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Thermal efficiency of heat pipe with alumina nanofluid

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ABSTRACT

The study presents the enhancement of thermal efficiency of heat pipe charged with nanofluid. The Al_2O_3/water nanofluid produced by direct synthesis method is used as the working fluid of experimental heat pipes with three different concentrations (0.5, 1.0 and 3.0 wt.%). The heat pipe is a straight copper tube with inner diameter and length of 8 and 600 mm, respectively. The heat pipes charged with distilled water and nanofluids are tested, respectively. The study discusses about the effects of charge amount of working fluid, tilt angle of heat pipe and weight fraction of nanoparticles on the thermal efficiency of heat pipe. According to the experimental results, the optimum condition of heat pipe is when nanoparticles being at 1.0 wt.%. Under this condition, the thermal efficiency is 16.8%, which is higher than that of heat pipe charged with distilled water. The charge amount can be decreased from 60% to 20%.

1. Introduction

To let components undergo heat dissipation in an extremely small space is currently a very important issue. The traditional ways of enlarging the surface area of cooling fin or increasing the wind volume of fan have reached bottleneck. Heat pipe can achieve optimum heat dissipation effect by the ways of internal phase change and convection heat transfer. It can also make use of the change of geometrical shape to transfer heat to the suitable heat dissipation zone, without being limited by the surrounding space of the heating component. Heat pipe has been extensively applied to the cooling system for electronic components, pre-cooling device for air-conditioning system, and solar collectors [1–3].

Water has very high latent heat of vaporization. However, because of its higher boiling point and the lower thermal conductivity of its liquid state, letting water to serve as the working fluid of heat pipe is under restriction. It was not until Choi [4] first named the fluid added with nanoparticles as nanofluid in 1995 that the research of the field of new working fluid had been started. Adding nanoparticles to liquid can immensely improve the defects of the past that the addition of millimeter and micrometer scale particles could easily cause sedimentation and pipe blockage. Through the collision between the molecules of liquid and particles, nanoparticles can produce better heat transfer effect in fluid, effectively enhancing the heat performance of traditional working fluid. Many researches have elucidated that nanofluid has extremely good performance in heat conduction and heat convection. There would be breakthrough development of nanofluid towards the improvement of heat transfer performance of traditional working fluid [5–16]. Nevertheless, the related references about the application of nanofluid to heat pipe were not published until 2004. The study of this domain is still being at the beginning stage.

First of all, in 2004, Tsai et al. [17] demonstrated that some of the Au particle solutions could be applied to heat pipes. The thermal resistance of heat pipe ranges from 0.17 to 0.215 °C/W. The measured results show that the thermal resistance of the heat pipes with nanofluids is lower than the pipes containing pure water. In 2005, Wei et al. [18] studied the enhanced thermal performance of grooved heat pipe charged with nanofluid consisting of silver nanoparticles and deionized water.

In 2006, Kang et al. [19] investigated the enhancement of thermal performance of heat pipe using Ag nanofluid as the working fluid. The higher thermal performance of nanofluid indicates that nanofluid is much more suitable to serve as a cooling fluid for devices with high energy density. Ma et al. [20,21] studied the pulsating heat pipe charged with diamond nanofluids. The heat pipe can achieve a thermal resistance of 0.03 °C/W at a power input of 336 W.

In 2007, Park and Ma [22] pointed out that an oscillating heat pipe charged with nanofluid had higher heat transfer capacity due to the enhancement of heat transfer during the strong oscillating motion of the working fluid and the higher effective thermal conductivity of nanofluid. Chiang et al. [23] applied the nanofluid with nano-diamond concentration of 0.5 wt.% in pulsating heat pipe (PHP). It was found that the optimum charge ratio of fluid depends

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on the PHP structure, with 50% and 20% being the optimum values for the 36-port and 26-port PHPs, respectively.

In 2008 Naphon et al. [24] used the heat pipe with TiO_2/alcohol nanofluid to study its heat transfer performance, and also compared it to the heat pipes with deionized water and alcohol being the working fluids. They focused their study on the effects of heat flux, charge amount, volume fraction of nanoparticles and tilt angle of heat pipe on the thermal efficiency of heat pipe. From the research results, it is found that under the optimum situation with a charge amount of 66% and a tilt angle of 45°, adding nanoparticles can really enhance the thermal efficiency. The optimum concentration of the added nanoparticles is 0.1 vol.%, which can enhance the thermal efficiency by 10.60%. If such concentration is exceeded, the thermal efficiency will be decreased instead. The main reason for this situation is that an addition of nanoparticles in excessively great volume will lead the liquid property to be of solid phase, which would contrarily lower the evaporation rate at evaporator section. Lin et al. [25] applied Ag/water nanofluid to PHP in order to study the heat transfer efficiency. Having added 20 nm of Ag nanoparticles to pure water, they studied the effects of the added particles with different concentrations, charge ratios and heating powers on the thermal efficiency of heat pipe. From the research results, it is found that the 100 ppm nanofluid with charge ratio of 60% has the highest efficiency. Under the heating power of 85 W, the temperature difference and thermal resistance between evaporator and condenser are reduced by 7.79 °C and 0.092 °C/W, respectively when compared to the use of pure water as the working fluid.

