Influence of filling ratio on heat transfer performance of pulsating heat pipe with self-rewetting nanofluid

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Abstract. An experimental investigation was conducted to explore filling ratio effect on the heat transfer performance of pulsating heat pipe (PHP) charged with self-rewetting nanofluid. The filling ratio is 30%, 50%, 70%, respectively. In the experiment, the Al_2O_3/water nanofluid was mixed with n-butanol solution at a volume ratio of 2.6 to 1 to form a self-wetting nanofluid. Among them, the concentration of n-butanol solution was 0.7wt%, and the concentration of Al_2O_3/water nanofluid was 0.1wt%. Experimental results show that the self-rewetting nanofluid has an enhancement effect on the heat transfer performance of the pulsating heat pipe, but the strengthening effect is not only related to the heating load, but also is related to the filling ratio. When the filling ratio is lower, the fluidity of the working fluid becomes worse. With the increase of the heating load, some parts of PHP are easily burnt out. In addition, the high thermal conductivity of the nanofluid and the surface tension of the self-wetting fluid are not easy to play. However, when the filling ratio is too high, the average temperature difference will increase, and the average thermal resistance will increase. Therefore, in order to enhance the heat transfer performance of the pulsating heat pipe, 50% filling ratio is chosen as the optimum filling ratio in this experiment.

1. Introduction

The pulsating heat pipe（PHP）, a new type of two-phase heat transfer devices,which is originally proposed by a Japanese scholar name Akachi[1] in 1990s. Faced with severe higher heat fluxes dissipation problems, strengthening the heat transfer performance of pulsating heat pipes becomes very necessary. Many researchers have given numerous ways to improve the heat transfer performance of PHPs. Such as changing pipe diameter[2,3], tube cross section shape[4], pipe diameter structure[5], evaporation section and condensing section length, turn number[6], inclination angle[7] and heating load[8,9] etc. Furthermore，in order to enhance the heat transfer performance of pulsating heat pipes, many new working fluids are used, for example Binary mixture of methanol and acetone[10], Nanofluids, Ferrofluidic [11], Fs-39E Microcapsule fluid[12]and Self-rewetting nanofluid[13].

Although many researchers studied that the effects of many factors on heat transfer performance of PHP. However, few researches have been done to study the influence of filling ratio on heat transfer performance of PHP with self-rewetting nanofluid. In order to better understand the heat transfer performance of the PHP, In the experiment, the Al2O3/water nanofluid was mixed with n-butanol solution at a volume ratio of 2.6 to 1 to form a self-wetting nanofluid(The particle diameter of the Al2O3 was 50nm)to study the heat transfer performance of the PHP under different filling ratio(fr). In this mixed solution, the concentration of n-butanol was 0.7wt%, and the concentration of Al2O3/water nanofluid was 0.1wt%.

2. Experimental system and procedure

2.1. Experimental setup

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. The entire experimental process was carried out in 21℃air-conditioned environment. The condensation section was immerged in the cooling water, which was pumped from the constant temperature bath. The flux was measured by a rotameter. The temperature of the cooling bath was 21℃. Before the experiment, the PHP was evacuated by a vacuum pump (AP-9925). As shown in Fig.1, valve A was firstly opened and valve B was closed. Then vacuum pump was operated to evacuate PHP. As the Vacuum degree reached fixed value, stopping vacuum process. Finally, valve A was closed and valve B was opened. Working fluid was charged into the PHP by a syringe. In experiment, heat load was supplied by power supply, which changed from 10W to 100W with steps of 10W. Under each power input, temperature data of the PHP were recorded by data acquisition system (MX-100) after the system had reached a steady state. The data acquisition frequency was 1Hz, for any given heat load. Before charged into the new working fluid, the PHP should be washed with de-ionized water for four times.

