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HEAT TRANSFER MECHANISM IN POROUS COPPER FOAM WICK HEAT PIPES USING NANOFLUIDS

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ABSTRACT

Porous copper foam was combined with three nanofluids comprised of three types of nanoparticles, $A1_2O_3$, CuO, and SiO_2 in order to develop a new type of heat pipe. The effects of factors, such as nanoparticles, filling ratio, and mass concentration, on the heat transfer performance of the heat pipe were investigated. Results showed that compared with water, the nanofluids improved the heat transfer performance of the heat pipe with varying degrees of success, and a low temperature difference was achieved. CuO nanofluids showed the best heat transfer enhancement, followed by $A1_2O_3$ and SiO_2. This study mainly focused on $A1_2O_3$ nanofluids, considering stability and thermal conductivity. The thermal resistance of the heat pipe first decreased and then increased with the filling ratio; with a 50% filling ratio being considered optimal. The heat pipe performed well with a 50% filling ratio and a 0.5% mass concentration. Wick microstructures were also investigated with a scanning electron microscope to compare the heat transfer mechanism between the porous copper foam and the mesh wicks. Results indicated that adsorption of Al_2O_3 nanoparticles onto the copper surface increased the roughness of the heat transfer surface and increased the active nucleation site density.

Keywords: Heat pipe, Nanofluids, Porous copper foam, Heat transfer.

1. INTRODUCTION

For good thermal conductivity and isothermal characteristic, heat pipes as efficient heat transfer components have been widely used in energy area, etc. Since nanofluids were first developed by Argonne National Laboratory, a series of experimental investigations[1-2] have been conducted, indicating effective thermal conductivity. To strengthen heat transfer, nanofluids can be an optimal choice as heat pipe working medium and a number of experiments have been conducted, such as gravity heat pipes and pulsating heat pipes [3–4]. Experiments showed that compared with pure fluid, nanofluids effectively increase the convection heat transfer coefficient and thermal conductivity, which can significantly enhance heat transfer [5]. Studies also indicated that using different nanoparticles, particle sizes, and mass concentrations can improve the heat transfer performance of heat pipes [6–9]. Shu et al. [10] observed that a high heat transfer coefficient in the mesh heat pipe can be obtained when nanoparticles are used in water. Pang et al. [11] investigated the effect of Cu particle size in a copper wire-bonded flat heat pipe. Another innovative method of improving heat transfer is to explore high thermal conductivity capillary wick[12-13]. Porous copper foam is a structural and functional material that can be used to replace the traditional capillary force wick because of its small proportion, high porosity, and large specific surface.

Some studies have found that heat pipes using porous copper foam not only have excellent isothermal characteristics but also extend the ability to transfer a high heat flux [14-15]. The present study tests a new type of heat pipe developed from the combination of porous copper foam with nanofluids under different conditions.

2. EXPERIMENTAL SYSTEM

The capillary wick used in this study was porous copper foam with a 200 pores per inch (PPI) pore density. Three different nanoparfluids, i.e., $A1_2O_3$, CuO and SiO_2, with an average nanodiameter of 35 nm were prepared as the working fluids. The outer diameter and length of the heat pipes tested in this experimental investigation were 10mm and 300 mm, respectively. Figure 1 shows the experimental system used to measure the wall temperature of the heat pipes. The entire system consisted of testing, cooling, measurement, and data acquisition systems. In the testing system, two electric copper rods were inserted as a heater into the copper block as a heater to simulate the supply of heat using the electronic chip. The heat load was controlled by a voltage regulator, displaying a power meter. The cooling jacket made of copper tube was used to cool down the condenser, and water flow rates were controlled by a flow meter with an accuracy of $\pm$4% of full scale. Eight K-type thermocouples with an accuracy of $\pm$0.75% were evenly installed on the outside wall to measure the temperature of the evaporator, adiabatic, and the condenser.

The entire testing system was insulated with asbestos fibers to minimize heat loss.

