suspended in the liquid. The magnetic ferro-fluid not only behaves like fluid but also reacts to the presence of a magnetic field. The aerospace applications of magnetic ferro-fluid are quite interesting. For example, NASA used magnetic ferro-fluid in a closed loop as the basis for a spacecraft's attitude control system. A magnetic field was applied to change the angular momentum to control the rotation rate of the spacecraft. The thermal application is also important. Since magnetic ferro-fluid obeys Curie's Law, it becomes less magnetic at higher temperatures. A local strong magnetic field near the heat source will attract cold magnetic ferro-fluid thus forcing the

heated magnetic ferro-fluid away from the hot spot. We believed that proper design of magnetic fields and corresponding micro-channels could enhance the thermo-magnetic convection in the hot spot area. Therefore, we considered adding magnetic ferro-fluid in the heat pipe. Because the magnetic field can provide an alternative driving body force (like gravity) to help the condensed cool liquid traveling to the evaporating hot side of heat pipe, we can take advantage of this to enhance the performance (i.e. maximum allowable heat flux) of heat pipe, especially in micro-gravity environment and in micro-scale devices. Experiments of a magnetic drop through a narrow passage were carried under various control parameters to study the flow. The goal is to enhance the performance of our next generation magnetic ferro-fluid heat pipe and further investigate the fluid motion in micro channels.

Governing Equations

Recall the momentum equation we presented.

$$\rho_l \frac{\partial V}{\partial t} = -G_l + \mu_l \left(\frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} \right) \quad (1)$$

Modified momentum equation with the new magnetic driving force term:

$$\begin{aligned} \rho_l \frac{\partial V}{\partial t} = & -G_l + \mu_l \left(\frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} \right) + \mu \cdot J \times H = \\ & -G_l + \mu_l \left(\frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} \right) + M_l \end{aligned} \quad (2)$$

G_l is the driving force term in liquid phase (gravity, capillary force, and...etc). M_l is the magnetic driving force term, and it is the function of location. Unless we have a homogeneous uniform magnetic field in the heat pipe, it will be very difficult to simulate the flow. In the other hand, flow could be unstable and temperature fluctuation could be observed at the presence of body force, as shown in Figure 2. The case when magnetic force and gravity act in different directions and thermal instability have been studied (Chandrasekhar, 1961). Magnetic ferro-fluid motions in homogeneous magnetic field have been investigated (Arkhipenko et al., 1978; Sero-Guillaume et al., 1992; Stone et

al., 1999). The numerical simulation of magnetic drop in a capillary tube has been studied (Chen et al., 2003; Lin et al., 2005). Motion of magnetic drop through a narrow passage has been also studied (Chen et al., 2006). In the other hand, energy equation will be much more complicated than thermal entry problem (Wang et al., 2007), and it makes the numerical simulation of magnetic heat pipe very difficult. In this paper, experimental results of a magnetic drop through a narrow passage were shown in order to understand the magnetic driving force term better. The experiments have shown the process of a ferro-fluid drop passing through narrow passages with different sizes (diameters = 0.3mm, 0.5 mm and 0.8mm) under various applied magnetic field strengths. The common characteristics are recorded in details, such as drop deformation, necking down, pinch-off, separation, and the formation of a satellite drop. Although the capillary driving force drops as the size of micro-channel increases, it is easier and faster for magnetic fluid to pass through larger size of micro-channel. Therefore, an optimized size or maybe several mixed-size micro-channels of magnetic heat pipe could be adopted for better thermal performance. Moreover, initial location of the field source (a coil of electromagnet) is also another important factor to be considered when a magnetic micro-channel heat pipe is designed. In Figure 1, it shows that our design goal of magnetic heat pipe is to increase the maximum allowable heat flux of heat pipe Q_{max} and maintain the thermal resistance R_{th} low by means of attracting cold magnetic ferro-fluid to the hot spot with proper magnetic field and corresponding micro-channels. Usually the thermo-magnetic convection in hot spot area could be enhanced and the liquid film thickness is roughly at same level. In Figure 2, it shows that we observed temperature fluctuation in the hot spot area of heat pipe at the presence of body force such as gravity or magnetic force, and further study of the flow in magnetic heat pipe by experiment is necessary.

