EXPERIMENTAL INVESTIGATION OF FLOW CHARACTERISTICS IN A VERTICAL VIBRATION TWO-PHASE LOOP THERMOSYPHON

by

Zhifeng WANG, Fajing LI*, and Mu CHAI

[a]School of Mechatronic Engineering and Automation,Foshan University, Foshan, Guangdong, China

Original scientific paper
https://doi.org/10.2298/TSCI211023014W

In this paper, flow characteristics of a two-phase loop thermosyphon under vertical reciprocating vibration are visually investigated with N-pentane as the working fluid. The tests are performed for a heating power range of 20 W to 40 W, the filling ratio of 30% to 70%, and a 30 m/s^2, 35 Hz vertical reciprocating vibration. The effect of vertical vibration on flow characteristics of the two-phase loop thermosyphon is investigated by comparing the obtained results with those acquired in static, thereby providing a basis for explaining the heat transfer process of two-phase loop thermosyphon under vibration. The results indicate that vertical vibration promotes the rupture of a liquid plug and the transformation of the plug flow to annular flow or wavy flow. Furthermore, the vertical vibration does not change the distribution law of liquid flow velocity in the two-phase loop thermosyphon. However, it will reduce the overheating and flow velocity in the two-phase loop thermosyphon at the start-up. With an increase in the heating power, the influence of vertical vibration on liquid flow velocity is reduced due to continuous disturbance of the working medium in the two-phase loop thermosyphon.

Key words*: two-phase loop thermosyphon, vertical vibration, flow characteristic, visualization*

Introduction

Two-phase loop thermosyphons (TPLT) have numerous advantages regarding efficient heat transfer, such as high heat exchange efficiency, no requirements for additional power, and low maintenance [1]. The application of TPLT widely covers the conventional heat transfer fields, involving the cooling of computer equipment, nuclear reactors, solar utilization, air-conditioning, energy storage [2], and even high-speed motorized spindles [3]. A TPLT is generally a closed-loop metal tube filled with a cyclic working fluid that consists of four parts: an evaporation section, a vapor pipeline (rising pipeline), a condensation section, and a liquid pipeline (downcomer pipeline). During the operating process, the evaporation section is heated and the condensation section is cooled. The liquid in the evaporation section boils, flows through the rising pipeline, condenses through the condensation section, and finally flows back to the evaporation section through the liquid pipeline under gravity [4].

*Corresponding author, e-mail: lifajing987519@126.com

Recent studies on the TPLT have focused on its heat transfer and flow characteristics at rest as well as the effects of liquid filling ratio and working fluids. In terms of heat transfer performance of TPLT, Swart [5] conducted thermal-hydraulic modelling of a TPLT for cooling a high temperature reactor. The obtained results indicated that the heat-removing capability of this reactor cavity cooling system reached 18.2 kW. Shao *et al*. [6] experimentally investigated the heat transfer performance of a loop thermosyphon with an evaporative condenser. Moreover, the author compared the results with a conventional loop thermosyphon. The results showed that the optimal distance of the test sample is 200-400 mm and that the heat transfer was enhanced by 7%-33% compared with the conventional condenser. To simulate operating conditions at the high filling ratio in a passive containment cooling system, Yin *et al*. [7] investigated the operating characteristics of a TPLT in a pressure vessel (0.32-0.46 MPa). The results showed that as the vessel pressure increased, a high filling ratio resulted in an improved heat transfer. Wang *et al*. [8] conducted visual experiments to investigate the two-phase flow in a water TPLT. Moreover, the authors developed a CFD model to elucidate the underlying heat and mass transfer regimes for TPLT. The results indicated that the flow regime changes from smooth unidirectional flow to geyser oscillation flow with an increase in filling ratio. Li *et al*. [9] designed and visually studied a TPLT for motorized spindle shaft cooling with an evaporation section and condensation section located at the same height. The results demonstrated that the velocity of the liquid flow in the upper adiabatic section of the TPLT is on the order of 0.1 m/s. Moreover, a reverse flow of liquid was observed in the upper pipeline and under low filling ratio.

