EXPERIMENTAL INVESTIGATION ON THE EFFECT OF VERTICAL VIBRATION ON HEAT TRANSFER PERFORMANCE OF TWO-PHASE LOOP THERMOSYPHONS WITH DIFFERENT DIAMETERS

by

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The two-phase loop thermosyphon (TPLT) is generally a technique used in conjunction with a fan when cooling an electronic chip to enhance the cooling effect. In this context, the TPLT heat transfer efficiency is directly affected by the vibration caused by the associated fan. In this paper, the heat transfer performances of TPLT with diameters of 4 mm, 6 mm, and 8 mm were experimentally investigated under a heating power capacity ranging from 40-400 W, a filling ratio of 40-70%, and a 30 m/s² 35 Hz vertical reciprocating vibration. The heat transfer performance of the TPLT is compared to the case of operation under the same working conditions in a static state. The influence of the vibration state caused by the fan rotation on the heat transfer performance of TPLT with different diameters is analyzed and discussed. The obtained results indicated that vertical vibration does not change the trend of TPLT heat transfer performance with the corresponding heating power capacity under each pipe diameter. On the other hand, it was found that the vibration enhances or inhibits the heat transfer characteristics of TPLT, affected by the pipe diameter, the heating power capacity, and the liquid filling ratio.

Key words*: TPLT, heat transfer performance, vibration*

Introduction

A TPLT is an efficient heat transfer technique. Due to its simple structure, high heat transfer efficiency, and wide working temperature range, it has been widely applied in electronic equipment cooling for various applications [1]. In recent years, a large number of studies have been presented aiming to investigate various aspects of TPLT, including the heat transfer characteristics and the impact of various parameters. The major identified parameters having a direct impact on the performance include the working fluid type, liquid filling ratio, heating power, and the inclination angle on the TPLT [2].

Albertsen *et al.* [3] experimentally investigated the influence of the working fluid on the TPLT performance, using R1233zd(E) and R1224yd(Z) as working fluids. The investigation results showed that both tested refrigerants lead to basically similar results, with minor differences regarding thermal performance and system stability. In another study, Bai *et al.* [4] numerically studied the thermal resistance of TPLT charged with nine fluids. They analyzed the effects of each of the working fluids on the performance and, as a result, obtained the optimum operating temperature range of those working fluids. This allows establishing a criterion

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for fluid selection, considering thermal resistance as a performance indicator. Moreover, the influence of carbon nanotubes on the maximum heat transfer capacity of TPLT used for electronics cooling has been studied by Bondarenko *et al.* [5]. The results suggested that due to the high thermal conductivity of the proposed nanofluids and the formation of a specific porous structure, the critical heat flux has increased more than twofold and the thermal resistance has decreased sharply compared to the case of water filling for cooling. Another investigation by Ding *et al.* [6] studied the indoor thermal environment of a data center along with the working conditions when employing CO_2 as a coolant in a TPLT cooling system. The study findings highlighted that the heat transfer performance of the CO_2-driven TPLT is better than that of a TPLT using R410A. In addition, the use of CO_2 is also found to be more appealing from an economic perspective. Elkholy and Kempers [7] investigated the geyser boiling phenomenon in a TPLT employing a mixture of deionized water and ethanol as a working fluid. The investigation considered an filling ratio (FR) ranging from 11-38% and a heating power ranging from 20-160 W. Employing the fast Fourier transform, the standard deviation of the evaporator temperature and the system pressure, and the flow regime visualization, it was demonstrated that the fluid with a higher pressure had better thermal resistance and temperature stability, but on the other hand, caused additional vibrations. Moreover, the evaporator design contributed to the resulting instabilities and had little influence on thermal resistance. Zhang *et al.* [8] has developed a prototype of a TPLT solar water heating system and conducted a series of long-term outdoor experiments to study the effect of the filling ratio on the system's performance, employing 10%, 20%, 30%, 50%, and 70% volume-filling ratios. The R600a was used as a working fluid in the TPLT. The findings showed that the TPLT solar water heating system had better thermal performance compared to similar conventional ones under 30% and 50% volume-filling ratio.