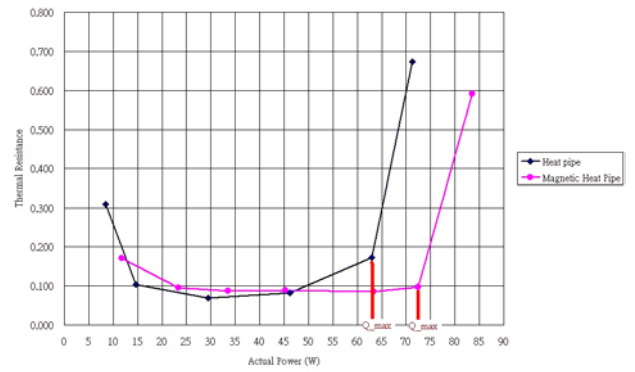


Figure 1. Our goal is to increase the maximum allowable heat flux Q_{max} of heat pipe.

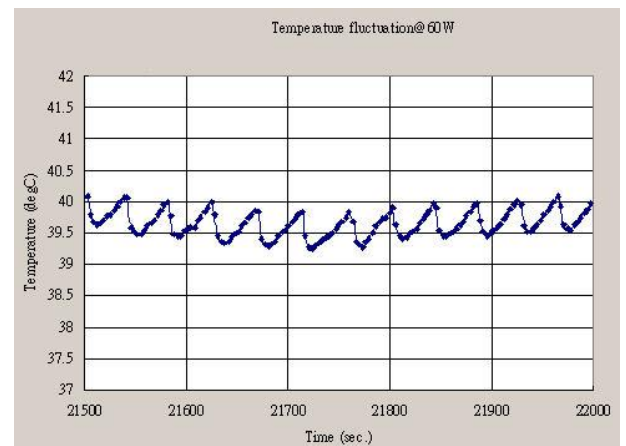


Figure 2. Temperature fluctuation in the hot spot area of the heat pipe.

Experimental Setup

The schematic chart of the experiment is shown in Figure 3. A magnetic ferro-fluid drop was originally located in the quartz tube, and then we applied the magnetic field to attract the drop through the narrow passage. We could change the diameter of the narrow passage. We could also change the intensity of magnetic field. Various distances between narrow passage and coil could be tested as well. The inner diameter of the quartz tube is 6mm and the outer diameter is 8mm. The diameter of the coil to generate magnetic field is 8.1mm. The both ends of the quartz tube were connected to the flexible tubes. The liquid surfaces in both flexible tubes were in the same level in this experiment. The width of the passage is 3mm and its outer diameter is 5.96mm. Several inner diameters of narrow passage have been designed, such as 0.3mm, 0.5mm, and 0.8mm, ...etc. The magnetic ferro-fluids

we chose are commercial light mineral oil-based ferro-fluids (EMG905) produced by Ferrotec Corp. Its specific weight is 1.24 at 25 ° C, and its viscosity μ_l is 9cp at 27 ° C. Its saturation intensity of magnetic field M_s is 400 gauss. We filled the quartz tube with water mixture that has the same density with EMG905. We used Tween-80 to change the inner surface property of quartz tube in order to avoid the magnetic ferro-fluid drop sticking to the wall of the quartz tube. The current of coil is controlled by the programmable power supply to provide the magnetic field we want. The magnetic ferro-fluid drop can be relocated to the place H by a magnet. When the magnetic field generated by coil is turned on, the camera will record the motion of the magnetic ferro-fluid drop.

