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STUDY ON ENHANCED HEAT TRANSFER FEATURES OF NANO-MAGNETIC FLUID HEAT PIPE UNDER MAGNETIC FIELD

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ABSTRACT

In order to enhance heat transfer speed of heat pipes, this paper uses external magnetic field to strengthen heat transfer of nano-magnetic fluid heat pipe. It designs the test rig and conducts experiments on the heat transfer of nano-magnetic fluid heat pipe under the influence of various magnetic fields. The study proves that nano-magnetic fluid heat pipe is superior to magnetic fluid heat pipe and water heat pipe under various circumstances; a variety of magnetic fields can enhance heat transfer of nano-magnetic fluid heat pipe and the static DC magnetic field can best improve the heat transfer speed of heat pipe with the maximum improvement rate of 19.2%.

Keywords: magnetic field; nano-magnetic fluid; heat pipe; heat transfer.

1. INTRODUCTION

With the rapid development of modern industry, tension grows between energy supply and increased energy demand. Much attention has been given to the heat pipe for its unique advantage in energy conservation and new energy development. At present, global researches on the application of heat pipe exchangers have achieved the following results: (1) used to recover waste heat in industrial exhaust; (2) used to remove heat dissipated by high-power electronic components or equipment; (3) used as an exchanger utilizing natural energy; (4) used as exchanger in chemical reactions [1-5]. All these applications have obtained great progress. The development direction and focus of heat pipe technique is to improve its heat transfer performance and develop more efficient heat pipes.

Experiments have proved that heat transfer of Cu-Water nano-fluids in self-oscillating heat pipe has some particularity and under certain conditions, nano-fluids can enhance heat transfer [6-7]. In addition, water's surface tension is significantly reduced after magnetization and the decline fluctuates with strengthened magnetic field. In other words, when magnetic field reaches certain strength, decline in water's surface tension will rather slow down [8-9].

Wu Songhai et al. (2005) found that under the influence of magnetic field, the maximum vapor condensation heat transfer coefficient could be 10% higher than that under no magnetic field but with the increase in the Renault number of liquid membrane, the influence would weaken [10]. Meanwhile, under magnetic field, evaporation rate was 1.1 times faster than that under no magnetic field and the rate would increase with strengthened magnetic field. When magnetic field was of fixed strength, the rate would increase with increased temperature [11].

Zhang Yunfeng et al. [12] discovered that under the influence of magnetic field, oil and water showed similar variations in the heating rate but under the same magnetic field and heat flux, oil had a larger heating rate than water. However, with strengthened magnetic field and prolonged magnetization, their heating rates were both markedly enhanced. Zhao Meng [13] conducted experiment research and proved that under magnetic field, magnetic fluid's viscosity would become larger and its size was determined by the acting time of magnetic field; viscosity would stabilize after certain time; viscosity would increase with strengthened magnetic field and stop increasing at certain strength.

In conclusion, it is of great scientific significance to utilize magnetic fluid and magnetic field to enhance heat transfer. Since heat pipe transfers heat well and magnetic field can enhance liquid's thermal conductivity, the experiment proposes to use external magnetic field to enhance the heat transfer of nano-magnetic fluid heat pipe.

2. EXPERIMENTAL INSTALLATION AND MEASURING METHOD

The experimental device and measuring system mainly consist of vacuum heat pipe, magnetic spiral coil, DC voltage regulator, Labview temperature acquisition system, and multiplex thermocouple inspector, as shown in Fig. 1.