The influence of special working conditions, such as ultrasonic vibration, electrical field, and rotation, on the heat transfer characteristics of TPLT has attracted researchers' attention and has been reported in a large number of investigations. The experimental investigation carried out by Chang and Wang [9] indicated that the ultrasonic vibration suppressed the deposition of TiO nanoparticles and improved the pool boiling heat transfer performance of nanofluids. In a connected study, the effect of the electric field on the thermal performance of TPLT with AL_2O_3 and CuO nanofluids as working fluids has been experimentally investigated by Heris *et al.* [10]. The results showed that the nanoparticles have a higher impact on the thermosyphon thermal performance compared to the effect of the electrical field. In addition, it was found that the electrical field has a direct impact on the Nusselt number ratio, with a relative improvement of up to 43%. A TPLT structure for cooling the shaft in a motorized spindle was developed and tested by Li [11] at rotational speeds in the range of 1000-2000 rpm. The results showed that at the same heat capacity, both the thermal resistance and the liquid fill ratio corresponding to it decreased with increasing the rotational speed. In addition, experiments were carried out by Abou-Ziyan *et al.* [12] to predict the performance of a stationary and vibrated (0-4.33 Hz) thermosyphon with water and R134a as working fluids. They reported that the effect of the vibration on the performance of the R134a thermosyphon is very minimal below the boiling limit, but leads to an enhancement of up to 250% above the boiling limit. Alae *et al.* [13, 14] measured the temperature difference between the evaporation and condensation sections of a horizontal heat pipe and analyzed the effects of low frequency vibrations on its heat transfer performance. The experimental results indicated that the low frequency vibrations enhanced the thermal performance of the heat pipe. A minimum thermal resistance of 0.05 K/W was achieved at a frequency of 25 Hz. Also, it was shown that the boiling heat transfer performance in cylindrical containers can be enhanced only by adding an appropriate amount of additives into the container with vibrations or reciprocating rotations. Sarafraz [15] experimentally investigated the thermal performance of a chevron type flat plate heat exchanger employing a CuO-water nanofluid. The results indicated that the thermal resistance is decreased by applying vibrations due to fouling of nanoparticles being mitigated via low frequency vibration.

In order to enhance the cooling effect, the TPLT is generally used in conjunction with a fan when cooling electronic chips, and thus it is in the vibration state under the influence of the fan. To some extent, the speed range of fans in different radiators is similar enough for interchangeability. Although comprehensive investigations into the heat transfer characteristics of TPLT have been carried out in the literature, including the impact of some special working conditions, there are few reported studies on the sensitivity of TPLT employing different pipe diameters in the specific vibration state. So, three TPLT with pipe diameters of 4 mm, 6 mm, and 8 mm, respectively, were designed in this study, and the heat transfer performance of each case was experimentally studied under the condition of vibration frequency of 40Hz and acceleration of 20 m/s^2. The influence of the vibration state caused by the fan rotation on the heat transfer performance of TPLT with different diameters is analyzed and compared with the scenario of operation in the static state.

Experimental apparatus and uncertainty analysis

Experimental apparatus

The experimental apparatus designed and employed in this study is shown in fig. 1. The employed TPLT is made of Cu tubes with a vertical placement. The bottom of the left vertical section is integrated with an electrical heating wire and forms the evaporation section of the tested TPLT. The electrical heating wire is connected with adjustable DC power supplies and a power meter, and the heating power is modified by adjusting the voltage applied to the heating wire. The upper part of the right pipe is placed in the cooling water jacket and forms the condensation section of the TPLT. The water jacket is connected to a thermostatic water container and is equipped with a flowmeter. The constant temperature water flows out of the thermostatic water tank, passing through the cooling water jacket to cool the condensation section.

