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Technical Note

Experimental study on pulsating heat pipe with functional thermal fluids

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ABSTRACT

An experimental investigation is conducted to explore the heat-transport capability of pulsating heat pipes (PHP) working with functional thermal fluids (FS-39E microcapsule fluid and Al_2O_3 nano-fluid), by comparing them with pure water. The test tube is a four-turn pulsating heat pipe, made of a copper tube with an external diameter of 2.5 mm, and an inner diameter of 1.3 mm. The results show that the heat-transport capability of PHP can be enhanced by using FS-39E microcapsule fluid and Al_2O_3 nano-fluid as working fluid under specific conditions. When using vertical bottom heat mode, FS-39E microcapsule fluid is the best working fluid and its best concentration is 1 wt%; when using horizontal heat mode, Al_2O_3 nano-fluid is the best working fluid and its best concentration is 0.1 wt%.

1. Introduction

Pulsating/oscillating heat pipe (PHP/OHP) is a new type of efficient heat transfer device which was introduced in the mid-1990s by Akachi [1]. It is getting a great deal of attention due to its simple design, small size and excellent thermal performance. PHP has shown high promise for electronic cooling and potential for thermal control applications for space and avionics. It is different from the conventional heat pipe in design and working principle. It is made of a long continuous capillary tube bent into many turns, and contains more working fluid. In addition, no wick structure is required to assist the condensed working fluid to flow back to the evaporator. Moreover, its ring circuit closed structure has avoided the vapor-liquid convection so that the thermal entrainment limit is reduced. PHP is the most promising solution for higher heat dissipation from the smaller electronic components.

How to improve and enhance the heat-transport capability of PHP has become a hot research topic. Among the numerous methods, the most direct and effective one is to find out the excellent functional thermal fluid as working fluid and the best liquid filling ratio.

Ma et al. [2,3], Shang et al. [4], Park and Ma [5], Chiang et al. [6], Lin [7], found that using nano-fluid as working fluid of PHP could effectively enhance heat transfer. Nevertheless, none of them used Al_2O_3 nano-fluid as working fluid. The present research used FS-39E microcapsule fluid and Al_2O_3 nano-fluid as working fluid comparing with pure water, explored and analyzed how functional thermal fluid influence the heat-transport capability of PHP in detail.

2. Experiment setup and process

In the experiment, a copper tube with external diameter of 2.5 mm and inner diameter of 1.3 mm was used as the materials, and it was welded into a four-turn pulsating heat pipe. Two operational orientations were investigated, viz. vertical bottom heat mode (inclination angle = 90°) and horizontal heat mode (inclination angle = 0°). The nickel chrome electric wires were wound around the copper tube which was wrapped in thermal insulation adhesive plaster. The length of evaporation section was 35 mm, the same as the condensation section; and the condensation section was cooled by water (setting the temperature of NC low-temperature thermostat bath at 22 ± 0.05 °C). As shown in Fig. 1, valve D was used to control water flow. Before the test, valve B must be closed, valve A opened and the vacuum pump was started to make the tube into vacuum (vacuum is under 1.0 kPa). And then, valve A turned to be closed and valve B turned to be opened, the working fluid was inhaled slowly into the tube under the pressure difference. Liquid filling ratio was calibrated at the end of the test. The OMEGA K-type thermocouples (accuracy ± 0.1 °C) were installed at different positions of PHP to measure the wall temperature at different heat load. The pulse of temperature was measured to reflect the internal working fluid oscillation indirectly. The detailed location of thermocouples was shown in Fig. 1. The entire experimental process was carried out in 25 °C air-conditioned environment.