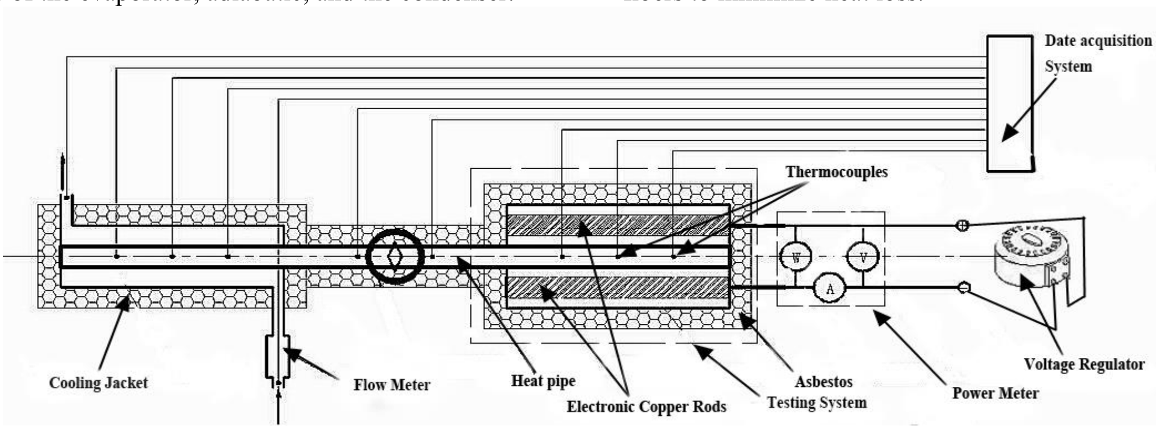
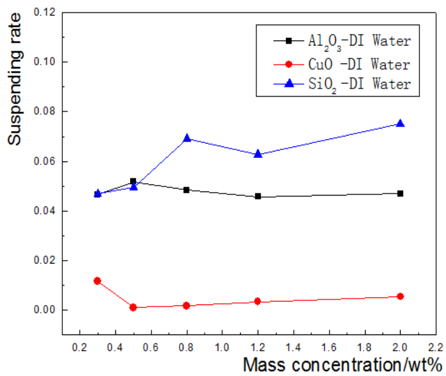


Figure 1. Experimental system

3. RESULTS AND DISCUSSION

3.1 Effects of different nanoparticles on temperature distribution

Three different nonofluids using $A1_2O_3$, CuO, and SiO_2 nanoparticles were prepared using a two-step method [16]. A 0.5 wt% nanofluid mass concentration was used in this chapter to compare the effects on temperature distribution of different nanoparticles.



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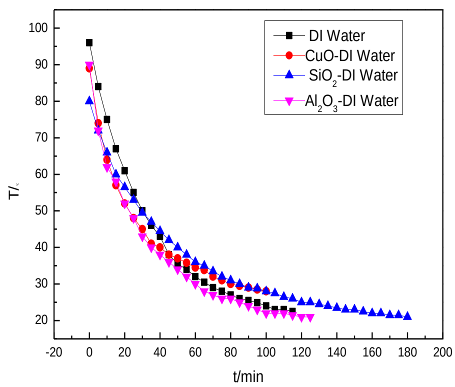


(b)

Figure 2. Migration characteristics of the nanofluids: (a) suspension rates, (b) temperature diffusion rates

Figure 2 shows the migration characteristics of the three nanoparticles, their stability, and thermal conductivity. Figure 2a illustrates that the nanofluid suspension rates, which indicate the stability of the nanoparticles, changed with the increase in mass concentration. The suspension rate is observed through the proportion of nanoparticles in nanofluids. Seen from Figure 2a, the A12O3, CuO, and SiO2 nanofluid suspension rates achieved the maximum value at mass concentrations of 0.5%, 0.3%, and 2%, respectively. Under watering-cooling condition, the nanofluids thermal conductivity can be reflected by temperature diffusion rates of the evaporation after the heat pipes are heated. Figure 2b shows that the temperature of all three types of nanofluids decreased as the time increased, but their temperature diffusion rates, which indicate their thermal conductivity, differed. A12O3 had the highest temperature diffusion rate, followed by CuO, and then SiO2. Figure 2 indicates that with the same concentration of 0.5 wt%, comparison of nanofluids stability can be represented as Al2O3 > SiO2 > CuO, and the thermal conductivity can be expressed as Al2O3>CuO>SiO2.