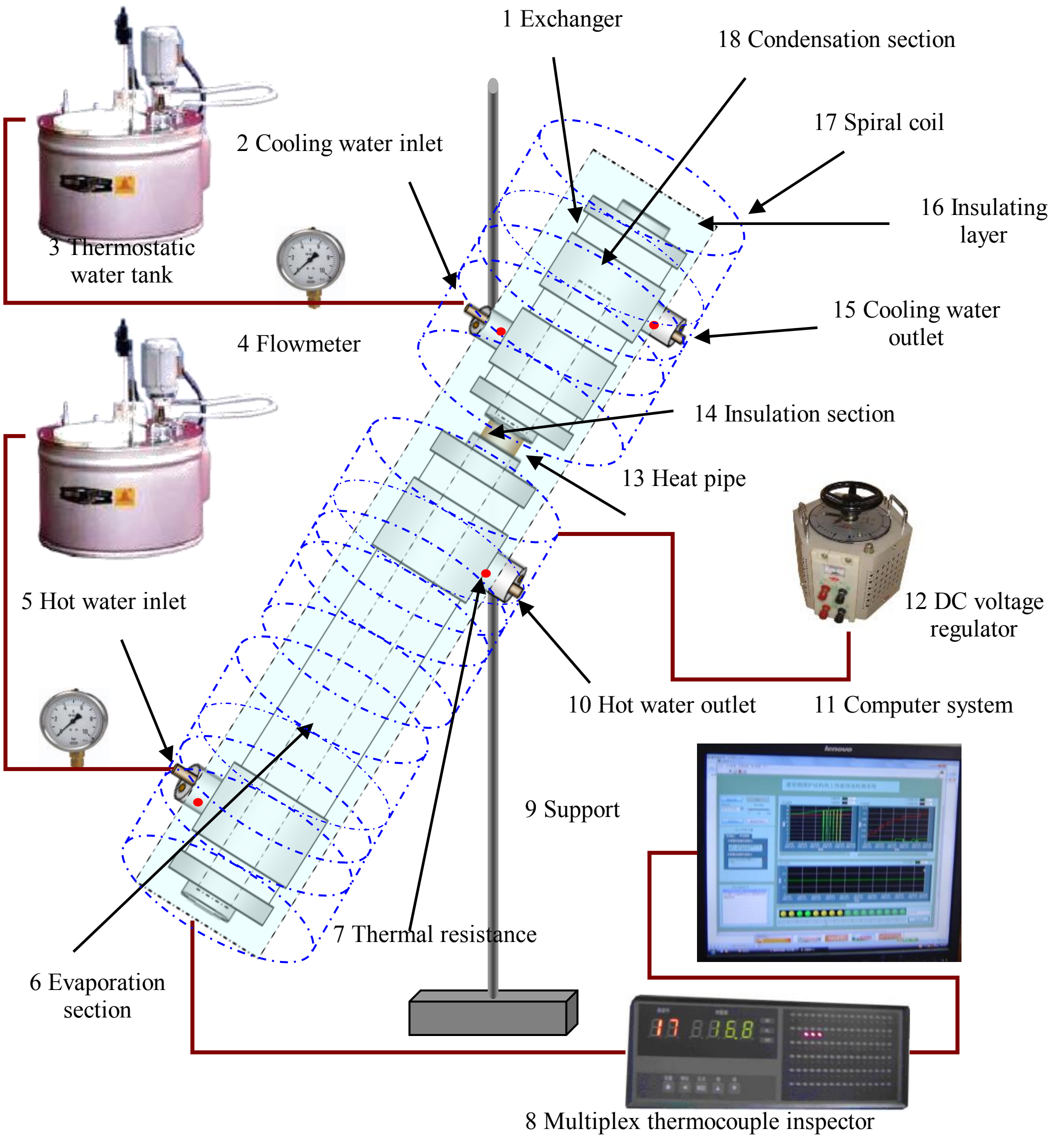

Figure 1. Schematic diagram for experiment on heat transfer features of heat pipe

The copper heat pipe is 1000mm long and its outer diameter is 16mm. Outside is PVC double-pipe heat exchanger. In order to prevent heat dissipation, around the exchanger wraps the 28-mm-thick Armaflex flexible insulation foam and around the foam wraps a layer of foil so as to reduce radiative heat transfer between the exchanger and the outside.

During the experiment, thermostatic water tank should provide hot water with temperature around 90℃; flow of cooling water and hot water is measured by flowmeter; voltage regulator is used to supply electricity for the spiral coil so as to generate magnetic field; and the temperature at the inlet and outlet of the exchanger is measured by resistance thermometer. After the experiment becomes stable, experimental data are directly collected by the inspector.