In 2009, Kang et al. [26] made a heat pipe by charging 1 mm wick-thickness sintered circular pipe with Ag/water nanofluid so as to study its heat transfer performance. The particle sizes of the added Ag nanoparticles are 10 and 35 nm, respectively, the concentrations of the added nanoparticles are 1, 10 and 100 mg/L, respectively, and the heating power of heat pipe is 30–70 W. The heating power of the nanofluid in heat pipe is around 20 W higher than that of deionized water. The particle size of nanoparticles does not have obvious effect on heat transfer performance.

Adopting direct synthesis method, the study uses Al_2O_3 nanoparticles to make nanofluid, which serves as the working fluid of heat pipe. According to the past research experience, the suspension property of Al_2O_3/water nanoparticles is good in water. The problem of density change cannot be caused by sedimentation easily, thus meeting the requirement of high durability. Besides, although the thermal conductivity of the added oxide nanoparticles is lower than that of metallic nanoparticles, the subsequent continuous oxidization will not produce any aging problem. The study shall make straight heat pipes with nanofluids of different weight fractions at different charge amounts. Focusing on how the nanofluids of different weight fractions, charge amount and tilt angle of heat pipe affect the heat transfer performance of heat pipes under the condition of fixed heat flux, the paper evaluates the feasibility of Al_2O_3/water nanofluid within the domain of heat pipe.

2. Experimental design and procedure

2.1. Preparation of nanofluid

The Al_2O_3/water nanofluid used in this study contains commercial nanoparticles (QF-Al-13P of Yong-Zhen Technomaterial Co., Ltd.), which are added with a solute at the required weight measured by a precise electronic balance, and also added with distilled water to prepare the nanofluids of three different concentrations: 0.5, 1.0 and 3.0 wt.%. The real density of Al_2O_3 particles is 3880 kg/m^3, which can be converted to be weight fraction and volume fraction. The nanofluid is dispersed for several times by ultrasonic vibrator and electromagnetic agitator. The Al_2O_3 nanofluid formed is added with cationic dispersant (0.3 wt.% of chitosan) in order to obtain good suspension. All the completed experimental samples have to be statically placed for 1 month until good suspension effect is achieved. Fig. 1 is the TEM photograph of Al_2O_3 nanoparticles with particle size of 20–30 nm.

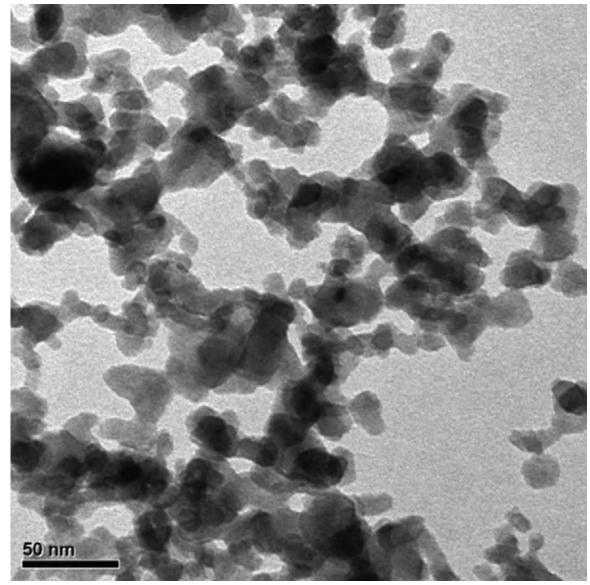

Fig. 1. The TEM photograph of Al_2O_3 nanoparticles.