As a high-efficiency heat conduction element, TPLT is generally used with a cooling fan. Moreover, the flow and heat transfer performance of the TPLT is affected by the fan vibration. To simulate the actual operating environment, the heat transfer performance of the heat pipe was investigated. Alaei [10] investigated the effects of low-frequency vibrations on the thermal performance of a horizontal heat pipe. The authors concluded that the low-frequency vibrations imposed a significant effect on the thermal performance, while the best performance was achieved for the frequency of 25 Hz. Chen *et al*. [11] investigated the effect of longitudinal vibrations on the heat transfer performance of a grooved cylindrical copper heat pipe with an 8 mm outer diameter. The authors demonstrated that longitudinal vibrations had a minor effect on heat transfer performance and that the thermal resistance of the tested heat pipe is relatively low and constant with the frequency of 3-9 Hz and amplitude of 2-25 mm. Arkady [12] investigated the heat transfer coefficient of short linear heat pipes. The authors concluded that the heat transfer coefficient demonstrates a resonance nature and is increased up to 20% with a limited amplitude of 0.15 mm and frequency equal to the frequency of arising internal vapor pulsations. Huber *et al*. [13] investigated the effect of longitudinal vibration on the capillary limit of copper. The authors employed a water heat pipe with vibration frequencies of 10-50 Hz and vibration amplitudes of 0.2-2.0 mm. The results indicate that the vibration amplitude caused degradation in capillary heat transport limit within 10%. Sugimoto *et al*. [14] visualized the working fluid in a self-vibration heat pipe by neutron radiography system, while periods of approximately 0.5-1.5 seconds of the column oscillation were obtained.

Many researchers have carried out in-depth investigations on the heat transfer characteristics of TPLT and achieved many guiding research results. However, the existing researchers pay more attention to the heat transfer characteristics of a static TPLT or a vibration heat pipe. Simultaneously, an insignificant amount of visualization research is carried out on flow characteristics of TPLT under vibration. The heat transfer mechanism of a TPLT under a vibration state is not clear due to the lack of existing research on flow characteristics. Therefore, in this paper, a quartz glass TPLT with an inner diameter of 6 mm is customized, and a vibration visualization experimental platform is built. The flow process of the TPLT is recorded by a high-speed camera with a heating power of 20-40 W, filling ratio of 30-70%, vibration frequency of 35 Hz, and vibration acceleration of 30 m/s^2. The effect of vibration on the two-phase flow pattern and flow velocity of the TPLT is analyzed by comparing the obtained results with the ones for the static state.

Experimental details

The experimental platform is shown in fig. 1 N-pentane, which is liquid at room temperature and has a relatively low boiling point, is selected as the working liquid. The TPLT is made of the quartz glass tube and placed vertically along the length direction. The 40 mm long pipeline on the lower left side of the TPLT is placed in the oil bath which is heated by two electric heating rods. Therefore, the evaporation section is formed. The heating input power is adjusted by changing the heating rod voltage. The heating power is monitored by a power meter, while the oil temperature is measured by a single *K*-type thermocouple. The 140 mm long pipeline on the upper right side of the TPLT is placed in the cooling water jacket to form the condensation section. For clearer observation, a plane light source with adjustable brightness is placed behind the TPLT. A flowmeter is employed to measure the constant temperature of water flowing through the cooling jacket. A high-speed camera was employed to record the flow process as well as two-phase flow patterns seen in the TPLT. In this experiment, the frame rate of the high-speed camera was 100 Hz.

The excitation system of the experimental sample mainly includes an exciter, a set of support, a signal amplifier, and a signal generator. The test TPLT is fixed on the support, and the bottom of the support is connected with the exciter. In order to eliminate the influence of gravity, four springs are employed to lift the support, as shown in fig. 2.