The working fluid FS-39E microcapsule fluid used in this experiment was made by Japan's Mitsubishi. The phase transition (from

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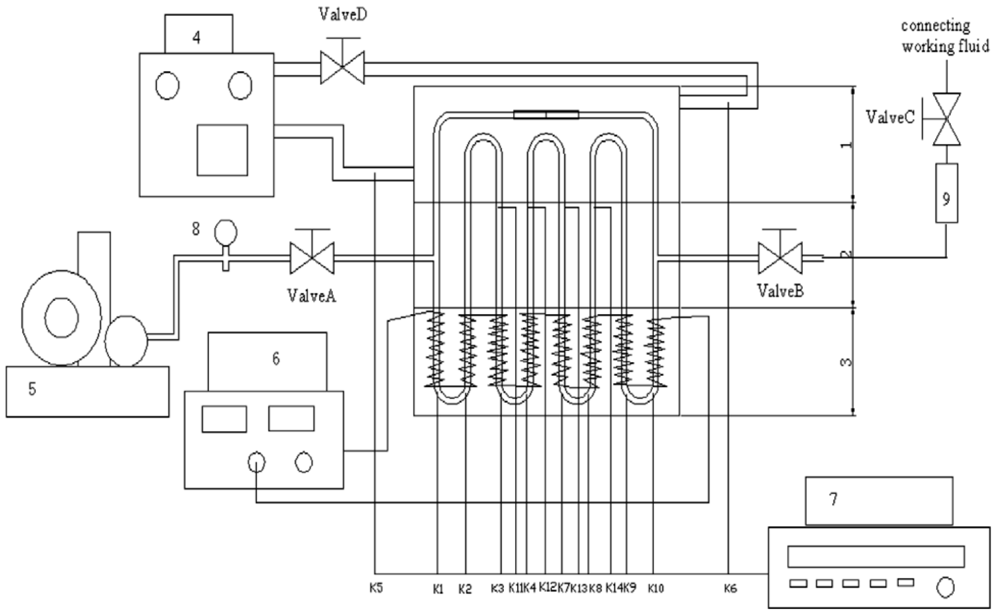

Fig. 1. Experimental apparatus of PHP. 1 – condensation section ; 2 – thermal insulation section; 3 – evaporation section; 4 – Tianheng SDC-6 NC low-temperature thermostat bath; 5 – DTC-21 diaphragm pump; 6 – DC power supply; 7 – Agilent34970a and data acquisition module; 8 – vacuum table; 9 – liquid flow meter; k1–k14 – the location of thermocouples.

solid to liquid) temperature of FS-39E microcapsule is 39.66 °C. The phase change latent heat is 165.5 J/g. The particle size of capsule is about 1 μm. In this experiment, FS-39E microcapsule particles were diluted to 0.5, 1, 2 and 3 wt%, respectively.

The preparation of Al_2O_3 nano-fluid was proceeded as following: mixed alumina nanometer powder (purity 99.98%, surface area 100 m^2/g, molecular weight 101.96, boiling point 2980 °C, density 3.965 g/cm^3, melting point 2045 °C) with chemical dispersants $C_{18}H_{29}NaO_3S$ (CP) at the ratio of 1:1, added pure water to an appropriate concentration under the ultrasound condition, and vibrated for about an hour to achieve physical dispersion (the temperature of water was kept below 38 °C). The Al_2O_3 nano-fluid was diluted to 0.1 and 0.5 wt%, respectively.

3. Results and analysis

Nickel chrome electric wire, which was wound around the evaporation section in this experiment, was used to simulate heating condition. There was insulation cotton packaged outside in order to avoid heat loss. The heat balance equation was calculated as follows: Q_h(heat load) = Q_t(heat transport by PHP) + Q_l(heat loss). The thermal resistance of PHP was equal to temperature difference between condensation and evaporation divided by heat load. $R_{PHP} = (Te - Tc)/Q_h$ (R_{PHP}: thermal resistance of PHP, Te: average temperature of evaporation section, Tc: average temperature of condensation section).

In order to keep a good operation of working fluid in PHP whether vertical bottom heat mode or horizontal heat mode, the working condition in 50% filling ratio was chosen for comparison with different working fluid as in the following test.

3.1. Heat-transport capability of PHP with FS-39E microcapsule fluid as working fluid

When using vertical bottom heat mode, the comparative analysis of thermal resistance between FS-39E microcapsule fluid and pure water at different heat load is shown in Fig. 2(a). It is found that when heat load is over 50 W, the heat-transport capability of PHP with FS-39E microcapsule fluid as working fluid is better than pure water, and the best concentration of FS-39E microcapsule fluid is 1 wt%. When the heat load is 80 W, the thermal resistance of PHP is decreased by 0.35 °C/W, comparing with pure water. The reasons about FS-39E microcapsule enhancing heat transfer are summarized as follows: FS-39E microcapsule fluid richly contains phase change particles which can strengthen the turbulent effect when evaporation and condensation of working fluid occur in the tube. It can be favor to form more vaporization cores when phase change particles contact with the tube wall. FS-39E microcapsule fluid presents the emulsion condition so that the homogeneity of working fluid is good. Moreover the density is lower than pure water, but the heat capacity is close with the pure water, so the operating speed of FS-39E microcapsule fluid is more rapid under the same thermal driving force. Thus, there should be a best concentration of FS-39E microcapsule fluid for optimal operation.