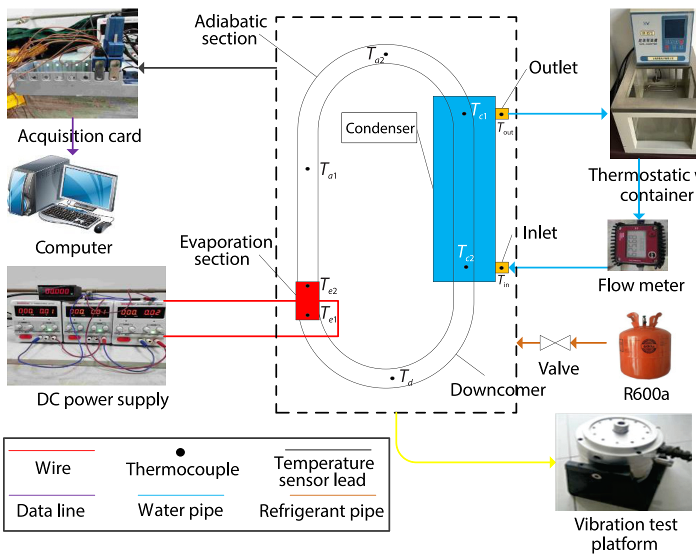

Figure 1. The experimental apparatus

Seven OMEGA *K*-thermocouples are placed at various locations on the surface of the experimental TPLT. Two of the thermocouples are fixed in the condensation section, two in the evaporation section, and the rest in the adiabatic section. In addition, two thermocouples are used to measure the inlet and outlet temperatures of the cooling water. All temperature sensor data is collected and recorded by the acquisition system, which is composed of Ni 9215 and Ni 9178 boards.

The experimental TPLT set-up is wrapped with insulating cotton provide proper thermal insulation and reduce heat dissipation. In addition, the experimental TPLT set-up, including thermocouples, electrical heating wire, and cooling water jacket, is fixed to the exciter support. The vibration action of the exciter is controlled by a connected PC through a signal generator and amplifier, and is closed-loop monitored by an online acceleration measuring instrument.

Generally, the speed of the fan used for chip cooling is about 2000 rpm. For example, the rated speed of the fan in the Intel E97379 radiator is 2100 rpm. In addition, the vibration frequency of the experiment is set to 35 Hz. In order to analyze the sensitivity of different pipe diameters to the vibration effect, three experimental samples with inner diameters of 4 mm, 6 mm, and 8 mm are designed. The detailed parameters of the experimental TPLT and the corresponding working conditions are listed in tab. 1.

Table 1. Specifications of the test samples and the experimental condition parameters

Specification	Value
Pipe diameter [mm]	4, 6, 8
Vertical side length [mm]	400
Upper and lower elbow radius [mm]	50
Evaporation section length [mm]	60
Condensation section length [mm]	240
Working fluid	R600a
Liquid filling rate [%]	40, 50, 60, 70
Heating power [W]	40, 80, 120, … heat transfer limit
State	Static or vibration (35 Hz, 30 m/s^2)
Cooling water flow rate [mLmin^{-1}]	300 ±20
Cooling water temperature [°C]	23 ±1

Data reduction and uncertainty analysis

The thermal resistance, *R*, is used as an index to measure the heat transfer performance of the tested TPLT and can be mathematically expressed:

$$R = \frac{\overline{T}_\mathrm{e} - \overline{T}_\mathrm{c}}{Q} \tag{1}$$

$$\overline{T}_\mathrm{e} = \frac{T_\mathrm{e1} + T_\mathrm{e2}}{2} \tag{2}$$

$$\overline{T}_\mathrm{c} = \frac{T_\mathrm{c1} + T_\mathrm{c2}}{2} \tag{3}$$

where *R* [°CW^{-1}] is the thermal resistance , *Q* [W]– the heating power transferred by the experimental TPLT, and $\overline{T}_\mathrm{e}$ and $\overline{T}_\mathrm{c}$ [°C] are the average temperatures of the evaporation section and the condensation section , respectively.