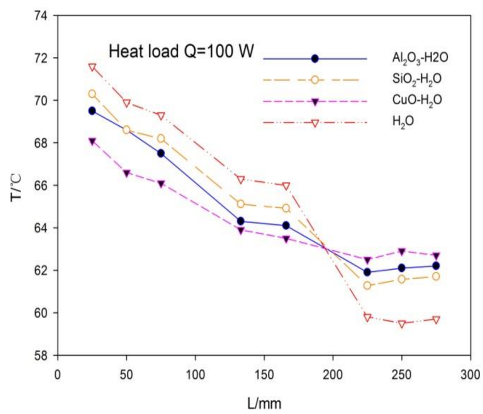
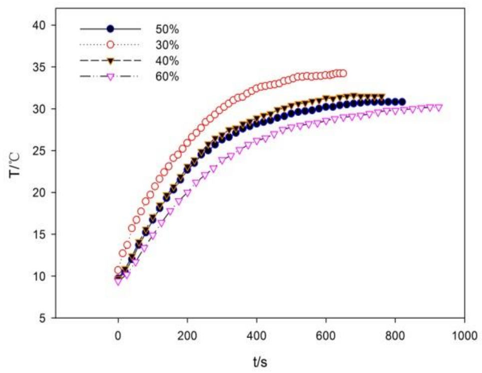


Figure 3. Temperature distribution along the heat pipes with different nanoparticles

Figure 3 shows the wall temperature distribution along the heat pipes with the same conditions of 50% filling ratio and 0.5% mass concentration. At the same heat load of 100 W, the temperature of both the evaporator and the condenser decreased compared with that of pure water. This result means that adding a certain amount of nanoparticles into pure water can enhance the heat transfer performance of heat pipes. Figure 3 illustrates that the temperature and temperature difference over time of the CuO nanofluid heat pipe were the lowest, followed by Al_2O_3 and SiO_2. Combined with the analysis of their stability and thermal conductivity in Figure 2, $A1_2O_3$ nanofluids were considered the optimal one as heat pipe working medium.

3.2 Effects of the filling ratio on heat transfer performance

The filling ratio refers to the percentage of working fluid that accounts for the evaporation volume. To determine the effects of different nanofluid filling ratios, the heat pipes were tested with various filling ratios and heat loads.



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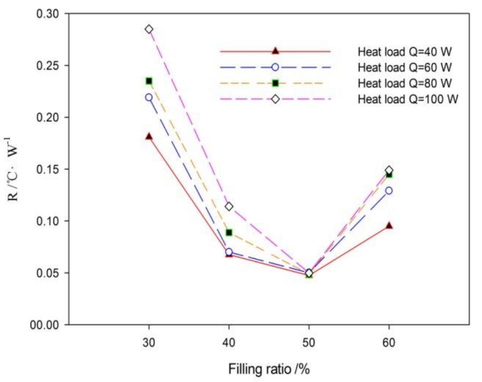


(b)

Figure 4. Effect of the filling ratio on the start-up and heat transfer performance, e.g., (a) change in start-up performance over time and (b) the thermal resistance with different filling ratios