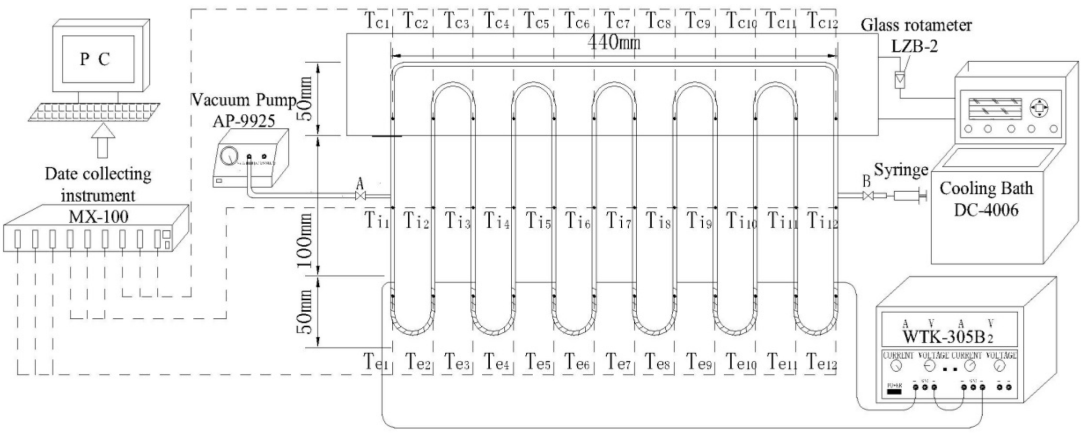


Fig. 1. Schematic of the experimental setup

2.2.Data reduction and uncertainty analysis

Average thermal resistance（$\bar{R}$）was calculated by following the equation given below:

$$\bar{R} = (\bar{T_e} - \bar{T_c}) / P \qquad (1)$$

Where $\bar{R}$ is a dimensionless parameter and it expresses the average thermal resistance and $\bar{T_e}$,

$\overline{T_c}$, 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:

$$P = UI \tag{2}$$

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

The uncertainties of the indirect measurement parameters (*Te, Tc, P* and *R*) were obtained according to error propagation principle. Total uncertainty (*E)* was estimated by calculating the system uncertainty (*Es)* from the precision of instruments (thermocouple, power supply) and the random uncertainty (*Er*) from the repeatability of data by following equation:

$$E = \sqrt{E_s^2 + E_r^2} \tag{3}$$

Table 1 lists the maximum uncertainties of main parameters for this study.

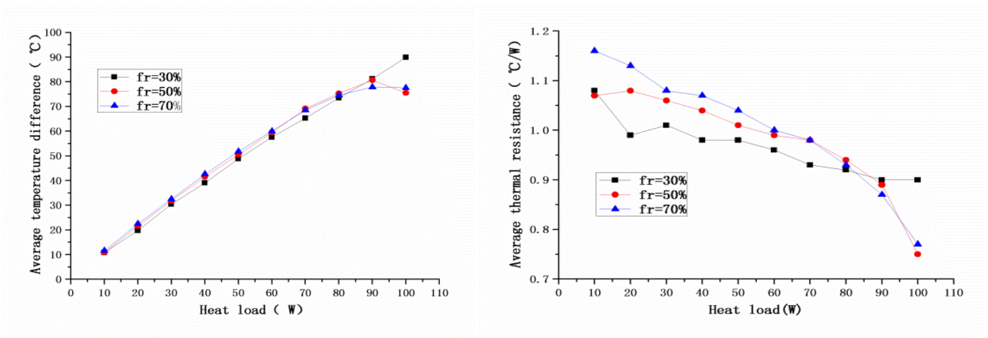
Table 1 Maximum uncertainty of main parameters

Parameters(unit)	Maximum uncertainties (%)
T_e (℃)	0.2
T_c (℃)	0.4
U (V)	0.5
I (A)	0.5
P(W)	5.5
R(℃/W)	6.5

3. Result and discussion

3.1.Comparison of average temperature difference or average thermal resistance of PHP with de-ionized water as working fluid at different filling ratios

Average temperature difference and average thermal resistance of the PHP charged with de-ionized water at different filling ratios are shown in Fig.2 (a) and Fig.2(b) respectively.