3. MATHEMATICAL MODEL

Nano-fluids can improve heat transfer performance. One main reason is that they can markedly increase fluid's heat transfer coefficient. Although some semi-empirical formulas have been employed to calculate two-phase flow's heat transfer coefficient, there has existed no accurate theory to describe heat transfer coefficient of nano-fluids so far. Heat transfer coefficient of two-phase fluid mixture is defines as follows [14]:

$$k_{eff} = \frac{k_p \alpha_p \left(dT/dx\right)_p + k_f \alpha_f \left(dT/dx\right)_f}{\alpha_p \left(dT/dx\right)_p + \alpha_f \left(dT/dx\right)_f} \tag{1}$$

Hamilton and Crosser [15] proposed a model to calculate heat transfer coefficient of liquid-solid mixture when the two-phase heat transfer coefficient ratio was over 100:

$$\frac{k_{eff}}{k_f} = \frac{k_p + (n-1)k_f - (n-1)\alpha\left(k_f - k_p\right)}{k_p + (n-1)k_f + \alpha\left(k_f - k_p\right)} \tag{2}$$

where k_p denotes the heat transfer coefficient of discontinuous particles; k_f denotes the heat transfer coefficient of liquid medium; α is particle volume fraction; n is empirical shape factor and $n = 3/\psi$; ψ denotes particle sphericity and is defined as the ratio of the surface area of a sphere (with the same volume as the given particle) to the surface area of the particle.

The formula is suitable for two-phase mixture with solid particle suspension at micron or mm level and can be used when there is no feasible formula to calculate heat transfer coefficient of nano-fluids.

According to Hamilton-Crosser model, heat transfer coefficient of nano-fluids depends on particle volume fraction and sphericity. For a given particle shape, the heat transfer coefficient of nano-fluids suspended with nano-solid particles increases with increased particle volume fraction; when particle volume fraction is fixed, the coefficient will increase with reduced particle sphericity. Therefore nano-particles' shape and property have great influence on the heat transfer coefficient and nano-fluids can enhance the fluid heat transfer coefficient.

4. EXPERIMENT RESULT AND ANALYSIS

4.1 The influence of DC magnetic field on heat transfer speed of vacuum nano-magnetic fluid heat pipe

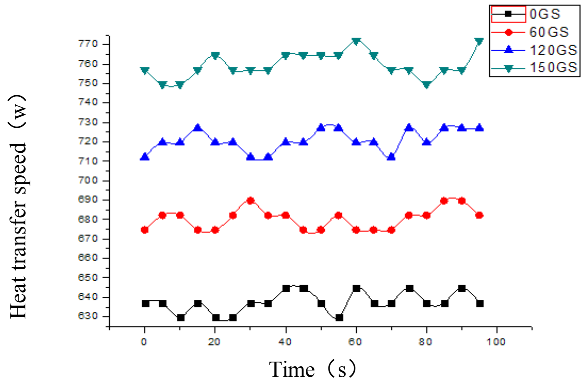

Figure 2. The influence of DC magnetic field on heat transfer of nano-magnetic fluid pipe

As shown in Fig. 2, DC magnetic field can significantly enhance the heat transfer speed of vacuum nano-magnetic fluid pipe and the speed increases with strengthened magnetic field. Averagely, 60-GS, 120-GS, and 150-GS DC magnetic fields can enhance the speed by 6.7%, 13%, and 19.2% respectively compared to the situation without magnetic field.

4.2 The influence of AC magnetic field on heat transfer speed of vacuum nano-magnetic fluid heat pipe

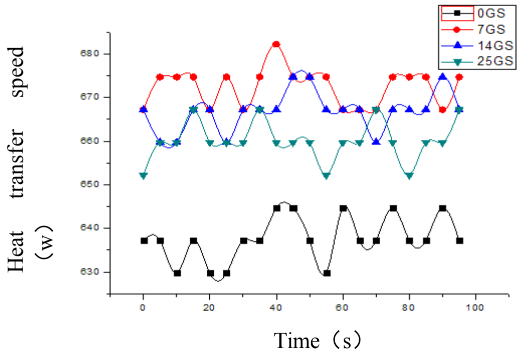

Figure 3. The influence of AC magnetic field on heat transfer of nano-magnetic fluid pipe

Fig. 3 indicates that AC magnetic field can also enhance the heat transfer speed of vacuum nano-magnetic fluid pipe but with strengthened magnetic field, the increase in the speed will first raise and then reduce. In other words, averagely, under the influence of 7-GS AC magnetic field, the heat transfer speed raises by 5.5%; when the magnetic field is 14GS, it raises by 4.6%; and when the magnetic field is 25GS, it raises by 3.5% compared to the situation without magnetic field.