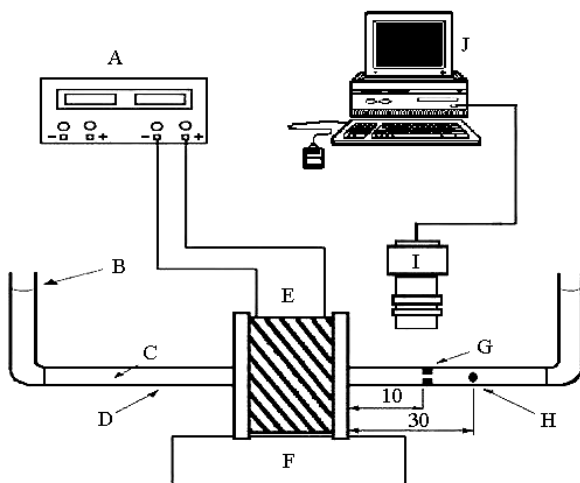


Figure 3. Schematic chart of the experiment (A: Power supply; B: Flexible Tube; C: Water mixture; D: Quartz tube; E: Coil; F: Fixture base; G: Narrow passage; H: Magnetic ferro-fluid drop; I: Camera; J: Computer)

Results and Discussions

Several forces compete with each other for the motion of the magnetic ferro-fluid drop through narrow passage, such as drag force, capillary force, magnetic force. Buoyancy and gravity are neglected because of the specific weight of water mixture and ferro-fluid drop are deliberated matched. When a large ferro-fluid drop attempted to pass the narrow passage, it stuck at the entry of the narrow passage in the beginning and then filled the narrow passage. In the transient state of

equilibrium, the magnetic ferro-fluid drop started changing the surface curvature and extended along the direction of the applied magnetic field to react to these forces. If the intensity of applied magnetic field is strong enough, the magnetic ferro-fluid will extend to deformable slender oval shape to run through the narrow passage. Beside drop deformation, other phenomena such as necking down, pinch-off, separation, and the formation of a satellite drop could happen as well. Because the diameter of the narrow passage is small, some residual magnetic ferro-fluid usually is left behind in the narrow passage. In this paper, we observe and analyze the motions and the deformations of magnetic ferro-fluid under various intensities of applied magnetic field. We also tried different diameters of the narrow passage and several distances between narrow passage and coil.

A. Control group ($d=0.3\text{mm}$, $I=3.0\text{A}$, $L=10\text{mm}$.)

First, we had a magnetic ferro-fluid drop $17\ \mu\text{l}$ (diameter of the drop is 3.2mm) float at the location H, and then we applied the magnetic field with current $I=3.0\text{A}$ ($H=5570\text{Oe}$) to attract the magnetic ferro-fluid drop. It approached the narrow passage and started to deform and go through the narrow passage. The motion is recorded by the camera and is shown in Figure 4. We take this as the control group of the experiment.

In Figure 4(a), the drop initially stayed at the location H near the inner wall of the quartz tube. After we turned on the magnetic field to attract the magnetic ferro-fluid drop, it simultaneously changed the shape and approached the narrow passage, as shown in Figure 4(b)~(d). It stuck at the entry of the narrow passage in the beginning and then filled the narrow passage, as shown in Figure 4(e)~(f). It extended along the direction of the applied magnetic field to react to these forces. The magnetic ferro-fluid drop extended to deformable slender oval shape and then started to neck down, as shown in Figure 4(g)~(h). We saw the process of necking down in Figure 4(i)~(j). The process of necking down led to the growth of new drop, and the growth of new drop led to the pinch-off and separation of the new drop, as shown in Figure 4(j). We found that the formation of a small satellite drop could happen in this

case, as shown in Figure 4(j)~(l). The interesting satellite drop phenomena have been discovered (Kowalewski et al., 1996; Henderson et al., 1997; Chen et al., 2006). For larger drag force and stronger magnetic force, the phenomena of necking down, pinch-off, and separation will keep happening all the time. Once magnetic force is not able to overcome the drag force at the narrow passage, the residual magnetic ferro-fluid is left behind in the narrow passage. In Figure 9, the front end of magnetic ferro-fluid drop through the narrow passage is shown for this case. The period of drop separation is very consistent and it is approximately 0.6 seconds. In Figure 14, extended length of the magnetic ferro-fluid drop ΔL for different cases is shown. If we increase the distances between narrow passage and coil, the extended length of the magnetic ferro-fluid drop ΔL will increase as well. In Figure 15, period of drop separation for different cases is shown. In Figure 16, number of drop separations for different cases is shown. In Figure 17, traveling time of the drop for different cases is shown. It is obvious that stronger magnetic field and larger inner diameters of the narrow passage will lead to shorter traveling time. The distance between narrow passage and coil is another important factor of the traveling time (comparing cases of $L=10\text{mm}$ with $L=15\text{mm}$).