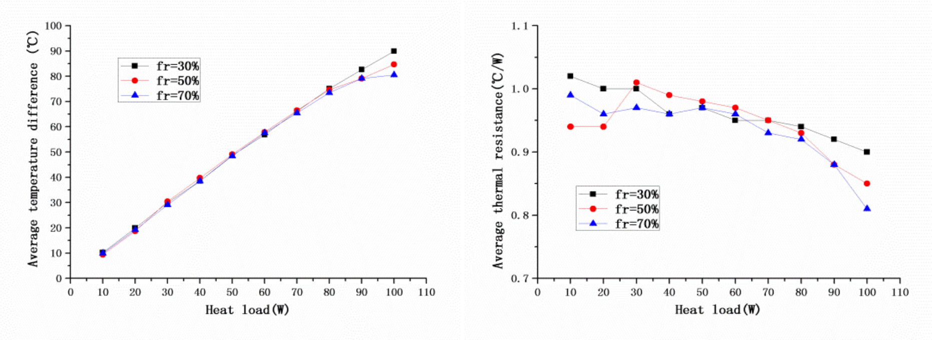
a b

Fig.2.Thermal performance of the PHP charged with de-ionized water at different filling ratio (a) average temperature difference versus heat load and (b) average thermal resistance versus heat load

As shown in Fig.2(a),it can be seen that the average temperature difference at the different filling ratios increases with the increasing of the heating load, and the change trend of the average temperature difference at different filling ratios is approximately the same, but with the increasing of the heating load, the gap of the average temperature difference corresponding to the different filling ratios is also constantly changing. When the heating load is small, the average temperature difference is approximately the same, but with the increasing of the heating load, the 30% filling ratio has a relatively smaller average temperature difference which reflects the better heat transfer performance. When the heating load is more than 90W, the 30% filling ratio is correspondingly larger average temperature difference. The average thermal resistance of PHP charged with de-ionized water at different filling ratios varies with the heating load as shown in Fig.2(b).The average thermal resistance of different filling ratios decreases with the increasing of heating load, but the changing trend is more flat. When the heating load is less than 90W, the 30% filling ratio has relatively smaller average thermal resistance at the same heating load. When the heating load is more than 90W, the average thermal resistance of the 30% liquid filling ratio is relatively larger. In addition, it is found that the PHP with 50% filling ratio has a relatively good heat transfer performance during the heating load changing from 10W to 100W, which shows that the de-ionized water with the 50% filling ratio has the optimum heat transfer effect in this experimental condition.

3.2.Comparison of average temperature difference or average thermal resistance of PHP with self-rewetting nanofluid as working fluid at different filling ratios

Average temperature difference and average thermal resistance of the PHP charged with self-rewetting nanofluid at different filling ratios are shown in Fig.3 (a) and Fig.3 (b) respectively.



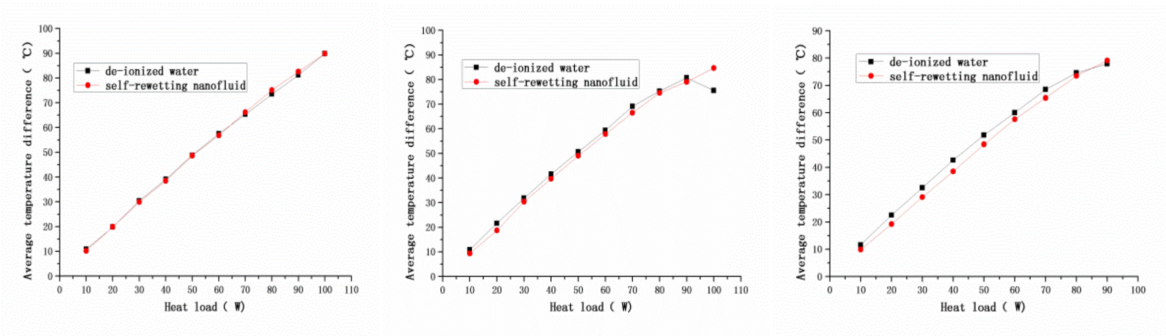
a b

Fig.3.Thermal performance of the PHP charged with self-rewetting nanofluid at different filling ratio: (a) average temperature difference versus heat load and (b) average thermal resistance versus heat load

