Combined effect of nanofluid concentration and filling ratio on heat transfer performance of pulsating heat pipe

Lina Bai[1], Xinjun Su[1,a], Wenhao Ren[1],and Wenzhe Yang[1]

[1]Tianjin Key Laboratory of Refrigeration Technology, Tianjin University of Commerce, Tianjin，P. R. China

[a] Corresponding author: suxinjun@tjcu.edu.cn(X. Su)

Abstract. An experimental work was investigated to study combined effect of nanofluid concentration and liquid filling ratio on heat transfer performance of pulsating heat pipe (PHP).The PHP was made of copper tube with external diameter of 4mm and inner diameter of 2mm and bended into a closed loop serpentine made of 6 U-turns. In the experiment, Al_2O_3/water nanofluid concentration changed from 0wt% to 0.7wt%, Al_2O_3/water nanofluid filling ratio ranged from 30% to 70%, and Al_2O_3 /water nanofluid or de-ionized water was the working fluid. Experimental results showed that there was a 0.3wt% optimum nanofluid concentration and a 50% optimum filling ratio, besides, the heat transfer efficiency of PHP with Al_2O_3/water could reach its maximum value (about 10.28%) only under the combined action of two parts when compared with the de-ionized water.

1. Introduction

The pulsating heat pipe (PHP) is a very promising device, which is possible to be widely used in Chip cooling with high heat flux. With the rapidly increase of chip heat flux, it is key for the PHP to enhance the heat transfer performance. Many researchers found that the most direct and effective way to improve the heat transfer performance of PHPs is to choose an excellent working fluid.

Many new working fluids, for example Binary mixture of methanol and acetone[1], Nanofluids, Ferrofluidic [2] and Fs-39E Microcapsule fluid[3]are used to enhance the heat transfer of pulsating heat pipes. Among those working fluids, due to high thermal conductivity, nanofluids attracted more and more attention in the last ten years [4, 5]. Nanofluids are suspensions of metallic or nonmetallic nanoparticles in a base fluid, and they were first used by Choi in 1995[6]. Lin et al.[7] performed an experiment in a PHP made by copper tube with 20nm silver nanofluid as the working fluids. Experimental results showed that the average temperature difference and the thermal resistance of evaporator and condenser are decreased by 7.79℃ and0.092℃/W at 85W heating power compared with pure water.Ma et al. [8, 9] showed the thermal enhancement of PHP performance charged with nanofluid (HPLC grade water and 1.0vol. % diamond nanoparticles of 5-50nm) was significantly improved. The investigated PHP could reach a thermal resistance of 0.03℃/W at a heat input of 336 W. Li et al. [10] conducted a series of experimental observation to explore the fundamental phenomena and operating performance in oscillating heat pipe with nanofluid and water. The results demonstrated that the suspensions of the nanoparticles caused a decrease of the required startup heat flux and an increase in the stop-over heat flux, compared with water. Jia et al. [11] studied the heat transfer performance of the PHP with different concentrations of SiO_2/H_2O nanofluid. It was pointed out that the mass concentration affects the thermal performance at different heat input. Ji et al. [12] indicated that Al_2O_3 particle size influence the heat transfer performance in an oscillating heat pipe. The measured results also show that the particle size can improve the start-up performance of the OHP. At the same time, Qu et al. [13] also carried out a study of the effect of spherical 56nm Al_2O_3 particles on the heat transport capability in an oscillating heat pipe, and proposed that alumina nanofluids significantly improved heat transfer. With further investigation of inner wall samples found that deposition of nanoparticles at the evaporator is the main reason for the enhanced thermal capability. Qu et al. [14] reported that the pulsating heat pipe charged water based TiO_2nanofluid could operate at lower heating powers and start up more quickly, and the thermal resistance between the heating section and the cooling section significantly decreased. At the same time, they explained that forming many micro nuclear centers for the boiling of the nanoparticles is the major contributor in several heat transfer enhancement.

These scholars have done a lot of research work by changing different or single influencing factors, but few scholars have studied the heat transfer of pulsating heat pipe under the combined action of different influencing factors. Therefore, in order to better understand the combined action of different influencing factors to the heat transfer mechanism of the PHP, this paper studies the heat transfer performance of the PHP under the combine influence of the Al_2O_3/water nanofluid concentration with filling ratio.