The heating energy absorbed by the cooling water, Q, is calculated using:

$$Q = \frac{C\dot{m}(T_{\text{out}} - T_{\text{in}})}{60} \tag{4}$$

where C [Jg^{-1}°C^{-1}] is the specific heat capacity of the cooling water, T_{out} and T_{in} [°C] are the inlet and outlet temperatures of the cooling water, respectively, and $\dot{m}$ [gmin^{-1}] is the cooling water mass-flow rate.

The percentage difference in the thermal resistance between vibration and static state is used to measure the influence of vibration on thermal resistance. This is highlighted by:

$$n = \frac{(R_{\text{V}} - R_{\text{S}})}{R_{\text{S}}} \times 100\% \tag{5}$$

where n is the percentage difference in the thermal resistance between the vibration and static state and R_{V} and R_{S} [°CW^{-1}] are the thermal resistances in the vibration and the static state, respectively.

When the heating power is low, the temperature difference between the inlet and the outlet of the cooling water is very small, and the obtained results from eq. (4) are not accurate enough. Therefore, the relationship between the heating power, P, applied to the TPLT and the heating power absorbed by the cooling water, Q, is established, as shown in fig. 2. It is found that when P is greater than or equal to 120 W, Q satisfies the following: $0.86P < Q < 0.94P$. Thus, Q is calculated by $Q = 0.9P$ when P is less than 120 W and by eq. (4) when P is greater than or equal to 120 W. This is highlighted in:

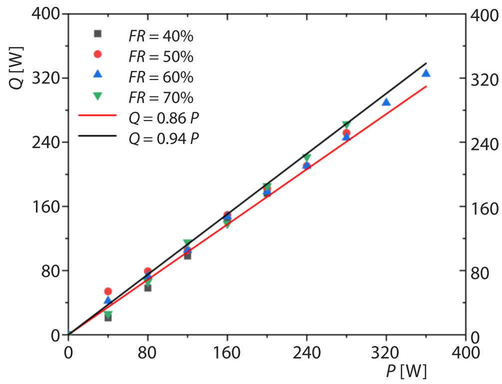

Figure 2. The change in the effective power with respect to the heating power

$$Q = \begin{cases} \dfrac{C\dot{m}(T_{\text{out}} - T_{\text{in}})}{60} & P \geq 120 \text{ W} \\ 0.9P & P < 120 \text{ W} \end{cases} \tag{6}$$

The standard error analysis method is utilized to evaluate and assess the uncertainty of the experimental parameters. The method presented by Coleman [16] was employed to evaluate the uncertainty calculations of the thermal resistance of the TPLT:

$$\frac{\delta R}{R} = \sqrt{\left(\frac{\delta \overline{T}_{\text{e}}}{\overline{T}_{\text{e}} - \overline{T}_{\text{c}}}\right)^2 + \left(\frac{\delta \overline{T}_{\text{c}}}{\overline{T}_{\text{e}} - \overline{T}_{\text{c}}}\right)^2 + \left(\frac{\delta Q}{Q}\right)^2} \tag{7}$$

$$\frac{\delta Q}{Q} = \begin{cases} \sqrt{\left(\dfrac{\delta \dot{m}}{\dot{m}}\right)^2 + \left(\dfrac{\delta T_{\text{in}}}{T_{\text{out}} - T_{\text{in}}}\right)^2 + \left(\dfrac{\delta T_{\text{out}}}{T_{\text{out}} - T_{\text{in}}}\right)^2} & P \geq 120\ W \\ 1.59\% & P < 120\ W \end{cases} \tag{8}$$

In this experiment, the measurement accuracy of the thermocouples used is ±0.5 °C, and the measurement accuracy of the flowmeter is 5 mL per minute. As a result, the holistic uncertainty of the thermal resistance is between 2.8% and 6.4% according to the experimental date.