Figure 4 shows that the Al_2O_3 nanofluid filling ratio significantly affected the start-up and heat transfer performance. Figure 4a illustrates that both the start-up temperature and time increased as the filling ratio increased because when the heat load had a constant value, the nanofluids took less time to absorb enough energy to evaporate at a low filling ratio, and the same goes for the start-up time. The thermal resistance first decreased and then increased as the filling ratio increased from 30% to 60%, as shown in Figure 4b. For example, when the heat load was 100 W, the thermal resistance of the 30%, 40%, 50% and 60% filling ratio heat pipes was 0.285, 0.114, 0.498 and 0.14 $°C·W^{-1}$, respectively. These results indicate that the heat pipes have an optimum filling ratio to achieve low thermal resistance. An insufficient filling ratio may cause burning at the evaporator section, and in this situation, the heat transport capability of the heat pipe will be limited if the liquid at the condenser section cannot be returned on time to the evaporator section by the capillary effect. As a result, the heat transfer process is blocked, and the temperature and thermal resistance will increase. With the excess filling ratio, a gas film could be generated when the nanofluids evaporate in the porous copper foam wick, and the fluids are removed from the pipe wall. Heat transfer deteriorates.

3.3 Effects of mass concentration on heat transfer performance

This study focused on the effect of nanofluid mass concentration on heat transfer performance. Al_2O_3 nanofluids with 0.1%, 0.3%, 0.5%, and 0.8% mass concentrations were prepared, and a qualitative approach in dealing with viscosity was applied, with a varying mass concentration range of 0% to 0.8%. Viscosity refers to how long it takes for the Al_2O_3 nanofluids to flow out of a certain volume of the tube, as shown in Figure 5. The longer the time takes, the higher the viscosity is. Figure 5 demonstrates that the time increased with the mass concentration; the viscosity of the Al_2O_3 nanofluids increased with the mass concentration increased. When nanoparticles were added into pure water, the entire suspension interaction force was increased. This improvement resulted in a significant positive correlation between viscosity and mass concentration, but stability decreased.

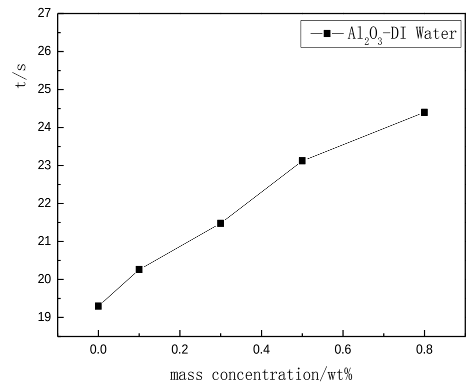


Figure 5. The time that the Al_2O_3 nanofluids take to flow out with different concentrations

Figure 6 shows the effect of Al_2O_3 nanofluid mass concentration on temperature distribution and thermal resistance. When the mass concentration increased from 0% to 0.5% (0% mass concentration refers to DI water), the average temperature and temperature difference between the evaporator and the condenser significantly decreased with the use of nanofluids instead of pure water as the working fluids. However, when the mass concentration continued to increase up to 0.8%, the heat transfer performance worsened with an increase in temperature and thermal resistance. This result means that when the mass concentration increases to a relatively high level, the stability of the nanofluids drastically decreases, and the nanoparticles easily aggregate [17-18]. Meanwhile, the change in thermal resistance had a “U” shape with the increase in mass concentration. The best mass concentration was 0.5%. For example, at heat loads of 40 W and 120 W, the thermal resistance decreased to 32% and 19.1%, respectively.