2. Experimental system

The PHP was made of copper tube with external diameter of 4mm and inner diameter of 2mm and bended into a closed loop serpentine made of 6 U-turns and three sections: evaporator, condenser and adiabatic sections with lengths of 50mm, 100mm, and 50mm, respectively (as shown in Fig.1). Two T-joints allowed the PHP to be connected to the vacuum pump and the filling syringe respectively. The experimental setup was oriented vertically(inclination angle =90°).The heat load was applied by Ni-Cr wire with a diameter of 0.4 mm which was wrapped on the outer wall surface of the evaporator, and it was dissipated from the condenser by cooling bath (DC4006) with a constant inlet temperature of 21℃. The input heat load was measured by a power supply (WYR-305B2). Both the evaporator and adiabatic section were well thermally insulated by aluminum silicate fibers. The temperature distribution of the PHP was measured by “T” type thermocouples and recorded by a data acquisition system (MX-100) which controlled by a personal computer. The detailed location of thermocouples was shown in Fig.1.For the current investigation, de-ionized water was used as the base fluid. Al_2O_3/water dispersions with diameter of 50nm were directly added into the base fluid of de-ionized water with a concentration for all tests.

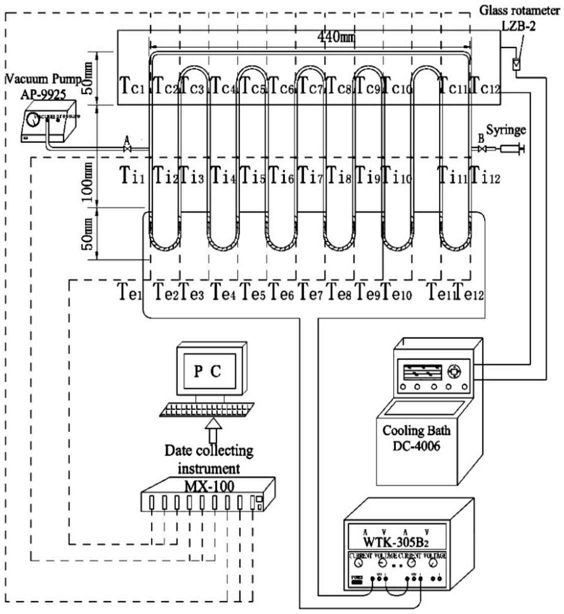


Fig. 1. Schematic of the experimental setup

3. Result and discussion

Average thermal resistance（R）was calculated by following the equation given below:

$$\overline{R} = (\overline{T}_e - \overline{T}_c) / P \qquad (1)$$

Where $\overline{R}$ is a dimensionless parameter and it expresses the average thermal resistance and $\overline{T}_e$, $\overline{T}_c$, P are average temperature in evaporator, average temperature in condenser and heat load supplied to evaporative section respectively.

Heat load P of the PHP was calculated by following equation:

$$P = UI \qquad (2)$$

Where U and I are the input voltage and electric current, respectively.

In order to analyze the heat transfer enhancement effect of Al_2O_3/water nanofluids with 0.3wt% concentration at 50% filling ratio on pulsating heat pipe, we define the enhancement rate Es as follows:

Es=[(Rw-Rn)/Rw] x 100% (3)

Where, Rw and Rn are the thermal resistance of de-ionized water and of Al_2O_3 /water nanofluids, respectively.

3.1Effect of Al_2O_3/water nanofluid concentration on heat transfer performance of pulsating heat pipe

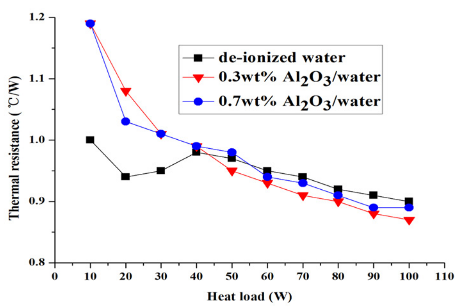
The variation of the average thermal resistance of PHP with different concentrations is shown in Fig. 3.

According to the Fig. 2(a), when the filling ratio is 30%, the average thermal resistance of three concentrations of nanofluids decreases with the increase of heating load. And the average thermal resistance of de-ionized water is the smallest in the range of 40w, this may be that the pulsating heat pipe has not been started-up. The nanofluids with high heat transfer coefficient can not play a role. However, with the increasing of heating load, the average thermal resistance of 0.3wt% Al_2O_3/water nanofluids is the smallest, the average thermal resistance of de-ionized water is the largest. The difference between them increases with the increase of heating load.