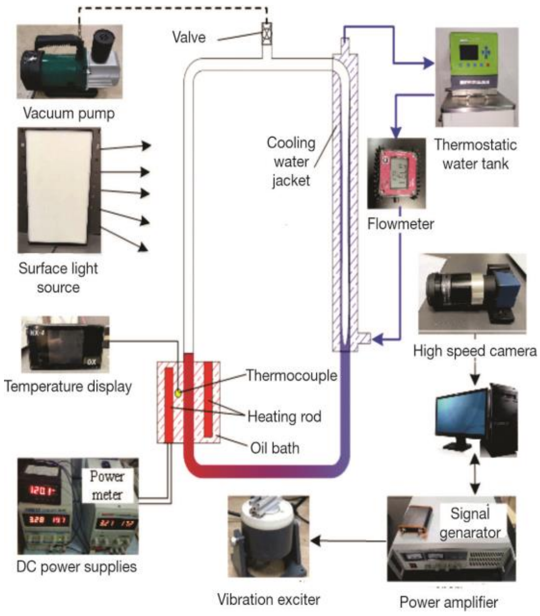

Figure 1. The experimental platform

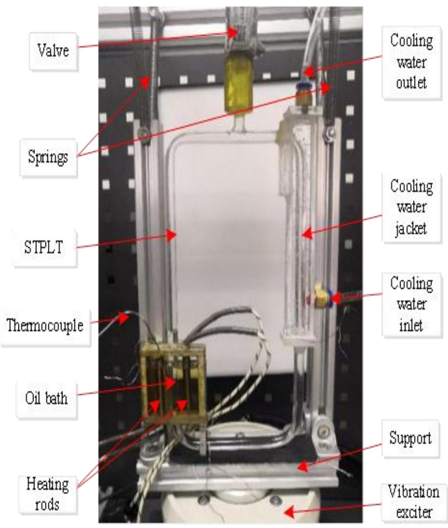

Figure 2. The connection of the TPLT

In the process of heat dissipation of electronic components, the fan speed matched with thermosyphons is about 2000 rpm. For example, the speed of Deepcool ultimate 300 CPU cooling fan is 2200 rpm. Thus, the vibration frequency of the excitation system is set to 35 Hz. Specifications of the TPLT and experimental conditions are listed in tab. 1. The shooting frame rate used in this experiment is 100 Hz and the time interval between two adjacent images is 1 second ($1\triangle t$ = 0.01 s).

Table 1. Test sample specifications and experimental conditions

Specification	Parameter	Specification	Parameter
Material	quartz glass	Working liquid	N-pentane
Total height [mm]	200	Filling ratio	30%-70%
Total width [mm]	100	Heating power [W]	20 W, 40 W
Pipe outer diameter [mm]	8	Mass flow of cooling water [gmin^{-2}]	400 ±20
Pipe inner diameter [mm]	6	Inlet temperature of cooling water [°C]	23 ±2
Water cooling jacket height [mm]	140	Vibration acceleration [ms^{-2}]	30 (3 g)
Oil bath height [mm]	40	Vibration frequency [Hz]	35
Heating rods [mm]	5(D)×38(L)	Frame rate [Hz]	100

The process of vacuum pumping and liquid injection of the experimental sample is:

– The total volume of TPTL is calculated according to its size, the experimental sample is filled with pure water, and the total volume is verified by observing the mass change.
– The volume of N-pentane to be injected is calculated under the set liquid filling rate and the liquid level height that can be reached. Then, the volume is marked on the glass tube.
– The sample is filled with N-pentane, and the valve and vacuum pump are connected.
– The vacuum pump is started, the valve is slightly opened, and part of N-pentane is pumped out. The aforementioned results in a slow decrease in the liquid level in the pipe.
– When the liquid level drops to the marked position, the valve is closed and TPLT is disconnected from the vacuum pump.

Experimental results

Two-phase flow pattern

When the heating power is 20 W and the liquid filling ratio is 40%, the two-phase flow pattern in the static state includes annular flow, slug flow in the vertical vapor pipeline, as well as stratified flow, and wavy flow in the horizontal pipeline. As shown in fig. 3(a), a bubble is generated at the bottom of the evaporation section. Then, it expands into a vapor plug when it moves up to the middle of the evaporation section. The vapor plug pushes the liquid upwards on its upper side and forms a slug flow. Due to gravity, the liquid above the vapor plug flows downward along the tube wall, whose length gradually decreases until the liquid plug finally breaks in the vertical pipeline. At this time, the liquid flows downward along the tube wall while the vapor flows upward along the vertical pipeline. Therefore, an annular flow is formed, figs. 3(b)-3(d). There is only a minor amount of condensed liquid in the upper horizontal pipeline, which is classified as stratified flow. On the other hand, in a few cases, the liquid slug is pushed and broken into the upper horizontal pipeline. The two-phase flow pattern in the vertical pipeline changes from annular flow to plug flow, fig. 3(e). For the horizontal pipeline, the flow pattern changes from stratified flow to wavy flow, fig. 3(f). Therefore, the two-phase flow of the TPLT is mainly composed of annular flow and stratified flow, accompanied by plug flow and wavy flow.