B. Assorted diameters of the narrow passage

First, we changed the inner diameter of the narrow passage from 0.3mm to 0.5mm, and the same intensity of applied magnetic field with current $I=3.0\text{A}$ ($H=5570\text{Oe}$). We found that the formation of a small satellite drop also happened, as shown in Figure 5(j)~(l). Because of the reduced drag (larger inner diameter), the period of drop separation reduced to approximately 0.4 seconds in this case, as shown in Figure 10.

When the inner diameter of the narrow passage is 0.8mm and the magnetic field is applied with current $I=3.0\text{A}$ ($H=5570\text{Oe}$), there is no pinch-off. The slender continuous ferro-fluid drop passes through the passage smoothly because of the stronger magnetic field and the larger inner diameter.

Then, we increased the inner diameter of the narrow passage to 0.8mm and lowered the intensity of applied

magnetic field with current $I=2.75\text{A}$ ($H=5100\text{Oe}$). The process of necking down led to the pinch-off and separation of the new slender drop, as shown in Figure 7(j)~(k). In Figure 7(l), we observed the formation of a satellite drop, which is bigger than previous case. Because of the reduced drag force (larger inner diameter), the period of drop separation reduced to approximately 0.2 seconds, as shown in Figure 12.

In Figure 16, the number of drop separations is shown for different situations. When we have the same intensity of the magnetic field, the larger inner diameter of the narrow passage will lead to the greater number of drop separation. In Figure 17, the traveling time of the magnetic ferro-fluid drop is shown for different situations. It is clear that the larger inner diameter of the narrow passage will result in the shorter traveling time of the magnetic ferro-fluid drop.

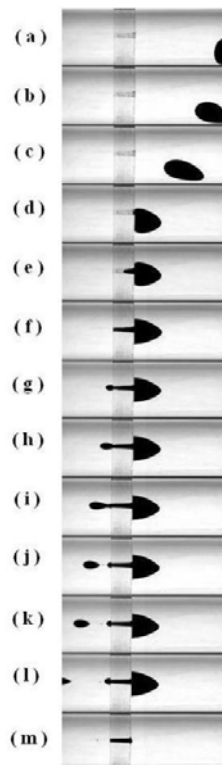


Figure 4. $d=0.3\text{mm}$

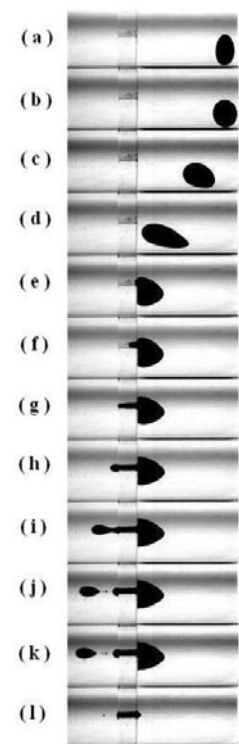


Figure 5. $d=0.5\text{mm}$

C. Various intensity of magnetic field

According the references (Arkhipenko et al., 1978; Sero-Guillaume et al., 1992; Stone et al., 1999), the shape of magnetic ferro-fluid drop will depend on the intensity of the magnetic field. The shape of magnetic ferro-fluid drop is usually oval in weak magnetic field. Once the critical intensity

of magnetic field is reached, the shape of magnetic ferro-fluid drop will become conical end.