2.2. Experimental setup and test procedure

The experimental setup of the study is shown in Fig. 2. The temperature of the experimental environment is controlled at 25 ± 1 °C. The heat pipe is mounted on a platform with changeable tilt angle. The two ends of the heat pipe are installed in two copper billets, respectively. Thermal couples (accuracy at 0.1%, uncertainty at ± 0.1 °C) are installed to measure the temperatures at different points. Inside the copper billet at the evaporator section is installed with electric heater, and provided with fixed heating power. The heat flux of heating is 10.65 kW/m^2. There is a cooling water passage inside the copper billet at condenser section, allowing the external thermostatic device to provide cooling water at fixed temperature for flowing to the copper billet at condenser section, and offer stable heat-dispelling temperature. The cooling water is set at the temperature of 25 ± 0.5 °C, with a flow meter (accuracy: 0.2%, uncertainty: ± 0.01 L/min) monitoring the fixed flowing volume. The heat pipe of the study is a straight copper tube with inner diameter and length of 8 and 600 mm, respectively. Its surface is wrapped by thermal insulation material in order to reduce temperature impact from the environment. The heat pipes have their vacuum pumped out, and are charged with nanofluids of different charge amounts and weight fractions, finally achieving the heat pipes used in the study. Through record and calculation the ratio of removed energy of cooling water by condenser section to the heating power by evaporator section with different charge amounts, weight fraction of nanoparticle, and tilt angle of heat pipe, the effects of thermal efficiency under different experimental parameters can be evaluated.

3. Results and discussion

Fig. 3 shows the variation of thermal efficiency of heat pipe when using distilled water as the working fluids of heat pipes at different charge amounts and tilt angles. As found in the figure, the increase of tilt angle can enhance thermal efficiency, but any increase beyond 60° will reduce thermal efficiency instead. This is mainly because of the effects of gravitational force between evaporator section and condenser section. A greater tilt angle will make the working fluid after condensation flow back to the evaporator section rapidly. However, the decrease of heat exchange time at condenser section has made the heat dissipation efficiency of cooling water at condenser section become worse. On the contrary, when the tilt angle is smaller, although the vapor of working fluid can be extended and there is more sufficient heat exchange at condenser section, the speed of backflow to evaporator section is reduced. It will also affect the efficiency of the phase change work of evaporation and condensation. Therefore, the tilt angle has to give consideration to the effects caused by the above two factors. As for the effects of charge amount on the thermal efficiency of heat pipe, as the charge amount is lower under fixed heating power, the working fluid at evaporator section shall be evaporated more

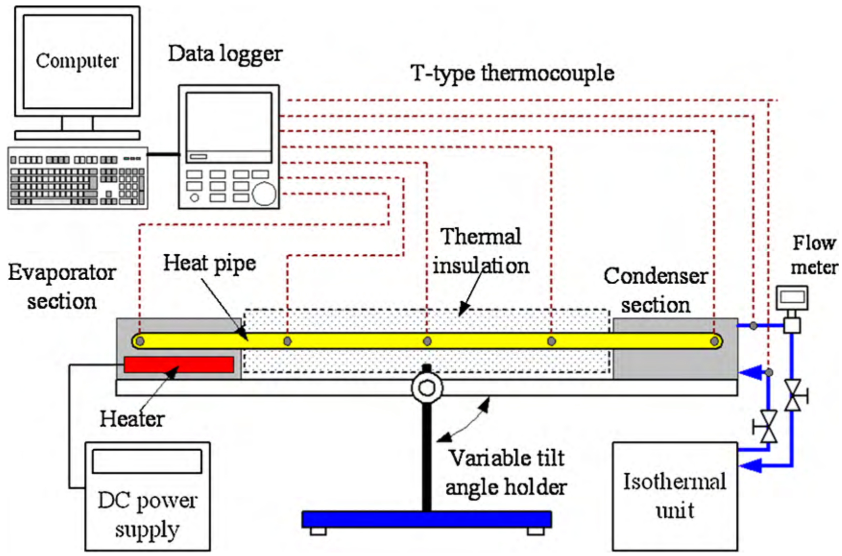

Fig. 2. Schematic diagram of experimental setup.

easily. When there is not enough time for the condensed working fluid at condenser section to return to condenser section, dryout phenomenon can be easily caused at evaporator section. The phase change is forced to delay or stop, leading to the low thermal efficiency of heat pipe. When the charge amount is excessively great, the temperature of working fluid at evaporator section will be lower, disabling the working fluid to evaporate easily. As a result, only a very small amount of vapor is flown to condenser section, and the thermal efficiency of heat pipe is also reduced. Furthermore, when the charge amount is greater, there is less space to accommodate vapor and higher the pressure inside heat pipe and suppresses the evaporation. The performance of heat pipe will also be affected accordingly. When the study uses distilled water as the working fluid of heat pipe, the optimum thermal efficiency occurs at the tilt angle of 60° and the charge amount of 60%. The achieved optimum thermal efficiency is 62.5%. When the working fluid is changed in the subsequent experiments, this numerical value is still taken as a reference of comparison in knowing the rise or reduction of thermal efficiency.