Experimental results

Temperature distribution

Figure 3 shows the temperature distribution of the experimental TPLT at FR = 60% with an inner diameter of 4 mm and 8 mm in the static state and vibration state, respectively. It is evident from the figure that the temperature of the TPLT increases rapidly with the increase in the heating power, and then tends to be stable, whether in the vibration or the static state. When the tested TPLT is about to reach the heat transfer limit, the temperature of the evaporation section with d = 4 mm fluctuates majorly, as shown in figs. 3(a) and 3(b). On the other hand, the fluctuation disappears, and the temperature is generally stable before reaching the heat transfer limit when d = 8 mm as shown in figs. 3(c) and 3(d). Comparing the data under static and vibration conditions, it can be noted that the vibration has a greater impact on the temperature distribution of the TPLT with d = 4 mm than the case with d = 8 mm. When d = 4 mm and FR = 60%, T_{a1} (near the evaporation section) is equivalent to T_{a2} (near the condensation section) in the static state, and the maximum temperature difference between the two sections is around 3.7 ℃. However, T_{a1} is significantly higher than T_{a2} in the vibration state, and the maximum reported temperature difference is 17.8 ℃.

Based on the working principle of a TPLT, the working fluid absorbs heat and evaporates in the evaporation section. Then, it flows along the pipe-line successively through the adiabatic section the condensation section under the action of gravity and buoyancy. After that,

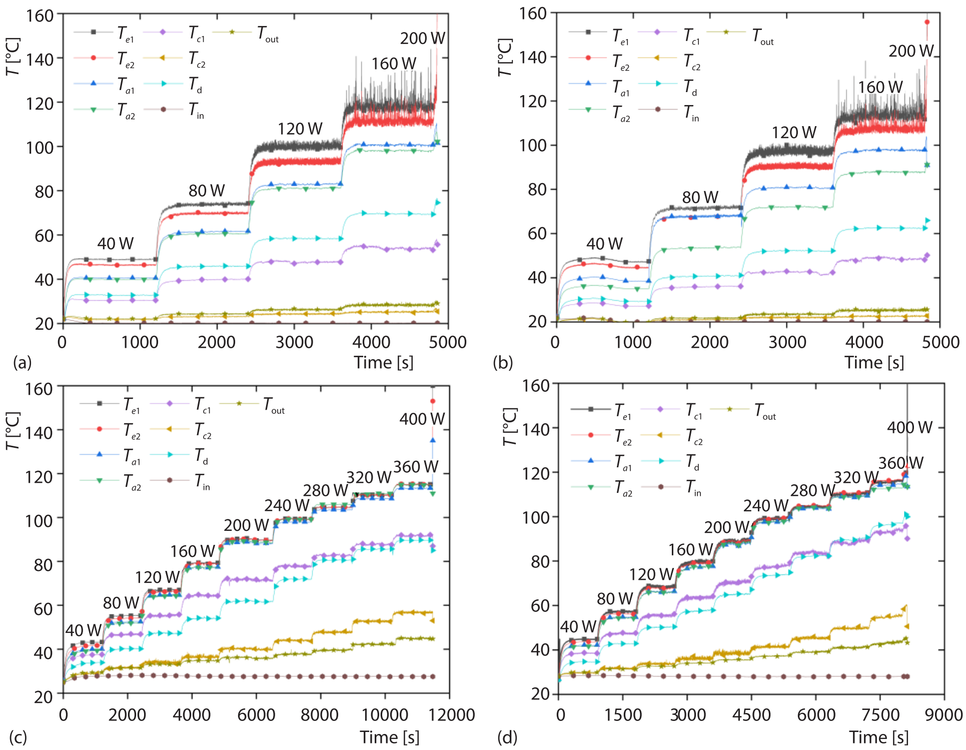

Figure 3. Temperature distribution of the experimental TPLT; (a) d = 4 mm, FR = 60%, static, (b) d = 4 mm, FR = 60%, vibration, (c) d = 8 mm, FR = 60%, static, and (d) d = 8 mm, FR = 60%, vibration