Figure 3. Flow process of a static TPLT with filling ratio = 40%; (a) t = 0△t, (b) t = 5△t, (c) t = 10△t, (d) t = 15△t, (e) t = 325△t, and (f) t = 335△t

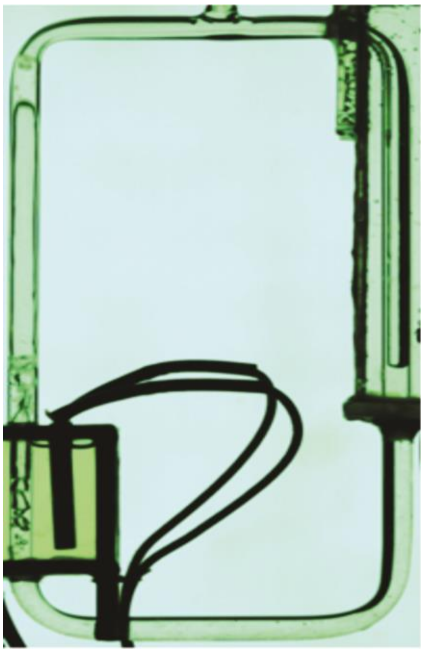

Figure 4. Flow process of a static TPLT with filling ratio = 50

When the filling rate increases to 50%, a flow process similar to 40% is observed for the same heating power, as shown in fig. 4. The difference is that the liquid plug on the upper side of the vapor is longer and will usually not break in the vertical pipeline. Under this condition, the vertical section is dominated by the plug flow and supplemented by the annular flow in the vertical section. On the other hand, the horizontal direction is dominated by wavy flow and supplemented by the stratified flow.

When the filling ratio is 60%, the annular flow in the vertical rising pipeline of the TPLT disappears. One or two large vapor plugs push the liquid upward into the upper horizontal pipeline, thus forming a plug flow in the vertical pipeline, fig. 5(a). After moving forward for a certain distance, the liquid plug pushed into the horizontal pipeline breaks and flows into the condensation section. The two-phase in the upper horizontal pipeline includes the plug flow and the wavy flow, figs. 5(b)-5(e). Due to the rupture of the liquid plug, the original vapor fuses with the newly generated vapor in the evaporation section. Moreover, the liquid in the upper horizontal pipeline flows smoothly into the condensation section without causing large oscillations.

When the filling ratio increases to 70%, the two-phased flow type in the vertical pipeline is similar to that at filling ratio = 60%. However, the liquid plug in the horizontal section enters the condensing section in the form of a complete liquid plug. Consequently, the two-phase flow type in both the upper horizontal and vertical pipelines is characterized as plug flow. At filling ratio = 60%, the liquid plug will flow through the upper pipeline in the form of a plug rather than rupture and enter the condensation section. This liquid plug makes the original vapor enter the condensation section in the form of a vapor plug. Then, the vapor rises slowly due to buoyancy, escapes from the liquid, and integrates with the vapor generated in the evaporation section. Since the movement direction of the vapor plug is opposite to the overall flow direction of the tested TPLT, the heat transfer performance of TPLT will be restricted. Furthermore, after a relatively large amount of liquid is pushed into the condensation section, abundant low temperature liquid in the condensation section returns to the evaporation section along the lower pipeline. This results in a decrease of liquid temperature in the evaporation section, consequently weakening the vaporization phenomenon, fig. 6(b). With continuous heating of the oil bath, the flow state of the test TPLT once again returns to the state shown in fig. 6(a). This cycle occurs between 2.04 and 2.67 seconds within the conducted experiment.

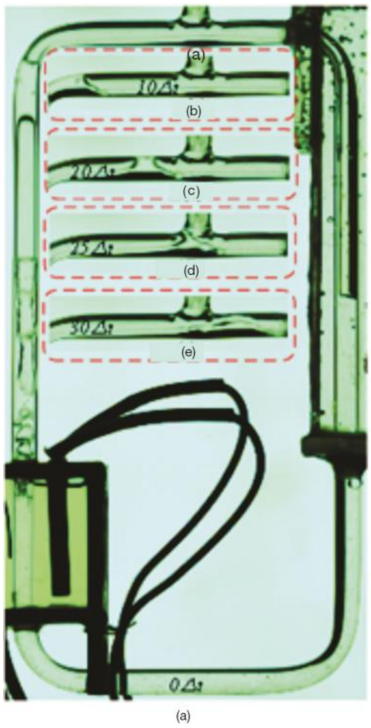

Figure 5. Flow process of a static TPLT with filling ratio = 60%; (a) t = 0Δt, (b) t = 10Δt, (c) t = 20Δt, (d) t = 25Δt, and (e) t = 30Δt