4.3 The influence of gradient magnetic field on heat transfer speed of vacuum nano-magnetic fluid heat pipe

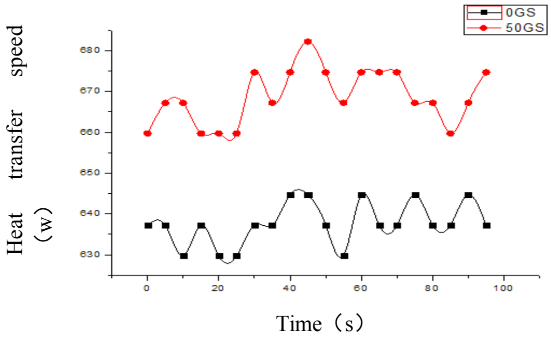

Figure 4. The influence of Gradient magnetic field on heat transfer of nano-magnetic fluid pipe

As seen from Fig. 4, 50-GS gradient magnetic field can improve the heat transfer speed of vacuum nano-magnetic fluid pipe and the average increase is 4.9%.

The improvement rates of heat transfer speeds of vacuum nano-magnetic fluid pipe under varied working conditions are presented in Table 1.

Table 1. The improvement rates of heat transfer speeds of vacuum nano-magnetic fluid pipe under varied working conditions

DC magnetic field	60GS	120GS	150GS
rate of improvement	6.7%	13%	19.2%
AC magnetic field	7GS	14GS	25GS
rate of improvement	5.5%	4.6%	3.5%
gradient magnetic field	50GS	——	——
rate of improvement	4.9%	——	——

4.4 Comprehensive experiment research on and analysis of vacuum heat pipes with various working fluids under no magnetic field

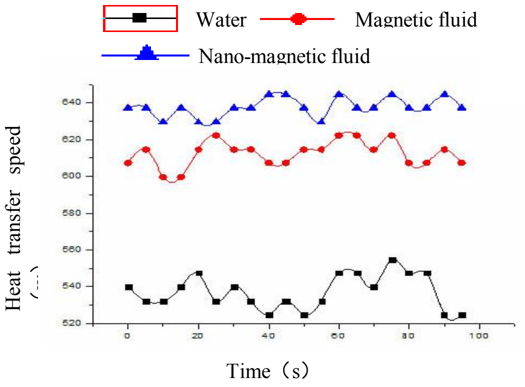

Figure 5. The relationship between time and heat transfer speed of vacuum heat pipe with various working fluids under no magnetic field

Fig. 5 reveals that under no magnetic field, heat transfer speeds of vacuum nano-magnetic fluid and magnetic fluid heat pipes are much higher than that of water heat pipe and averagely, they are 18.7% and 14% higher. This is largely due to the solid particles and surfactants in nano-magnetic fluid and magnetic fluid: collision between solid particles improve fluid’s heat transfer coefficient; and surfactants reduces liquid’s surface tension and helps to enhance nucleate boiling of liquid.

4.5 Comprehensive experiment research on and analysis of vacuum heat pipes with various working fluids under the influence of DC magnetic field

(1) Under the influence of 60-GS DC magnetic field

As shown in Fig. 6, under the influence of 60-GS DC magnetic field, the heat transfer speeds of vacuum nano-magnetic fluid and magnetic fluid heat pipes are much higher than that of vacuum water heat pipe and averagely, they are 23% and 17.5% higher. Besides, vacuum nano-magnetic fluid pipe transfers heat 4.7% faster than vacuum magnetic fluid pipe.

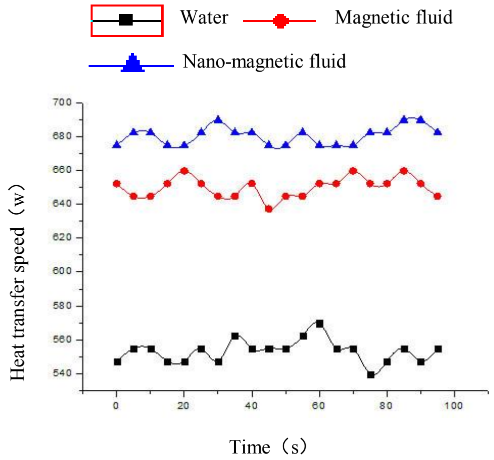

Figure 6. Heat transfer of heat pipes with various working fluids under the influence of 60-GS DC magnetic field