The thermal resistance curve of FS-39E microcapsule fluid has obvious inflection point on heat-transport performance after 50 W. It is possibly because the phase change of microcapsules occur, which makes the process of evaporation and condensation more complex. At this time, the multiphase flow of steam, liquid and different forms of FS-39E microcapsule in the PHP strongly enhance heat transfer.

When using horizontal heat mode, the superiority of microcapsule fluid is not obvious in Fig. 2(b). It is possibly because FS-39E microcapsule fluid flows without the help of gravity and the perturbation of phase change is weakened. The effect of viscosity and surface tension becomes more important on heat-transport performance. However, under the high heat load (80 W), the performance is close to pure water as well.

3.2. Heat-transport capability of PHP with Al_2O_3 nano-fluid as working fluid

As shown in Fig. 3, after a certain degree of heat load (40 W), the heat-transport capability of PHP with Al_2O_3 nano-fluid as working fluid is better than pure water regardless of vertical bottom heat mode or horizontal heat mode.

The reasons about the Al_2O_3 nano-fluid enhance heat transfer in the vacuum tube are summarized as follows: (1) The nano-powder particles have big surface area so that the heat conduction area

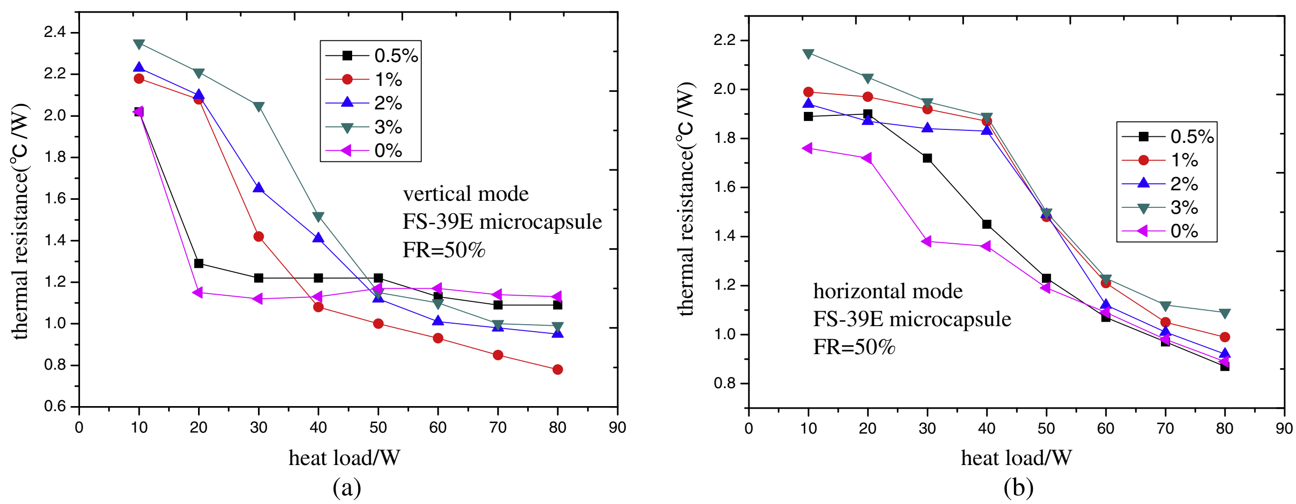

Fig. 2. Relationship between heat load and thermal resistance of FS-39E microcapsule fluid: (a) vertical mode and (b) horizontal mode.