According to the Fig. 2(b), when the filling ratio is 50%, the average thermal resistance of three concentrations of nanofluids all decreases with the increase of heating load, and the changing trend of the three is roughly the same. The average thermal resistance first decreases and then increases with the increase of nanofluid concentration. When the heating load is less than 20W, the average thermal resistance of 0.7wt% Al_2O_3/water nanofluids is the largest and that of 0.3wt% Al_2O_3/water nanofluids is the smallest, and the gap between them becomes smaller gradually; when the heating load is more than 20W and less than 90W, the average thermal resistance of 0.3wt% Al_2O_3/water nanofluids is the smallest, and in this range of heating load, the Al_2O_3/water nanofluids of 0.3wt% and 0.7wt% respectively have enhanced the heat transfer of pulsating heat pipe; when the heating power is greater than 90W, the average thermal resistance of de-ionized water is the smallest, this means that the addition of nanoparticles weakens the heat transfer of pulsating heat pipe.

According to the Fig. 2(c), when the filling ratio is 70%, the average thermal resistance of three concentrations of nanofluids decreases with the increase of heating load, and the changing trend of the three is roughly the same. The average thermal resistance of de-ionized water is always the highest when the heating load increases from 10W to 100W. The average thermal resistance of Al_2O_3/water nanofluids with 0.3wt% and 0.7wt% respectively is similar. Under the same heating load, with the increase of heating load, the difference of average thermal resistance of Al_2O_3/water nanofluids with 0.3wt% and 0.7wt% experienced the process of first increasing, then decreasing and then increasing.

According to the analysis of the variation of thermal resistance with heating load under different concentrations, it can be concluded that no matter how the liquid filling ratio changes, the concentration of nanofluids is not the higher the better. Too high or too low concentration is unfavorable for heat transfer. These may be that when the concentration is too low, the number of nucleation centers is limited, which is not conducive to the formation of bubbles, thus affecting the boiling heat transfer; when the concentration is too high, the thermal movement of molecules is very intense at high temperature, and the probability of collision between molecules is increased. Particle aggregation and sedimentation are easy to occur, which makes the heat transfer process become slow. Besides, it can be found that in the whole range of heating load, the thermal resistance of nanofluids with 0.3wt% concentration is the lowest when the liquid filling ratio is 50%, which is most conducive to heat transfer.



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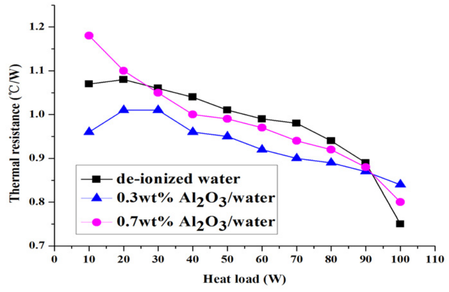

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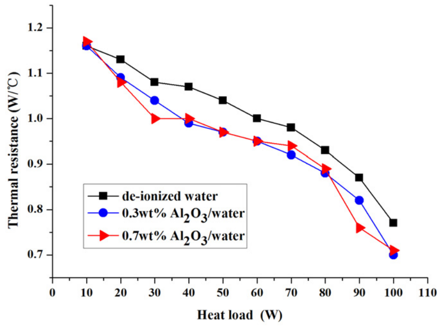

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Fig.2.Thermal resistance of PHP with different concentrations of nanofluid under the same filling ratio(fr):(a)fr=30%; (b)fr=50%;(c)fr=70%

3.2 Effect of Al_2O_3/water nanofluid filling ratio on heat transfer performance of pulsating heat pipe

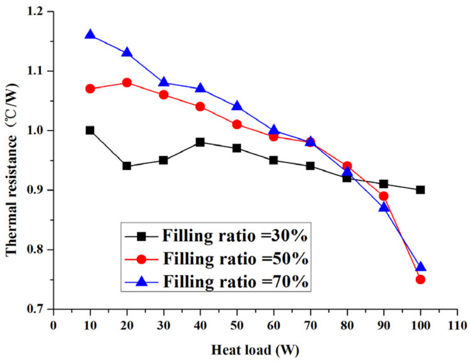
Fig.4 illustrated the evolution of the average thermal resistance of PHP with different filling ratio.

As shown in Fig. 3(a), when the concentration is 0wt%, the thermal resistance of the three filling ratios decreases with the increase of heating load, but the amplitude of the decrease becomes smaller and smaller, and the change curve tends to be flat. At the same heating load, de-ionized water with 30% filling ratio has the lowest thermal resistance, but too small filling ratio will affect the heat transfer efficiency of PHP, especially at high heating load, the thermal resistance is larger.

As shown in Fig. 3(b), when the concentration is 0.3wt%, the average thermal resistance of the three filling ratios decreases with the increase of heating load, and the trend is almost the same. It can be seen that the thermal resistance of 50% filling ratio is the smallest and that of 70% filling ratio is the largest when the heating load is lower than 80W. The difference between them becomes smaller with the increase of heating load. However, the thermal resistance of 50% filling ratio is the largest and that of 70% filling ratio is the smallest when the heating load is more than 80W, Therefore, increasing the filling ratio of nanofluids will not further enhance the heat transfer performance of pulsating heat pipes.