As shown in Fig.3 (a), it can be seen that the average temperature difference increases with the increasing of heating load. When the heating load is less than 80W, the average temperature difference of the self-rewetting nanofluid is basically the same at different filling ratios, which means that the heat transfer performance of PHP at different filling ratios is the same. The reason for this phenomenon is that the higher concentration of n-butanol is needed under the low heat load conditions, which produces enough bubble driven fluid to oscillate effectively, but the concentration cannot be too large, otherwise the heat transfer performance of PHP will be weakened. When the heating load is more than 80W, the average temperature difference of the 70% filling ratio is the smallest. The average thermal resistance of PHP charged with self-rewetting nanofluid at different filling ratios varies with the heating load as shown in Fig.3(b). The average thermal resistance of different filling ratios decreases with the increasing of heating load, and the trend of variation is almost the same, and the difference between them is not large. In addition, it was found that when the heating load was less than 20W, the average thermal resistance of the 50% filling ratio was the smallest, the average thermal resistance of the 30% filling ratio was the largest. And the gap between them with the changing of heating load was first decreased and then increased. The average thermal resistance of the 70% filling ratio was the smallest and the average thermal resistance of the 50% filling ratio was the largest when the heating load exceeded 20W. Therefore, increasing the liquid filling ratio of self-rewetting nanofluid will not further enhance the heat transfer performance of PHP. In addition, it is found that the PHP with 50% filling ratio has a relatively good heat transfer performance during the heating load changing from 10W to 100W, which shows that the self-rewetting nanofluid with the 50% filling ratio has the optimum heat transfer effect in this experimental condition.

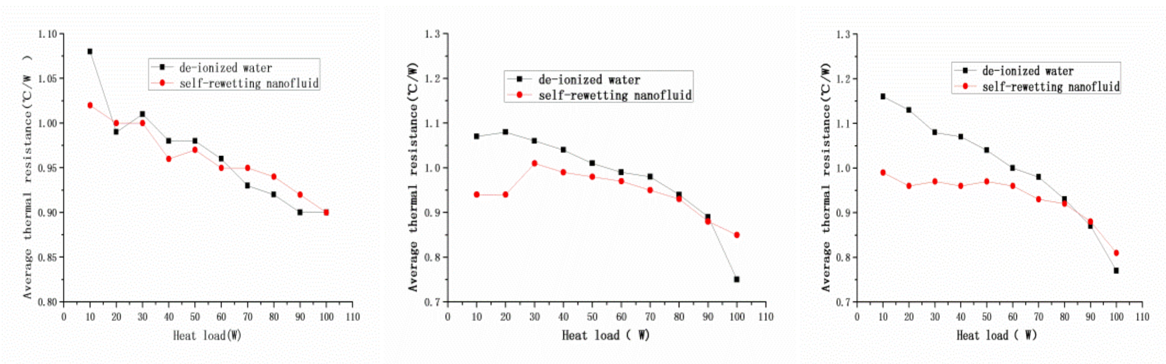
3.3.Comparison of average temperature difference or average thermal resistance between self-rewetting nanofluid and de-ionized water at different filling ratios

The comparison of the average temperature difference between the self-rewetting Nanofluid and the de-ionized water at different filling ratios was shown in Fig.4. It can be seen that when the filling ratio is 30%, with the increasing of the heating load, the average temperature difference of the two working fluids is basically the same; at 50% filling ratio, when the heating load is less than 90W, the average temperature difference of de-ionized water is obviously larger than that of self-rewetting nanofluid, but when the heating load is more than 90W, the average temperature difference of de-ionized water is smaller than the average temperature difference of self-rewetting nanofluid. When the filling ratio is 70%, with the increasing of heating load, the temperature difference of de-ionized water is obviously larger than that of self-rewetting nanofluid. The comparison of the average thermal resistance between the self-rewetting nanofluid and the de-ionized water at different filling ratios was shown in Fig.5. It can be seen that at 30% filling ratio, when the heating load is less than 70W, the average thermal resistance of the de-ionized water is larger. When the heating load is more than 70W, the average thermal resistance of self-wetting nanofluid is larger; At the 50% filling ratio, when the heating load is less than 90W, with the increase of heating load, the average thermal resistance of de-ionized water is obviously larger than that of self-wetting nanofluid, but when the heating load is more than 90W, the average thermal resistance of de-ionized level is obviously smaller than that of self- wetting fluid; At the 70% filling ratio, the average thermal resistance of the two working fluids is similar to that of the 50% filling ratio, but the difference of the average thermal resistance between two working fluids gradually increases with the increasing of the heating load.