it returns to the evaporation section through the downcomer after releasing heat and condensing in the condensation section. Both T_{a1} and T_{a2} are fixed in the adiabatic section, and the heat dissipation of the high temperature working medium moving from T_{a1} to T_{a2} can be ignored. Thus, the temperature at T_{a1} and T_{a2} should be similar if the tested TPLT operates normally, as shown in fig. 3(a). When d = 4 mm, the surface tension of the liquid in the TPLT is equivalent to the gravity and the tested sample is in the transition stage between oscillating heat pipes and TPLT. In this case, T_{a2} is lower than T_{a1}, meaning that the temperature at T_{a2} is affected by the condensation section. This indicates that the vibration changes the overall flow direction of the working fluid in the tested TPLT and leads to the emergence of large reciprocating fluctuations. When d = 8 mm and FR = 60%, the vibration has little impact on the temperature distribution of the TPLT, and the temperature distribution under static and vibration states is found to be similar.

Heat transfer performance

Figure 4 shows the variation of the thermal resistance with the change in the effective heating power of the employed TPLT with different diameters under static and vibration states. It is shown in the results that the variation trend of the thermal resistance against the heating power is different at different FR and diameter. When the FR is low (such as FR = 40%) and the heating power is increased, the thermal resistance decreases first and then increases in the cases of d = 4 mm and 6 mm, while it continuously decreases in the case of d = 8 mm. When the FR is high, the thermal resistance decreases with the increase of heating power.

In addition, it is noted that as the heating power is increased, the vaporization phenomenon in the evaporation section is more severe, resulting in a larger pressure difference between the evaporation section and the condensation section. Therefore, the circulation flow speed of the working fluid in the TPLT is accelerated, which improves its heat transfer performance and reduces the thermal resistance. When FR = 40%, the surface tension of the liquid in the TPLT is equivalent to the gravity at d = 4 mm, resulting in the easy formation of a liquid plug. The vapor generated in the evaporation section exerts some pressure on the liquid, resulting in a joint movement, before escaping. However, with the increase in the heating power, the flow speed of the working fluid in TPLT is accelerated, and the gas cannot escape from the liquid before reaching the condensation section, which leads to pushing part of the liquid into the condensation section. As a result, the TPLT changes from a vapor phase heat transfer to vapor-liquid two-phase mixed heat transfer. The thermal resistance of the liquid heat transfer is generally larger

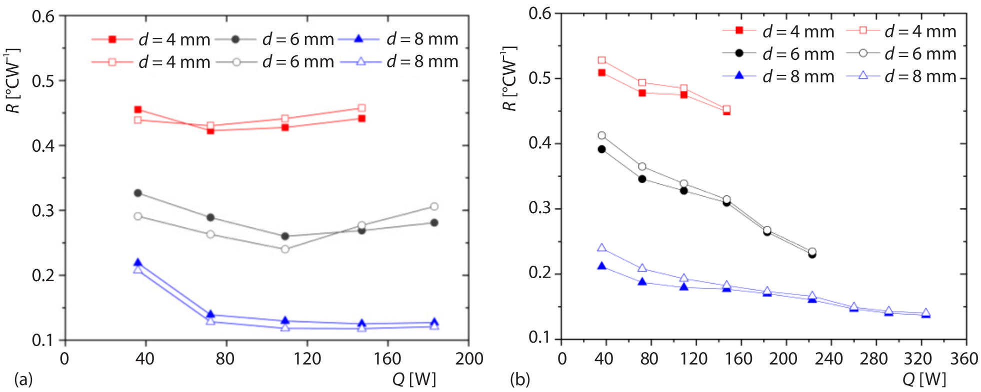

Figure 4. Variation of the thermal resistance with the change in heating power and using different pipe diameters; (a) *FR* = 40% and (b) *FR* = 60%