Figure 6. Flow process of a static TPLT with filling ratio = 70%; (a) t = 0Δt and (b) t = 45Δt

The process flow of the tested TPLT with 35 Hz vertical vibration at filling ratio = 40% is shown in fig. 7. Compared with the static TPLT under the same working conditions, vaporization occurs preferentially in the middle of the evaporation section rather than at the bottom, fig. 7(b). The vapor plug pushes the liquid upwards, and the liquid plug breaks relatively quickly. No liquid plug is pushed into the upper horizontal pipeline within the experiment. The two-phase flow pattern is characterized as annular flow in the vertical pipeline and stratified flow in the horizontal pipeline. Until filling ratio increases to 50%, the liquid plug is pushed into the upper horizontal pipeline by the vapor plug, figs. 8(f)-8(g). However, in most cases, the liquid plug is still broken in the vertical pipeline, figs. 8(b)-8(e). The flow process is similar to the static TPLT flow process with filling ratio = 40%. Vapor and liquid plugs exist alternately in the vapor-rising pipeline, fig. 8(d). During the rising process, the liquid plug breaks and the vapor plug escapes, thus forming an annular flow.

Figure 7. Flow process of a vibrational TPLT with filling ratio = 40%; (a) $t = 0\triangle t$, (b) $t = 5\triangle t$, (c) $t = 10\triangle t$, and (d) $t = 15\triangle t$

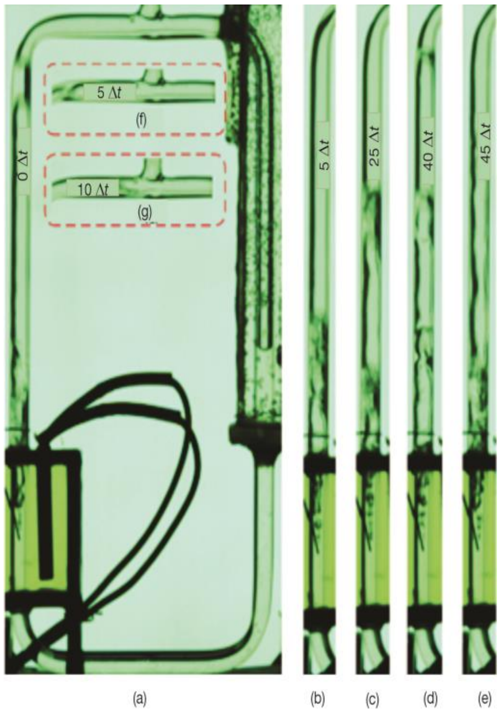

Figure 8. Flow process of a vibrational TPLT with filling ratio = 50%; (a) $t = 0\triangle t$, (b) $t = 5\triangle t$, (c) $t = 25\triangle t$, (d) $t = 40\triangle t$, (e) $t = 45\triangle t$, (f) $t = 5\triangle t$, and (g) $t = 10\triangle t$

When filling ratio ≥60%, the vapor generated in the evaporation section pushes the liquid in its upper part to the upper horizontal pipeline. Thus, the liquid flows into the condensation section. However, vapor plugs in the vertical pipeline are smaller in size, fewer, and rupture earlier compared with the static TPLT under the same operating conditions, fig. 9. Bubble flow and plug flow both appear in the rising pipeline at filling ratio = 70%, fig. 10(a), and the liquid is divided into many small size liquid plugs. When the original vapor of the test TPLT is pushed into the condensation section to form a vapor plug, the vapor plug escapes from the liquid with relative ease. The intermittent violent vaporization is also present, fig. 10(b).