a b c

Fig.4.Comparison of average temperature difference between self-rewetting nanofluid and de-ionized water at different filling ratios: (a) fr=0.3, (b) fr=0.5, (c) fr=0.7



a b c

Fig.5.Comparison of average thermal resistance between self-rewetting nanofluid and de-ionized water at different filling ratios: (a) fr=0.3, (b) fr=0.5, (c) fr=0.7

4. Conclusion

In this paper, we have experimentally investigated the influence of filling ratio on heat transfer performance of PHP with self-rewetting nanofluid. The experiment results demonstrate that compared with de-ionized water, self-rewetting nanofluids enhance the heat transfer of pulsating heat pipes. But different filling ratio cause different strengthening effect. Larger or smaller filling ratio is not conducive to the heat transfer of pulsating heat pipes. Therefore, in order to give full play to the heat transfer characteristics of self-rewetting nanofluids and improve the heat transfer of the pulsating heat pipe within the range of the whole heating load, 50% filling ratio is chosen as the optimum filling ratio.

Acknowledgements

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References

[1] Akachi, H. (1990) US Patent No.4, 921041.
[2] Yang, H. H., Khandekar, S., Groll, M. (2008) Operational limit of closed loop pulsating heat pipes. Appl. Therm. Eng., 28(1):49-59.
[3] Yang, H. H., Khandekar, S., Groll, M. (2009) Performance characteristics of pulsating heat pipes as integral thermal spreaders. Int. Therm. Sci., 48(4):815-824.
[4] Han, X., Wang, X., Zheng, H., Xu, X., Chen, G. (2016) Review of the development of Pulsating Heat Pipe for heat dissipation.Renew. Sustain. Energy Rev., 59:692-709.
[5] Liu, S., Li, J. T., Dong, X. Y., Chen, H. Z. (2007) Experimental study of flow patterns and improved configurations for pulsating heat pipes. Therm. Sci., 16(1):56-62.
[6] Quan, L., Jia, L. (2009) Experimental study on heat transfer characteristic of plate pulsating heat pipe. In: Proceedings of the ASME 2009 2nd micro/nanoscale heat & mass transfer international conference, Shanghai, China.
[7] Xian, H. Z., Yang, Y. P., Liu, D. Y., Du, X. Z. (2010) Heat transfer characteristics of oscillating heat pipe with water and ethanol as working fluids. Heat Transfer ASME, 132(12):121501.
[8] Hu, C. F., Jia, L. (2011) Experimantal study on the startup performance of flat plate pulsating heat pipe.Therm. Sci., 20(2):150-154.
[9] Thompson, S. M., Cheng, P., Ma, H. B. (2011) An experimental investigation of a three dimensional flat-plate oscillating heat pipe with staggered microchannels. Int. J. Heat Mass Transf., 54(17-18):3951-3959.
[10] Wang, W. Q., Cui, X. Y., Zhu, Y. (2016) Heat transfer performance of a pulsating heat pipe charged with acetone-based mixtures. Heat Mass Transf., 53(6):1-12.
[11] Taslimifar, M., Mohammadi, M., Afshin, H., et al. (2013) Overall thermal performance of ferrofluidic open loop pulsating heat pipes: An experimental approach. Int. J. Therm. Sci., 65: 234-241.
[12] Wang, S. F., Lin, Z. R., Zhang, W. B., et al. (2009) Experimental study on pulsating heat pipe with functional thermal fluids. Int. J. Heat Mass Transf., 52:5276-5279.
[13] Xuan, Y. M., Li, Q. (2003) Investigation on Convection Heat Transfer and Flow Features of Nanofluids. J. Heat Transf., 125:151-155.