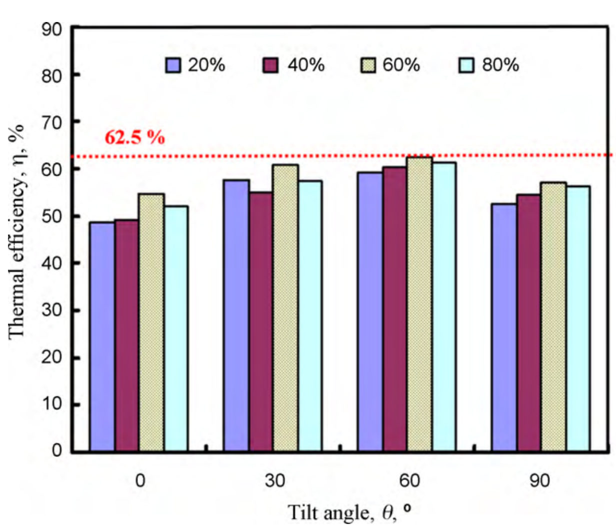

Fig. 3. Variation of thermal efficiency of heat pipes with different tilt angles of heat pipes at different charge amounts of distilled water.

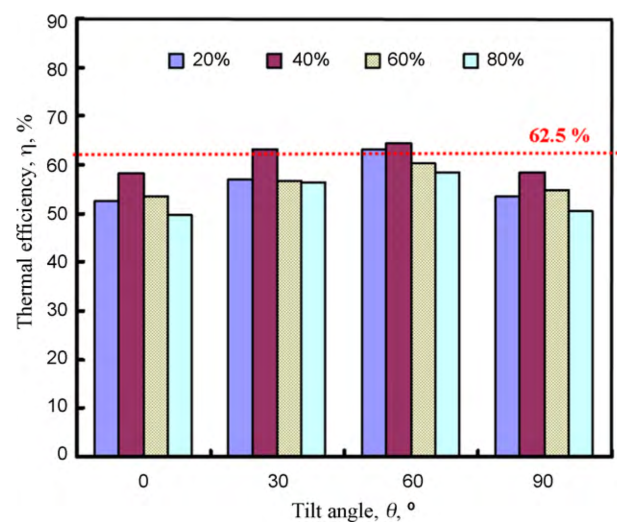

Fig. 4. Variation of thermal efficiency of heat pipes with different tilt angles of heat pipes at different charge amounts of Al_2O_3/water nanofluid at 0.5 wt.%.

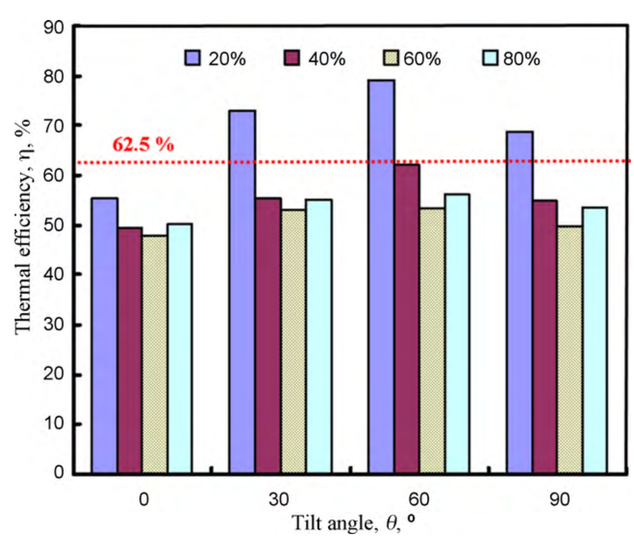

Fig. 5. Variation of thermal efficiency of heat pipes with different tilt angles of heat pipes at different charge amounts of Al_2O_3/water nanofluid at 1.0 wt.%.

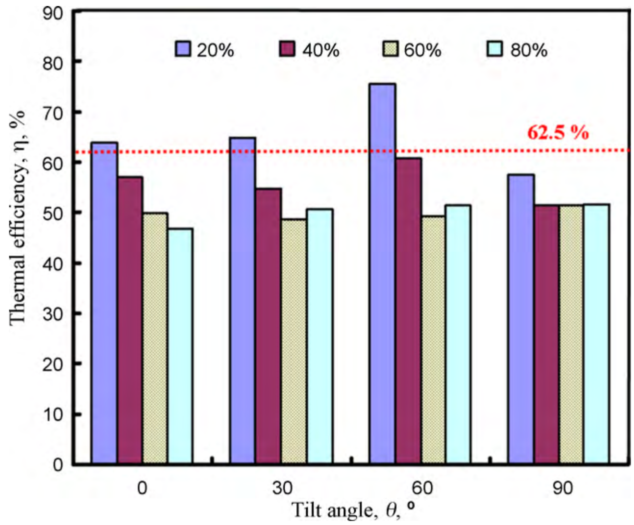

Fig. 6. Variation of thermal efficiency of heat pipe with different tilt angles of heat pipes at different charge amounts of Al_2O_3/water nanofluid at 3.0 wt.%.