Various intensity of magnetic field will be studied in the session. First, the inner diameter of the narrow passage is 0.5mm, and applied the magnetic field with current $I=2.5A$ ($H=4640e$). As we expected, it approached the narrow passage and started to deform and go through the narrow passage (inner diameter $d=0.5mm$, located at G with $L=10mm$). In Figure 6(a), the oval drop initially stayed at the location H near the inner wall of the quartz tube. After we turned on the magnetic field to attract the magnetic ferro-fluid drop, it simultaneously changed the shape and approached the narrow passage, as shown in Figure 6(b)~(d). It stuck at the entry of the narrow passage in the beginning and then filled the narrow passage, as shown in Figure 6(e)~(f). It extended along the direction of the applied magnetic field to react to these forces. The magnetic ferro-fluid drop extended to deformable slender oval shape and then started to neck down, as shown in Figure 6(g)~(i). The process of necking down is shown in Figure 6(i). The process of necking down led to the pinch-off and separation of the new drop, as shown in Figure 6(j). We found that the formation of a small satellite drop also happened, as shown in Figure 6(j)~(m). The normal operation of the magnetic coil is limited to sixty seconds. In Figure 11, the front end of magnetic ferro-fluid drop through the narrow passage is shown for this case. The period of drop separation is much longer than other cases. Because the magnetic driving force is smaller, we will have longer period of drop separation, as shown in Figure 15. If the magnetic driving force is weak or adverse gravity plays an important role, the magnetic ferro-fluid drop may stick at the entry of the narrow passage and will never pass the narrow passage. In other words, appropriate intensity of magnetic field is required in order to improve the maximum allowable heat flux of heat pipe.

In Figure 16, the number of drop separations is shown for different situations. The stronger magnetic field will lead to the greater number of drop separation. In Figure 17, the traveling time of the magnetic ferro-fluid drop is shown for different situations. It goes with saying that the stronger

magnetic field will result in the shorter traveling time of the magnetic ferro-fluid drop.

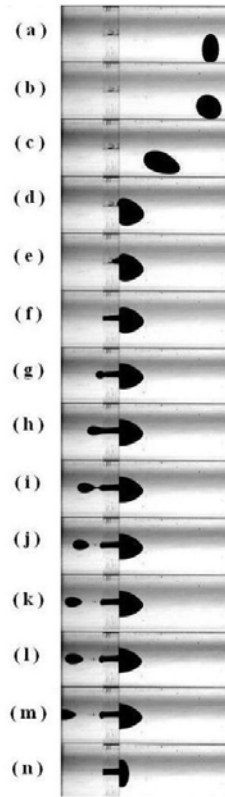


Figure 6. $I=2.5A$

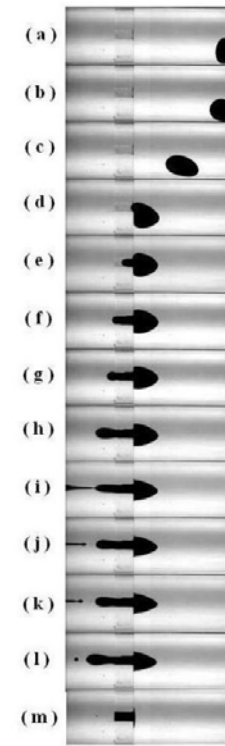


Figure 7. $d=0.8mm$

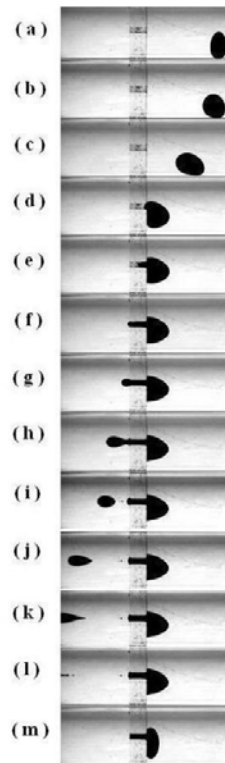


Figure 8. $L=15mm$

D. Different distance between the magnetic field source and the narrow passage

In the previous cases, the distance L between the coil and the narrow passage is 10 mm. In order to study the effects of L , we adjusted the distance L from 10mm to 15mm. The current is same as control group A, which is 3.0A. The process of necking down is shown in Figure 8(h). The process of necking down led to the growth of new drop, and the growth of new drop led to the pinch-off and separation of the new drop, as shown in Figure 8(i). We found that the formation of a small satellite drop also happened, as shown in Figure 8(i)~(l). We found that the period of drop separation is longer than sixty seconds, as shown in Figure 13. The extended length of the magnetic ferro-fluid drop ΔL for different cases is shown in Figure 14. When the distance between narrow passage and coil is increased, the extended length of the magnetic ferro-fluid drop ΔL will increase. We have the longest extended length of the magnetic ferro-fluid drop in this case ($L=15\text{mm}$), and the extended length of the magnetic ferro-fluid drop ΔL is about 7mm.