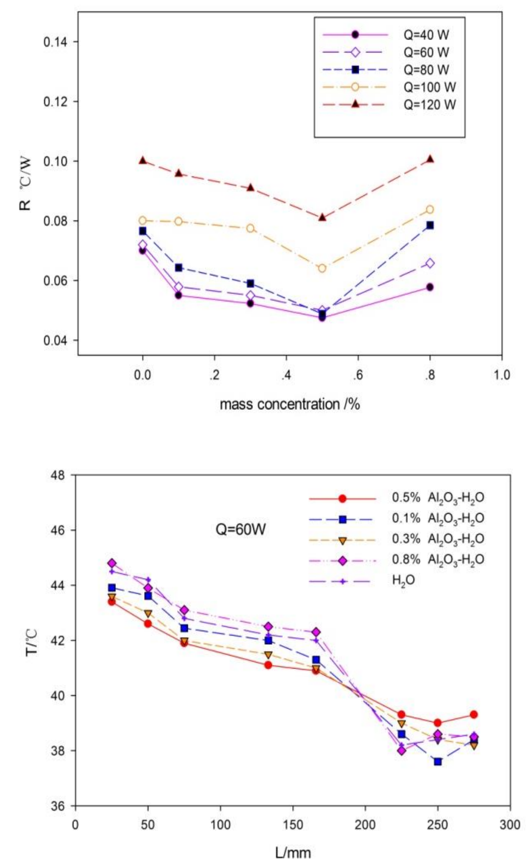


Figure 6. Effect of mass concentration on heat pipe heat transfer performance

3.4 Comparative research on the heat transfer enhancement mechanism

A previous investigation of a porous copper wick heat pipe using Al_2O_3 nanofluids as the working fluids in the literature [19－20] showed that both the porous copper foam and the nanofluids can significantly improve heat transfer. Furthermore, the combination of these two materials was better than that of mesh wick and DI water.

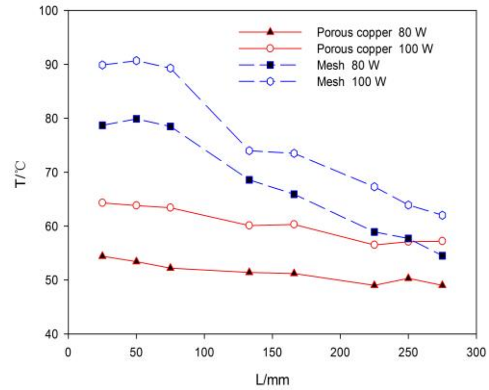


Figure 7. Comparison of heat pipe using porous copper foam and mesh wick

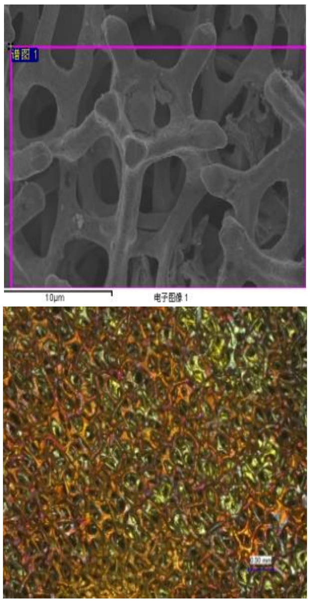
Figure 7 shows that under a certain filling ratio and mass concentration, a 200 PPI porous copper foam wick showed more advantages in terms of both temperature and temperature difference over time than a 200 PPI mesh wick. The conclusions of previous studies indicate that the mechanism by which nanofluids and porous copper foam enhance the heat transfer in heat pipes can be described as follows. On one hand, the addition of nanoparticles can increase the effective thermal conductivity of the base fluid, and the small size effect and the Brownian motion of nanoparticles enhance the energy transfer from the base fluid to the nanoparticles. On the other hand, porous copper foam has a complex 3D porous structure and metallic characteristics. It can provide a large heat transfer area and capillary force, but also can facilitate strong transverse mixing.

The two preceding points are based on the respective advantages of using porous copper foam and mesh wick. The matching of heat transfer in the porous copper foam wick heat pipe with nanofluids is complicated. To further understand the mechanism by which nanofluids enhance heat transfer in a porous copper foam wick heat pipe, the heat pipe was cut open, so the capillary wicks can be removed as samples. After the wick samples were cleaned, a scanning electron microscope (SEM) was used to explore surface ultrastructure and morphology. Residual elements in the wick samples were determined, as shown in Table 1.