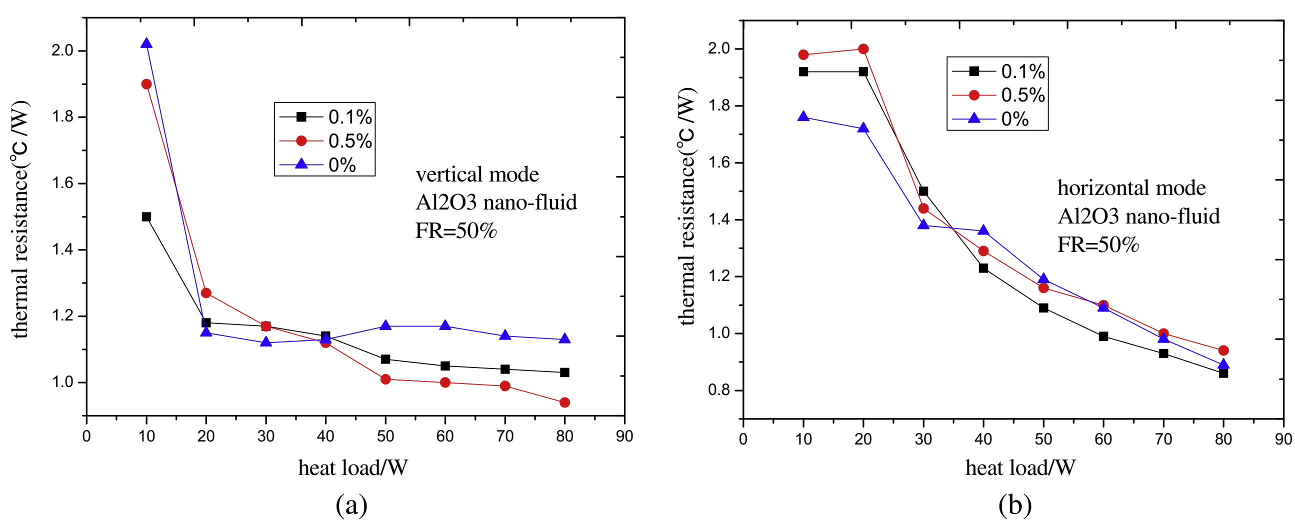

Fig. 3. Relationship between heat load and thermal resistance of Al_2O_3 nano-fluid: (a) vertical mode and (b) horizontal mode.

between the base fluid and the particles is increased when nano-powder particles spread into the base fluid. (2) The size of the nano-powder particles is so small and the particles speed of Brownian motion is so quick that micro-convection heat movement can not be ignored. (3) The thermal conductivity of nano-fluid should be common result of the base fluid heat conduction and the nano-particles migration. (4) The size of nano-powder particle is close to the phonon by which heat transfer is achieved so that the nano-powder particle can penetrate the based fluid to form a heat short-circuit and reduce the thermal resistance. Because of the violent disturbances of nano-powder particles, the thermal resistance curve of Al_2O_3 nano-fluid has obvious inflection point at 40 W, when the thermal driving force is enough to form chaotic flow.

When using vertical bottom heat mode, the best concentration of Al_2O_3 nano-fluid is 0.5 wt%; while using horizontal heat mode, the best concentration of Al_2O_3 nano-fluid is 0.1 wt%. It may be because the surface tension becomes the main obstacle for operation of working fluid without gravity at the horizontal. The Al_2O_3 nano-fluid in low concentration (0.1 wt%) means lower viscosity and density so that the speed of operation is faster at the same thermal driving force. In contrast, when using vertical bottom heat mode, with the help of gravity, even if the Al_2O_3 nano-fluid in high concentration (0.5 wt%), which means containing more nano-powder particles, can enhance disturbances to improve heat-transport capability.

3.3. Comparison on the heat-transport capability of PHP with different working fluids

In view of the analysis above, it is found that when FS-39E microcapsule fluid and Al_2O_3 nano-fluid are used as working fluid, the PHP shows better heat-transport capability than pure water under certain heat load. When using vertical bottom heat mode, the best concentration of FS-39E microcapsule fluid and Al_2O_3 nano-fluid is 1 and 0.5 wt%, respectively. As shown in Fig. 4(a), comparing with pure water as working fluid, when using 1 wt% FS-39E microcapsule fluid and 0.5 wt% Al_2O_3 nano-fluid, the thermal resistance of PHP is decreased by 0.35 and 0.19 °C/W in the heat load of 80 W, respectively. Obviously, with the help of gravity, the role of enhanced heat transfer by FS-39E microcapsule fluid which contains phase change particles is superior to Al_2O_3 nano-fluid which just includes a single solid-liquid mixture. It is because phase change particles are in favor to form more complex multi-phase mixed-flow in the process of condensation and evaporation.