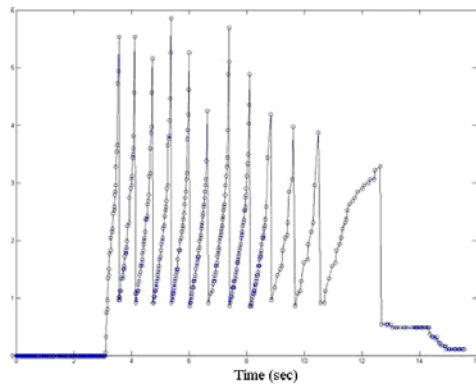


Figure 9. Front end of drop $d=0.3\text{mm}$

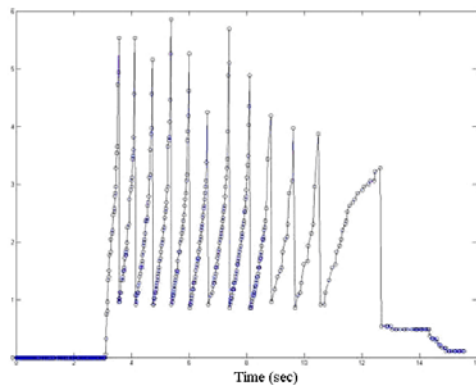


Figure 10. Front end of drop $d=0.5\text{mm}$

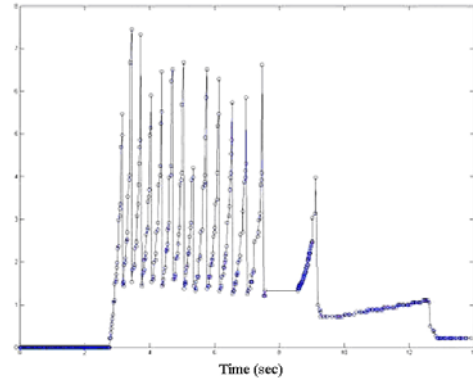


Figure 11. Front end of drop $I=2.5\text{A}$

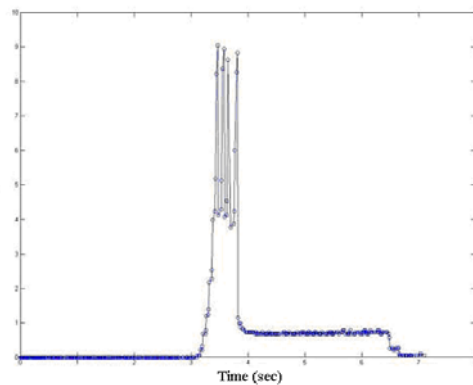


Figure 12. Front end of drop $d=0.8\text{mm}$

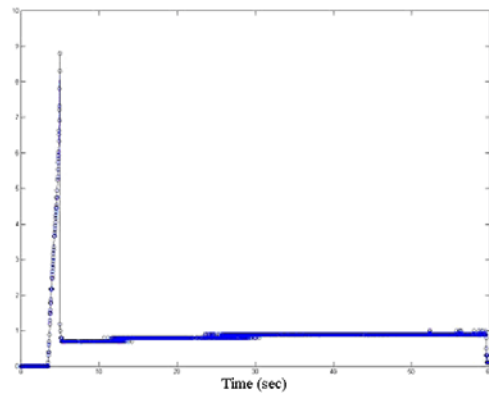


Figure 13. Front end of drop $L=15\text{mm}$.