Table 1. Capillary wick element percentages with SEM

Wick samples			Element (%)		
Filling ratio (%)	Mass concentration (%)	Capillary wick	Cu	O	Al
50	0.3	Porous copper foam	98.52	1.05	0.43
	0.5		96.69	1.76	1.56
	0.8		98.2	0.84	0.96
	0.5	Mesh	86.3	4.71	8.91

Table 1 shows that three elements were observed in the capillary wick, namely, Cu, O, and Al. The residual Al element in the table represents the adsorption amount of the Al_2O_3 nanoparticles into the capillary wick. At a certain filling ratio and capillary, the residual element percentages were different in the heat pipes with varying mass concentrations. The Al element percentages with 0.3%, 0.5%, and 0.8% mass concentrations were 0.43%, 1.56%, and 0.96%, respectively. This difference in Al percentages corresponded with the differences in thermal resistance shown in Figure 6. The results indicated that the adsorption of the Al_2O_3 nanoparticles onto the copper surface increased the roughness of the heat transfer surface in the evaporator. As a result, the active nucleation site density increased. The adsorption of nanoparticles therefore favorably affects heat transfer in a porous copper foam wick heat pipe.



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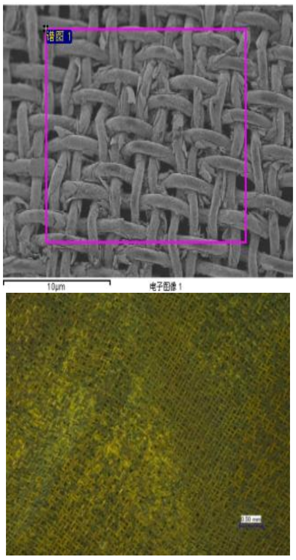

(b)

Figure 8. SEM and ultra-depth digital microscope pictures of (a) a 200 PPI porous copper foam and (b) a 200 PPI mesh wick

The figure shows that the complicated 3D porous structure generated through the interlinking of open cells on the interface can be considered as the capillary structure. The hole in the regular 2D net structure of the mesh wick was generated through the interlinking of two copper wires over each other. The comparison of the structures of porous copper foam with mesh wicks indicates that the use of a 200 PPI porous copper foam wick had the following three advantages over that of a 200 PPI mesh wick:

1) The 2D net structure of the mesh wick was generated through the interlinking of two copper wires over each other. The mesh wick had a large thermal contact resistance, whereas the three porous structures in the porous copper foam had a large thermal conductivity.

2) In another project on pool boiling [21], the coefficient of boiling heat transfer of porous metal material tube was found to be seven to eight times higher than that of a smooth tube. This enhancement was also applied to boiling heat transfer in the heat pipe.

3) The adsorption of $A1_2O_3$ nanoparticles on the copper skeleton can increase surface roughness and the number of active nucleation sites on the boiling surface. While excessive nanoparticle accumulation in the mesh holes, which results in clogging, not only leads to flow resistance but also decreases the number of active nucleation sites on the boiling surface.

4. CONCLUSION

A new type of heat pipe has been developed in this study from the combination of porous copper foam using three nanofluids comprised of three types of nanoparticles, $A1_2O_3$, CuO, and SiO_2. The effects of factors, such as nanoparticles, filling ratio, and mass concentration, on the heat transfer performance of the heat pipe were investigated. The conclusions of the experimental investigation are as follows:

1) The heat transfer enhancement of the CuO nanofluid heat pipe was the best, followed by $A1_2O_3$ and then SiO_2. Therefore, considering the two factors of stability and thermal conductivity considered, $A1_2O_3$ nanofluids were considered the optimal one and studied in this study, mainly.

2) When Al_2O_3 nanoparticles were used as the working fluids, the heat pipe had an optimal filling ratio and mass concentration to achieve low thermal resistance. A 50% filling ratio and a 0.5% mass concentration were found to be the optimal levels in this study.

3) The combination of Al_2O_3 nanoparticles with porous copper foam within heat pipes can also increase active nucleation site density.

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