than that of the vapor heat transfer. Thus, the new vapor-liquid two-phase mixed heat transfer is associated with a decrease in the thermal resistance initially, before increasing again with the increase in the heating power when $d = 4$ mm. Similarly, the same phenomenon happens when $d = 6$ mm. However, the critical heating power for the transformation from vapor-phase heat transfer to vapor-liquid two-phase heat transfer is larger in the case of $d = 6$ mm due to the larger diameter. When the diameter increases further to 8 mm, the TPLT is dominated by vapor phase heat transfer until the drying limit is reached. So, the thermal resistance gradually decreases with the increase in the heating power without a subsequent increase. When $FR = 60\%$, the tested TPLT with different diameters are mainly dominated by liquid-phase heat transfer, so their thermal resistance decreases with the increase in heating power.

The effect of the vibration on the thermal resistance of TPLT with different diameters is shown in fig. 5. It can be seen that with the increase in the heating power at $FR = 40\%$, the vibration first enhanced and then suppressed the heat transfer efficiency of the TPLT at $d \leq 6$ mm. The inhibition effect disappears at $d = 8$ mm. Considering the results provided in a previous study by Amir *et al.* [17], the vibration state can enhance the heat transfer efficiency between the liquid and the wall due to the elevation of the driving force within the liquid layer and the reduction in the liquid film thickness. Also, the vibration accelerates the rupture of the liquid plug and thus facilitates the escape of bubbles from the liquid [18].

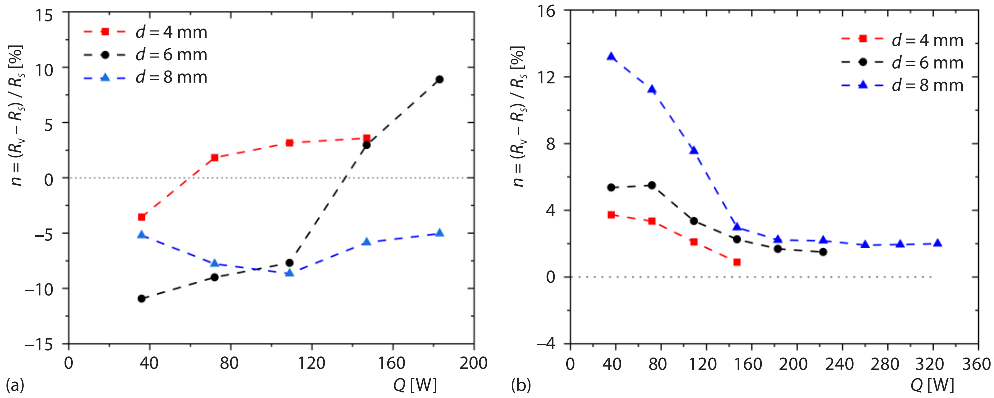

Figure 5. Effect of vibration on the thermal resistance; (a) *FR* = 40% and (b) *FR* = 60%

At $FR = 40\%$, the TPLT is dominated by a vapor phase heat transfer at low heating power and with a $d \leq 6$ mm. The vibration accelerates the vapor escaping from the liquid, reducing the flow resistance in the evaporation section and enhancing the heat transfer efficiency between the liquid and the wall. Therefore, the heat transfer thermal resistance of TPLT in the vibration state is lower than that in the static state. However, with the increase in the heating power, the flow speed of the working fluid in TPLT accelerates, and the liquid plug above the vapor does not break before the vapor reaches the condensation section. At this level, the TPLT is transformed from a vapor phase heat transfer to a vapor-liquid two-phase heat transfer. The vibration will accelerate the rupture of the liquid plug, resulting in a significant reduction in the length of the liquid plug. So, part of the liquid pushed out of the evaporation section by the vapor flows back along the pipe wall and thus has no capacbility to transfer heating power. As a result, the heat transfer thermal resistance of TPLT in the vibration state is higher than that in the static state. In addition, when $FR = 40\%$ and $d = 8$ mm, due to the increase in the pipe diameter, the liquid plug above the vapor bubble breaks before the vapor reaches the condensation section, and no liquid plug enters the condensation section. Therefore, the acceleration of the vapor escape by vibration can effectively reduce the rising height of the liquid plug, leading to a reduction in the vapor flow resistance and an enhancement in the heat transfer performance.