(2) Under the influence of 120-GS DC magnetic field

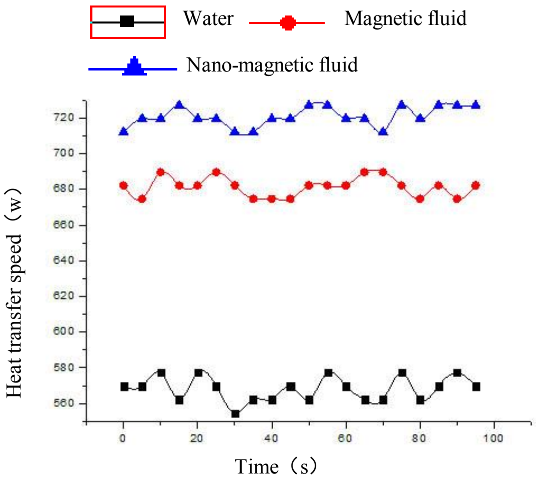

Figure 7. Heat transfer of heat pipes with various working fluids under the influence of 120-GS DC magnetic field

From Fig. 7, it can be seen that under the influence of 120-GS DC magnetic field, the heat transfer speeds of vacuum nano-magnetic fluid and magnetic fluid heat pipes are much higher than that of vacuum water heat pipe and averagely, they are 26.8% and 19.9% higher. What is more, vacuum nano-magnetic fluid pipe transfers heat 5.8% faster than vacuum magnetic fluid pipe.

(3) Under the influence of 150-GS DC magnetic field

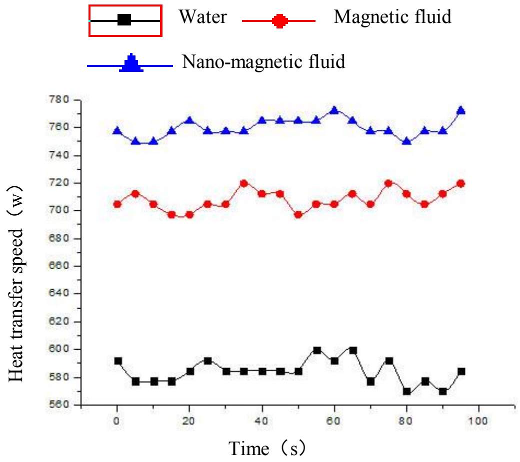

Figure 8. Heat transfer of heat pipes with various working fluids under the influence of 150-GS DC magnetic field

Fig. 8 indicates that under the influence of 150-GS DC magnetic field, the heat transfer speeds of vacuum nano-magnetic fluid and magnetic fluid heat pipes are much higher than that of vacuum water heat pipe and averagely, they are 30% and 21.1% higher. In addition, vacuum nano-magnetic fluid pipe transfers heat 7.3% faster than vacuum magnetic fluid pipe.

(4) Comprehensive analysis of the situation under the influence of various magnetic fields

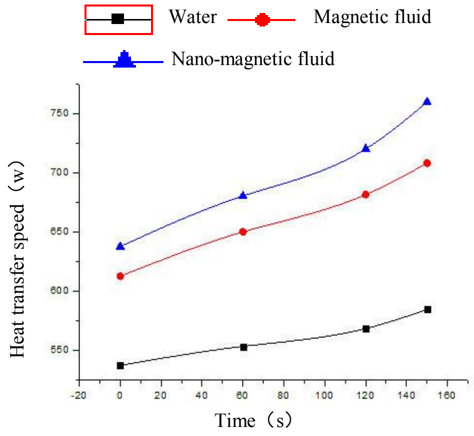

Figure 9. The relationship between heat transfer speed of vacuum heat pipes with various working fluids and magnetic field strength under the influence of DC magnetic field

As seen in Fig. 9, under DC magnetic field, heat transfer speeds of three heat pipes are all improved and they increase with strengthened DC magnetic field. Besides, with strengthened magnetic field, nano-magnetic fluid heat pipe shows the largest improvement rate in the speed, followed by magnetic fluid heat pipe and water heat pipe.

In evaporation section, DC magnetic field enhances apparent density of nano-magnetic fluid and magnetic fluid and strengthens natural convection heat transfer of magnetic fluid; in condensation section, static DC magnetic field improves dissipation and accelerates steam condensation. DC magnetic field exerts influence in the evaporation and condensation section so it can enhance the heat transfer of heat pipes.