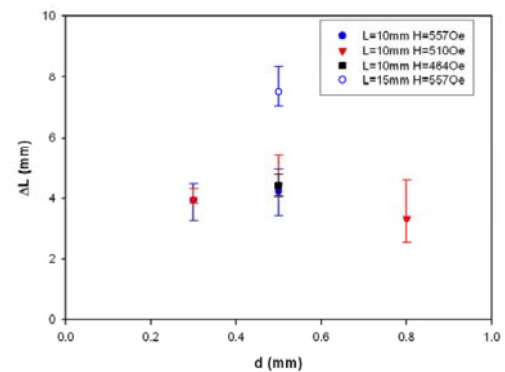


Figure 14. Extended length of drop ΔL

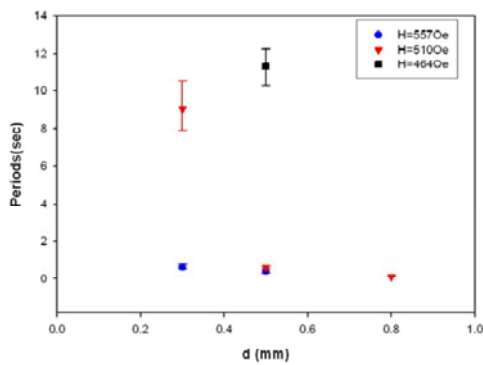


Figure 15. Period of drop separations

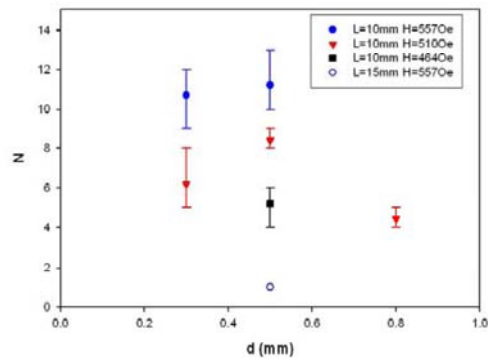


Figure 16. Number of drop separations

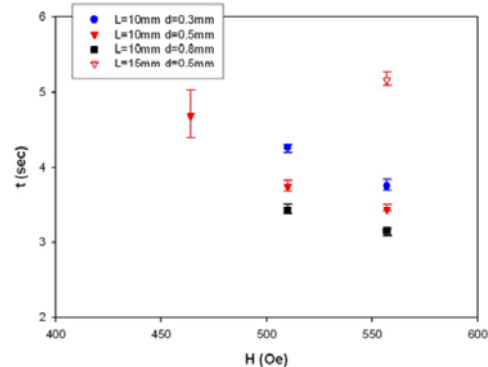


Figure 17. Traveling time of the drop

E. Improvement of the TEC thermal module

In Figure 18, traditionally the heat pipe conducts the heat generated by TEC to the radiator without taking advantage of the magnetic field generated by the wire of TEC. The TEC is usually used to cool the FPA (Focal Plane Assembly) of the optical payload of satellite. The improvement we proposed is shown in Figure 19, the magnetic heat pipe conducts the heat generated by TEC to the radiator, and the magnetic heat pipe can utilize the magnetic field generated by the wire of TEC. The maximum current of the wire can reach up to 20.0A for a 50mm*50mm TEC, so we should make good use it. After the improvement, the

maximum allowable heat flux of heat pipe can be increased, which means better cooling capacity of the TEC thermal module. As we demonstrated, we won't need additional power to improve the performance of the TEC thermal module. Basically, we can utilize the magnetic field from any high power DC devices, such as TEC, heater, and reaction wheel, ...etc. The time variation of the magnetic field may be also helpful to the thermo-magnetic convection in the hot spot area.