When FR = 60%, the vibration reduces the heat transfer efficiency of the TPLT and the suppression effect decreases with the increase of heating power. In this regard, the thermal resistance of TPLT with diameters of 8 mm, 6 mm, and 4 mm decreases from 13.2-1.9%, from 5.4-1.2% and from 4.2-1.1%, respectively, as fig. 5(b) shows. In the case of FR = 60%, the vertical pipe-line contains a large amount of liquid, and the height difference required for the liquid to move to the condensation section is far less than that in the case of FR = 40%. During the expansion and upward escape of bubbles generated in the evaporation section at the bottom of the vertical pipe-line, the liquid is pushed to move together and enter the condensation section for heat exchange. Thus, the vibration accelerates the backflow of the liquid along the pipe wall and the escape of the vapor, reducing the amount of liquid entering the condensation section contribute to the heat transfer. Therefore, the thermal resistance of TPLT in the vibration state is greater than that in the static state. However, with the increase in the heating power, the flow speed of the working medium in TPLT accelerates, and the time required for the liquid plug to flow from the vertical pipe to the condensation section becomes shorter. At the same time, the reflux liquid is received by the rising liquid plug driven by the next vapor bubble and continues to move upward, resulting in the reduction of the inhibition effect of vibration on the heat transfer performance.

Conclusions

In this paper, the heat transfer performance of TPLT with diameters of 4 mm, 6 mm, and 8 mm was experimentally investigated under both a vibration state of 35 Hz and 20 m/s^2 and a static state. By comparing both operational scenarios, the influence of the vertical vibration on TPLT with different diameters was analyzed and assessed. The following conclusions can be drawn from the current investigation, are as follows.

- The influence of vertical vibration on the overall temperature distribution of TPLT decreases with the increase in the diameter from 4-8 mm. The TPLT, with a d = 4 mm, is found to be in the transition stage between the pulsating heat pipe and the TPLT. In this case, the vertical vibration leads to large reciprocating fluctuations of the vapor-liquid plug, which affects the overall temperature distribution. This phenomenon decreases with the increase in the pipe diameter.
- As the heating power is changed, the vertical vibration does not change the variation trend of the heat transfer performance of TPLT. With the increase in the heating power, the thermal resistance of TPLT, both in vibration and static state, first decreases and then increases in the case of $d \leq 6$ mm. On the other hand, the thermal resistance decreases continuously with d = 8 mm at low filling ratio, and decreases at high filling ratio.
- The impact of the vertical vibration on the heat transfer performance of TPLT depends on the corresponding diameter, the heating power, and the liquid filling ratio. With the increase in the heating power, the heat transfer efficiency of TPLT is first enhanced, and then suppressed in the case of $d \leq 6$mm. Heat transfer efficiency, on the other hand, increases when d = 8 mm with an increase in heating power at low filling ratios and improves at high filling ratios.

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Nomenclature

C – specific heat capacity, [$Jg^{-1}°C^{-1}$]
FR – filling ratio, [%]
$\dot{m}$ – mass-flow rate, [$gmin^{-1}$]
n – difference percentage
Q – effective heating power, [W]
P – heating power, [W]
R – thermal resistance, [$°CW^{-1}$]
T – temperature, [°C]

Subscripts and superscripts

c – condensing section
diff – difference
e – evaporation section
in – inlet
out – outlet
S – static
V – vibration

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