4.6 Comprehensive experiment research on and analysis of vacuum heat pipes with various working fluids under the influence of AC magnetic field

(1) Under the influence of 7-GS AC magnetic field

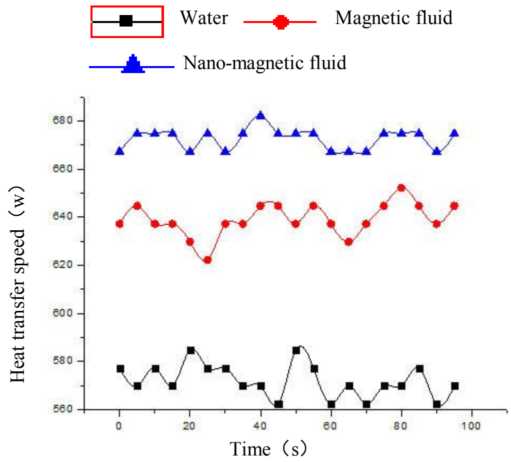

Figure 10. Heat transfer of heat pipes with various working fluids under the influence of 7-GS AC magnetic field

Fig. 10 shows that under the influence of 7-GS AC magnetic field, the heat transfer speeds of vacuum nano-magnetic fluid and magnetic fluid heat pipes are higher than that of vacuum water heat pipe and averagely, they are 17.6% and 11.7% higher. In addition, vacuum nano-magnetic fluid pipe transfers heat 5.2% faster than vacuum magnetic fluid pipe.

(2) Under the influence of 14-GS AC magnetic field

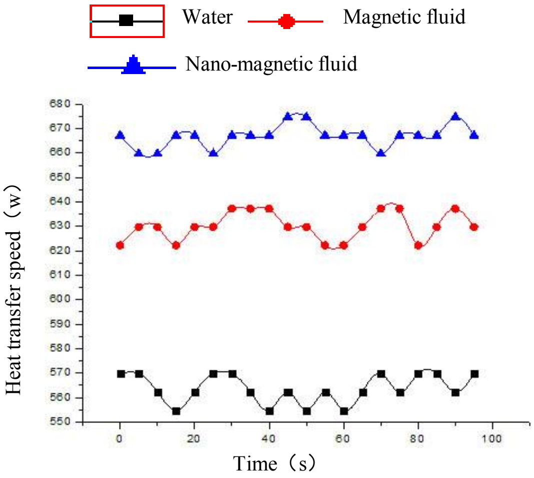

Figure11. Heat transfer of heat pipes with various working fluids under the influence of 14-GS AC magnetic field

Fig. 11 reveals that under the influence of 14-GS AC magnetic field, the heat transfer speeds of vacuum nano-magnetic fluid and magnetic fluid heat pipes are higher than that of vacuum water heat pipe and averagely, they are 18.3% and 11.7% higher. In addition, vacuum nano-magnetic fluid pipe transfers heat 5.8% faster than vacuum magnetic fluid pipe.

(3) Under the influence of 25-GS AC magnetic field

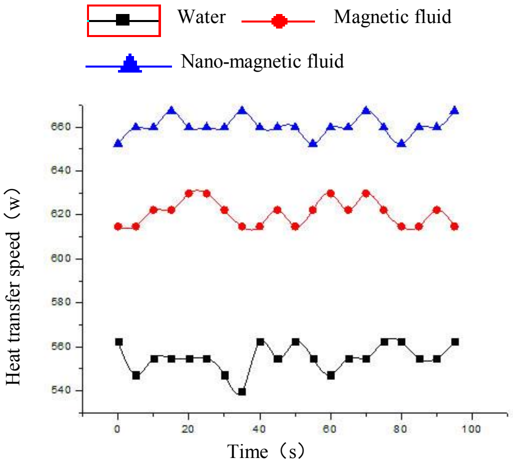

Figure 12. Heat transfer of heat pipes with various working fluids under the influence of 25-GS AC magnetic field

As seen from Fig. 12, under the influence of 25-GS AC magnetic field, the heat transfer speeds of vacuum nano-magnetic fluid and magnetic fluid heat pipes are higher than that of vacuum water heat pipe and averagely, they are 18.9% and 11.8% higher. In addition, vacuum nano-magnetic fluid pipe transfers heat 6.3% faster than vacuum magnetic fluid pipe.