However, as shown in Fig. 4(b), when using horizontal heat mode, 0.1 wt% Al_2O_3 nano-fluid is the best working fluid for improving the heat-transport capability of PHP. The advantage of

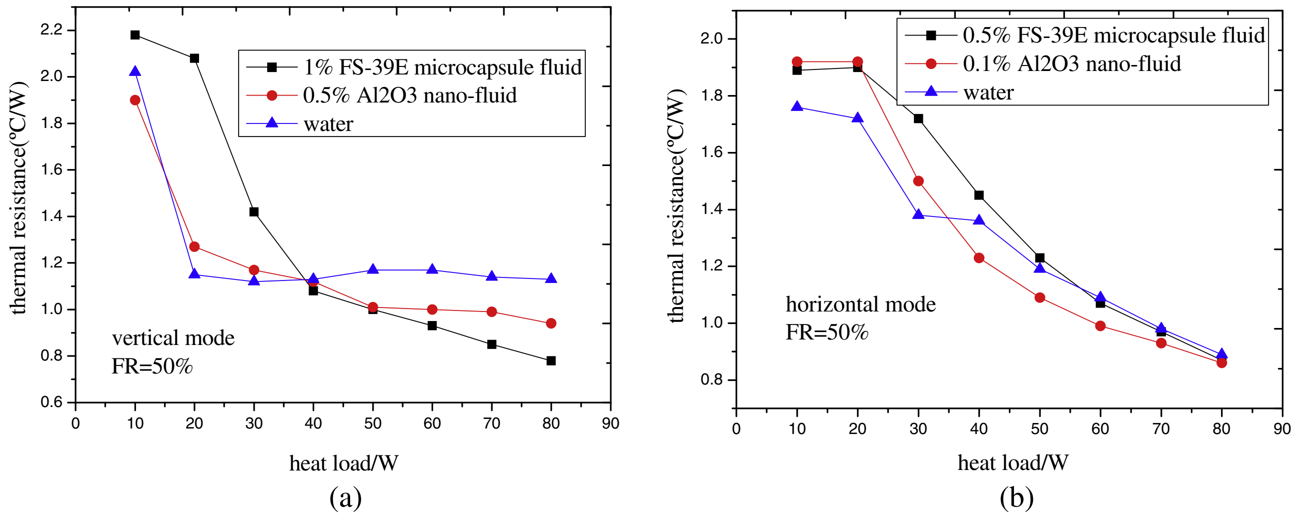

Fig. 4. Relationship between heat load and thermal resistance of different working fluids: (a) vertical mode and (b) horizontal mode.

FS-39E microcapsule fluid has not been shown. As mentioned in Section 3.1, when FS-39E microcapsule fluid flows without the help of gravity and the perturbation of phase change is weakened, the effect of viscosity and surface tension becomes more important on heat-transport performance. But under the high heat load (80 W), the thermal resistance of different working fluid is little different. This may be because convection of liquid-based plays a leading role in this condition.

4. Conclusion

(1) Comparing with pure water, functional thermal fluids (FS-39E microcapsule fluid and Al_2O_3 nano-fluid) as working fluid in PHP can enhance its heat-transport capability.
(2) When using vertical bottom heat mode, FS-39E microcapsule fluid is the best working fluid comparing to Al_2O_3 nano-fluid and pure water. The best concentration of FS-39E microcapsule fluid is 1 wt%. When heat load increases up to 80 W, the thermal resistance is decreased by 0.35 °C/W. But when using horizontal heat mode, the superiority of microcapsule fluid is not obvious.
(3) Like FS-39E microcapsule fluid, Al_2O_3 nano-fluid as working fluid can enhance heat-transport capability of PHP. Especially when using horizontal heat mode, its performance surpasses pure water and FS-39E microcapsule fluid, and the best concentration of Al_2O_3 nano-fluid is 0.1 wt%.

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