Figs. 4–6 show the variation of thermal efficiency of heat pipe when using nanofluids of different weight fractions as the working fluids of heat pipes at different charge amounts and tilt angles. As shown from these figures, the optimum tilt angle of heat pipe is still 60°; but with the increase of concentration of nanoparticles, the optimum charge amount tends to move towards lower charge amount. When the concentration of the added Al_2O_3 nanoparticles is 0.5 wt.%, the optimum efficiency occurs at the tilt angle of 60° and charge amount of 40%. The optimum thermal efficiency is 64.5%, only 2% higher than that with the use of distilled water, so the enhancement of efficiency is not obvious. When the concentration of the added Al_2O_3 nanoparticles is 1.0 wt.%, the optimum efficiency occurs at the tilt angle of 60° and charge amount of 20%. The optimum thermal efficiency is 79.3%, being 16.8% higher than that with the use of distilled water, so the enhancement of thermal efficiency is extremely good. When the concentration of the added Al_2O_3 nanoparticles is 3.0 wt.%, the optimum efficiency occurs at the tilt angle of 60° and charge amount of 20%. The optimum thermal efficiency is 75.6%, being 13.1% higher than that with the use of distilled water. Although the thermal efficiency is much higher than that with the use of distilled water, it is around 3.7% lower than the situation when the concentration of the added Al_2O_3 nanoparticles is 1.0 wt.%. There appears the phenomenon that the concentration rise of the added nanoparticles contrarily reduces the thermal efficiency of heat pipe. This result was achieved because the addition of too many nanoparticles to fluid made the property of working fluid at evaporator section tend to be in solid phase, and made the convection performance of nanofluid inside evaporator section reduced. Hence, it was disadvantageous to the thermal efficiency of heat pipe.

As found in the above experimental results, adding Al_2O_3 nanoparticles to distilled water could really enhance the thermal efficiency of heat pipe. Regardless of the use of distilled water or Al_2O_3/water nanofluid, the optimal rake angle was 60°. Using nanofluid could enhance the thermal efficiency of heat pipe, mainly because of these reasons: (a) nanofluid had higher thermal conductivity. (b) The collision of nanoparticles with water molecules and pipe wall had strengthened the heat convection performance of fluid. (c) The adherence of nanoparticles to the inner wall surface of heat pipe had increased the area of heat exchange, and helped enhance the thermal efficiency of heat pipe. Furthermore, as seen from the experimental results, the optimum value of thermal efficiency tended to occur when the charge amount had to be reduced with the rise of concentration of the added nanoparticles. This situation happened mainly because after the addition of nanoparticles, although nanoparticles had enhanced the heat conduction performance of fluid and helped its thermal efficiency at evaporator section, the absorbability between nanoparticles and water molecules restricted the evaporation of water. Therefore, it was required to place nanofluid under lower pressure to help perform its phase change. When the charge amount was smaller, there was more space to accommodate vapor and make the pressure inside heat pipe become relatively lower. It helped nanofluid undergo vaporization and enhance its heat transfer performance. Besides, when the concentration of added nanoparticles was 3.0 wt.%, the thermal efficiency turned out to be lower than the concentration of 1.0 wt.%. In addition to the influence of the abovementioned absorbability between nanoparticles and water molecules, adding too many nanoparticles to fluid would make the property of working fluid at evaporator section tend to be in solid phase, and would make the convection performance of nanofluid at evaporator section reduced. This was disadvantageous to the thermal efficiency of heat pipe.

4. Conclusion

An experimental investigation was conducted for finding the thermal efficiency of a straight copper heat pipe charged with Al_2O_3/water nanofluids. Under different experimental conditions, the optimal thermal efficiency occurred when the charge amount was 60%. As the added nanoparticles are at the concentration of 1.0 wt.%, the optimum value of thermal efficiency can be enhanced by 16.8% when compared with based fluid. The required charge amount can also decrease from 60% to 20%, making heat pipe achieve a higher thermal efficiency by taking a smaller charge amount only.

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