(4) Comprehensive analysis under the influence of varied magnetic fields

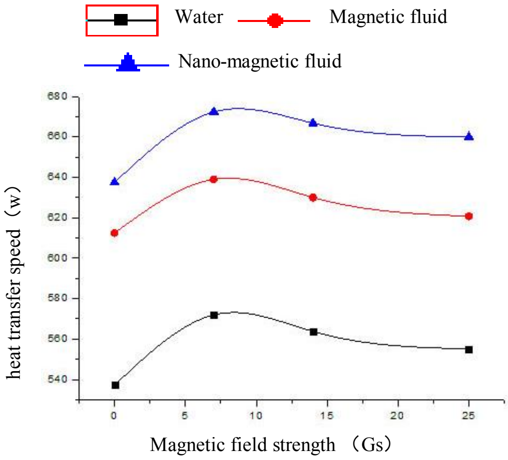

Figure 13. The relationship between heat transfer speeds of vacuum heat pipes with various working fluids and magnetic field strength under the influence of AC magnetic field

From Fig. 13, it can be seen that under the influence of AC magnetic field, heat transfer speeds of vacuum heat pipes with three working fluids are all improved; but with strengthened AC magnetic field, improvement rates for the speeds of three heat pipes will first raise and then reduce and peak at 7GS.

In the experiment, AC magnetic field changes its direction 50 times every second so it has strong penetration ability. Fluid is affected by the magnetic force which is closely related to the temperature field of the fluid. Magnetic force changes with changed temperature, which gives rise to fluid flow. The flow is called thermomagnetic convection and can enhance natural heat convection in evaporation section [16-20]. But the magnetic force changes its direction as magnetic field changes its direction. So thermomagnetic convection cannot be strengthened all the time. Instead, it has a peak value with strengthened magnetic field. Thus, AC magnetic field's enhancement in the heat transfer of heat pipe has its peak value.

4.7 Comprehensive experiment research on and analysis of vacuum heat pipes with various working fluids under the influence of gradient magnetic field

(1) Hourly analysis of gradient magnetic field

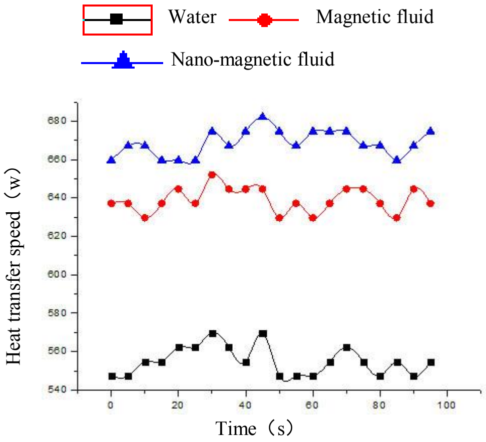

Figure 14. Hourly analysis of gradient magnetic field

Fig. 14 indicates that under the influence of 50-GS gradient magnetic field, the heat transfer speeds of vacuum nano-magnetic fluid and magnetic fluid heat pipes are higher than that of vacuum water heat pipe and averagely, they are 20.4% and 15.1% higher. In addition, vacuum nano-magnetic fluid pipe transfers heat 4.6% faster than vacuum magnetic fluid pipe.

(2) Average comprehensive analysis of gradient magnetic field

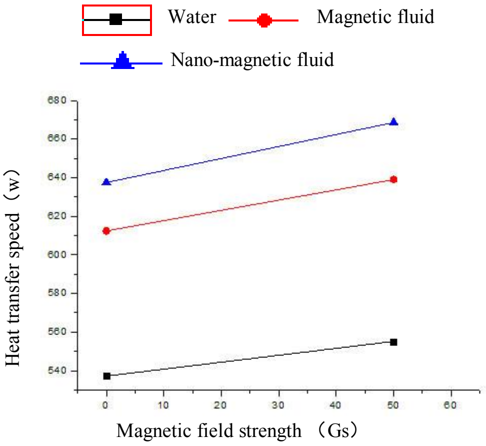

Figure 15. The relationship between heat transfer speeds of vacuum heat pipes with various working fluids and magnetic field strength under the influence of gradient magnetic field

As shown in Fig. 15, under the influence of gradient magnetic field, heat transfer speeds of three heat pipes are all improved; but the enhancement is slight: 4.9% for nano-magnetic fluid heat pipe, 4.3% for magnetic fluid heat pipe, and 3.4% for water heat pipe. To investigate its reasons, on one hand, gradient magnetic field can improve magnetic fluid's apparent density and strengthen the natural heat convection; on the other hand, fluid in uneven gradient magnetic field also has thermomagnetic convection, which strengthens natural convection in evaporation section.