As shown in Fig. 3(c), when the concentration is 0.7wt%, the average thermal resistance of the three filling ratios decreases with the increase of heating load, and the trend is almost the same. At this concentration, with the increase of liquid filling ratio, the thermal resistance will increase, which is not conducive to the heat transfer of pulsating heat pipes.

According to the analysis of the variation of thermal resistance with heating load under different filling ratio, it can be concluded that selecting an appropriate liquid filling ratio to enhance the heat transfer of the pulsating heat pipe is related to a certain concentration. The previous research results find that the liquid filling ratio is key to the start-up and stable operation of pulsating heat pipe, in addition, the size of the liquid filling ratio determines the change of flow pattern in the pipe.



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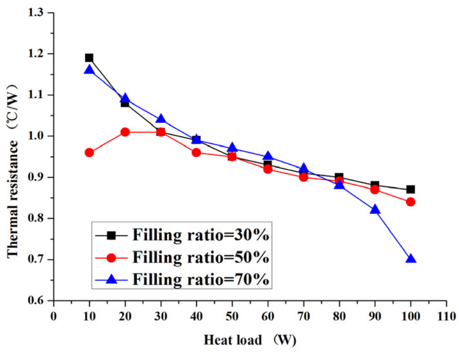

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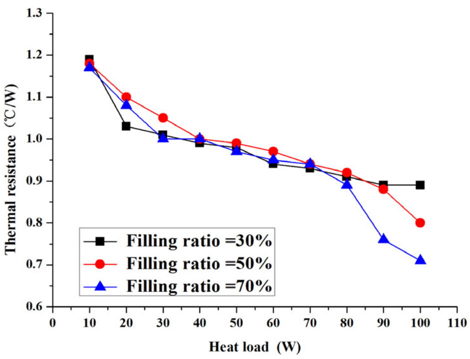

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Fig.3. Thermal resistance of PHP with different filling ratio of nanofluid under the same concentration:(a)de-ionized water; (b)0.3wt% Al_2O_3/water;(c) 0.7wt% Al_2O_3/water

3.3 Enhancement of heat transfer performance of pulsating heat pipe with 0.3wt%Al_2O_3/H_2O nanofluids at 50% filling ratio

Fig.4 showed the evolution of the enhancement ratio of PHP with 0.3wt% Al_2O_3 /water nanofluid at 50% filling ratio. When the heating load is less than 90 W, 0.3wt% Al_2O_3 /water nanofluids can enhance the heat transfer of pulsating heat pipe with de-ionized water as working fluid, and the enhancement ratio ranges from 2.25 to 10.28. In this heating load range, 0.3wt% Al_2O_3 /water nanofluids can enhance the heat transfer of pulsating heat pipe. However, when the heating load increases, the strengthening effect is negative, which will weaken the heat transfer of the pulsating heat pipe.

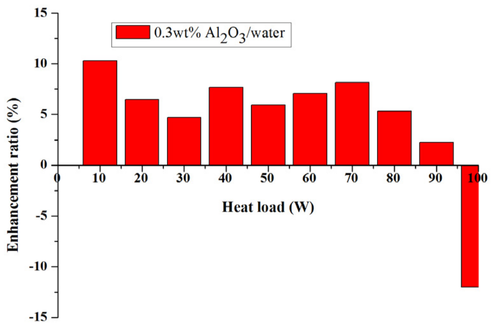

Fig.4.Enhancement ratio of pulsating heat pipe with 0.3wt% Al_2O_3/water nanofliud at 50% filling ratio

4. Conclusion

In this paper, we have experimentally investigated the combined effect of nanofluid concentration and liquid filling ratio on the heat transfer performance of the PHP charged with different concentration of Al_2O_3 /water nanofluid. The experiment results demonstrate that no matter how the liquid filling ratio changes, the concentration of nanofluids is not the higher the better. Too high or too low concentration is unfavorable for heat transfer. Further more, selecting an appropriate liquid filling ratio to enhance the heat transfer of the pulsating heat pipe is related to a certain concentration. Because the liquid filling ratio is key to the start-up and stable operation of pulsating heat pipe, in addition, the size of the liquid filling ratio determines the change of flow pattern in the pipe. Finally, it found that there was an optimum nanofluid concentration of 0.3wt% and an optimum filling ratio of 50% for the experimental device, and the enhancement ratio could reach the maximum value (about 10.28%).

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