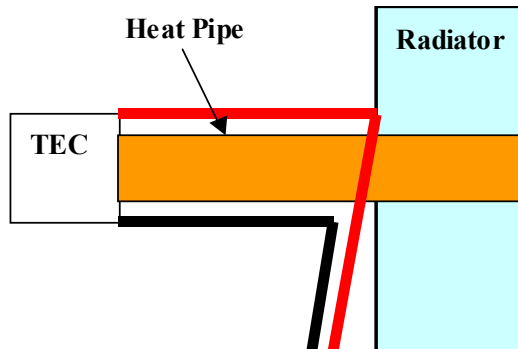


Figure 18. Traditional heat pipe

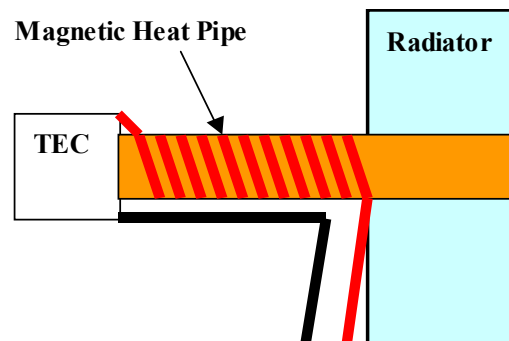


Figure 19. The magnetic heat pipe

Conclusion

The magnetic field can provide an alternative driving force in heat pipe and improve the performance of heat pipe. Since the magnetic field attracts cold ferro-fluid instead of hot ferro-fluid thus pushing the heated ferro-fluid away from the hot spot, it locally enhanced the thermo-magnetic convection. Temperature fluctuation in the hot spot area of heat pipe at the presence of body force sometimes can be observed. Applying magnetic field to enhance the performance of heat pipe is now possible, especially in micro-gravity and micro-scale devices.

References

- Rosensweig, R. E., *Ferrohydrodynamics*, Cambridge University Press, New York, 1985.
- Chandrasekhar, S., *Hydrodynamics and Hydromagnetic Stability*, Dover Publications Inc., New York, 1981.
- Raj, K., Moskowitz, B., and Casciari, R., "Advances in Ferrofluid technology", *J. Magn. Magn. Mater.*, vol. 149, pp. 174-180, 1995.
- Hartshorne, H., Backhouse, C. J., and Lee, W. E., "Ferrofluid-Based Microchip Pump and Valve", *Sensors and Actuators B*, vol. 99, pp.592-600, 2004.
- Chen, C. Y., Hong, C. Y., and Chang, L. M., "Displacements of Miscible Magnetic Fluids in a Capillary Tube", *Fluid Dyn. Res.*, Vol. 32, pp. 85-98, 2003.
- Ganguly, R., Gaiind, A. P., Sen, S., and Puri, I. K., "Analyzing Ferrofluid Transport for Magnetic Drug Targeting", *J. Magn. Magn. Mater.*, vol.289, pp. 331-334, 2005.
- Greivell, N. E., and Hannaford, B., "The Design of A Ferrofluid Magnetic Pipette", *IEEE Trans. On Biomedical Eng.*, Vol. 44, No. 3, pp.129-135, 1997.
- Arkipenko, V. I., Barkov, Y. D., and Bashtovoi, V. G., "Shape of A Drop of Magnetized Fluid in A Homogeneous Magnetic Field", *Magneto- hydrodynamics*, vol. 14, No. 3, pp.131- 134, 1978.
- Sherwood, J. D., "Breakup of Fluid Droplets in Electric and Magnetic Field," *J. Fluid Mech.* vol. 188, pp. 133- 146, 1988.
- Sero-Guillaume, O. E., Zouaoui, D., Bernardin, D., and Brancher, J. P., "The Shape of a Magnetic Liquid Drop", *J. Fluid Mech.* vol.241, pp. 215- 232, 1992.
- Stone, H. A., Lister, J. R. and Brenner, M. P., "Drops with Conical End in Electric and Magnetic Fields," *Proc. R. Soc. Lond. A*, vol.455, pp. 329- 347, 1999.
- Sudo, S., Nakagawa, A, Shimada, K., and Nishiyama, H., "Interactions of Two Functional Fluid Drops in Magnetic Field", *Magnetohydrodynamics*, vol. 39, No. 3, pp.361- 368, 2003.
- Lin, S. Y., Chen, C. Y., Tsai, W. K., and Wu, B.Y., "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.
- Kowalewski, T. A., "On the Separation of Droplets from a Liquid Jet", *Fluid Dyn. Res.*, vol. 17, pp.121-145, 1996.
- Henderson, D. M., Pritchard, W. G., and Smolka, L. B., " On the Pinch-Off of a Pendant Drop of Viscous Fluid", *Phys. Fluids*, vol. 9, No. 11, pp.3188-3200, 1997.
- Chen, C. H., Chen, C. Y., "Motion of a Magnetic Drop through a Narrow Passage", *Proc. of the 30th (ROC) National Conference on Theoretical and Applied Mechanics, DYU*, Changhwa, December 15-16, 2006.