5. CONCLUSIONS

Based on experiment data processing and theoretical analysis, we can reach the following conclusions:

(1) DC magnetic field, AC magnetic field, and gradient magnetic field can all enhance transfer speed of vacuum heat pipes with various working fluids and static DC magnetic field can best improve the heat transfer effect of heat pipe.

(2) Nano-magnetic fluid heat pipe is superior to magnetic fluid heat pipe while the latter is superior to water heat pipe.

On one hand, under various working conditions, nano-magnetic fluid heat pipe possesses the largest heat transfer speed, followed by magnetic fluid and water heat pipe. For instance, under the influence of DC magnetic field, the maximum heat transfer speeds of nano-magnetic fluid and magnetic fluid heat pipes are 30% and 21.1% higher than that of water heat pipe. On the other hand, under the influence of DC magnetic field and gradient magnetic field, nano-magnetic fluid heat pipe has the largest improvement rate of heat transfer speed, followed by magnetic fluid heat pipe; and under the influence of AC magnetic field, improvement rates of heat transfer speed of nano-magnetic fluid heat pipe and water heat pipe are almost the same.

(3) DC magnetic field shows the best effect of enhancing heat transfer of heat pipes.

Due to the limited experiment equipment, the maximum DC magnetic field is 150-GS. Under the influence of this magnetic field, the improvement rates of heat transfer speed of vacuum water, magnetic, and nano-magnetic fluid pipes are 8.8%, 15.6%, and 19.2% respectively. If the magnetic field can be further strengthened, the heat transfer speed of heat pipe will continue to increase.

(4) The improvement rate of heat transfer speed under the influence of AC magnetic field has its peak value and water heat pipe can be best enhanced.

AC magnetic field of around 7GS can increase heat transfer speed to its maximum. Under the influence of this magnetic field, the improvement rates of heat transfer speed of vacuum water, magnetic, and nano-magnetic fluid pipe are 6.5%, 4.3%, and 5.5% respectively. When the strength of AC magnetic field is over 7GS, the improvement rates of heat transfer speed will decrease.

(5) Gradient magnetic field cannot significantly improve heat transfer speed. Under the influence of 50-GS gradient magnetic field, the improvement rates of heat transfer speed of vacuum water, magnetic, and nano-magnetic fluid pipe are 3.4%, 4.3%, and 4.9% respectively.

In the experiment on heat transfer features of nano-fluids in vacuum heat pipe under the influence of external magnetic field, heat transfer performance of vacuum nano-magnetic fluid heat pipe has been tested. Combing the result with micro-scale heat transfer, external magnetic field, and materialization of nano-particle, we have carried out an in-depth research on the law of how magnetic field, magnetic fluid, and nano-particle enhance heat transfer of heat pipes. This provides basic data and scientific basis for optimizing and designing efficient heat transfer systems and preparing magnetic fluid. The study on the enhancement of heat transfer of magnetic fluid under the influence of external magnetic field will also help solve problems in high-tech field, such as efficient heat transfer, heat dissipation, and heat recovery. For example:

(1) Nano-fluids can be used to optimize working temperature of engine so that cooling system can become smaller and lighter and fuel consumption can be reduced.
(2) It can be used to cool cutting tools in machining to improve the speed and precision of work piece processing and prolong service life of cutting tools.
(3) It can be used in power electronics industry. Heat dissipation restrains the operating efficiency, speed, and service life of computers, micro-electronics, micro-motors, large-scale motors, transformers, integrated circuits, and communication systems. Efficient nano-fluid cooling techniques can play an important role.
(4) It can be used as refrigerant in HVAC system and heating medium in solar energy recovery to greatly improve the heat transfer performance, reduce volume, and enhance efficiency.
(5) It can be used to produce more efficient heat exchangers, radiators, and heat pipe exchangers.

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