Effect on velocity distribution and reciprocating fluctuation

Due to gravity and pressure differences, the high temperature vapor and liquid in the evaporation section are moved to the condensation section via a vapor vertical rising pipeline and horizontal pipeline. To analyze the effect of vertical vibration on flow velocity and reciprocating fluctuation in the TPLT test, the process of the liquid plug flow from the evaporation section to the condensation section is studied. For convenience, the left side of the test sample is taken as the co-ordinate origin ($X = 0$). The range of axial length of evaporation section (X) is 0-40 mm. As shown in fig. 11(a), vapor vertical rising pipeline, and upper horizontal pipeline are respectively defined as X:40-185 mm and X: 185-285 mm. In the experiment, the frame rate of the high-speed camera was 100 Hz. The flow velocity in the TPLT can be calculated by measuring the moving distance of the liquid plug between adjacent pictures, as shown in figs. 11(b)-11(c).

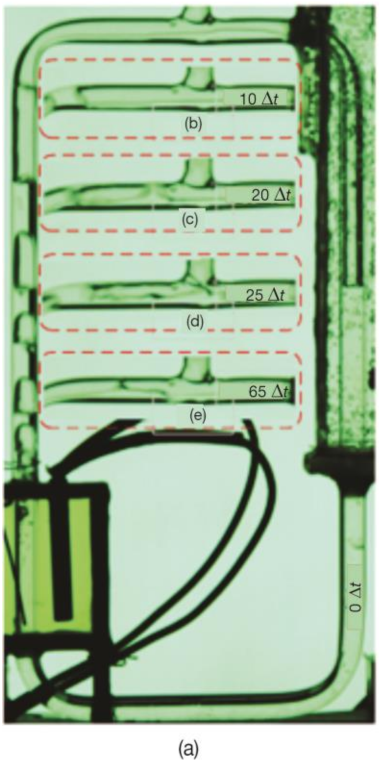

Figure 9. Flow process of a vibrational TPLT with filling ratio = 60%; (a) t = 0Δt, (b) t = 10Δt, (c) t = 20Δt, (d) t = 25Δt, and (e) t = 65Δt

Figure 10. Flow process of a vibrational TPLT with filling ratio = 70%; (a) t = 0Δt and (b) t = 125Δt

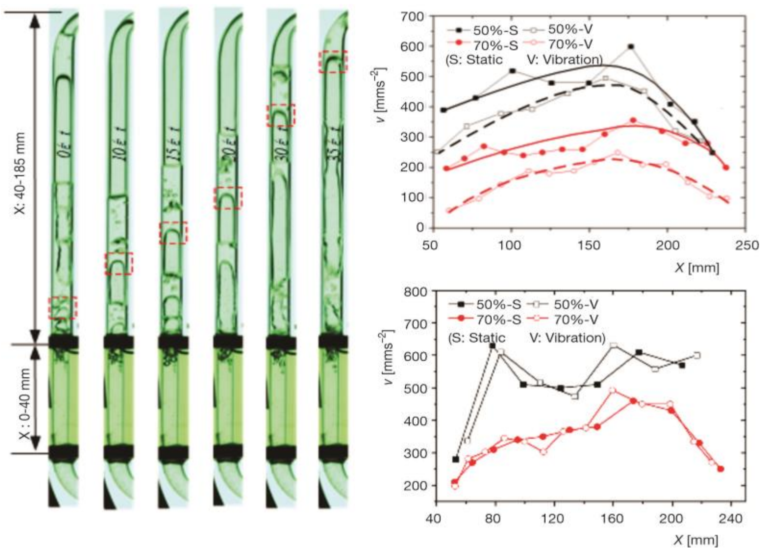

Figure 11. Velocity distribution of the TPLT; (a) definition of X, (b) P = 20 W, and (c) P = 40 W

The flow velocity of the liquid plug in a vertical vibration TPLT is lower than that in a static TPLT with the same filling ratio and heating power at P = 20 W, as shown in fig. 11 (b). When filling ratio = 50%, the velocity of the liquid plug in both vibration and static TPLT increases as it flows through the vertical rising pipeline. Then, the velocity decreases when it reaches the top of the vertical rising pipeline. A similar situation occurs at filling ratio = 70%, but the inflection point occurs further away. When the vapor plug pushes the liquid plug upward, its volume expands while its pressure decreases. Once the vapor generated in the evaporation section cannot make up for the pressure loss caused by the volume expansion of the vapor plug, the thrust acting on the liquid plug as well as the flow velocity will be reduced. The vapor generation rate is similar due to the same heating power. Therefore, positions of the flow velocity inflection points of both the static and vibration TPLTs are close.

According to the aforementioned two-phase flow-type analysis, vertical vibration suppresses the formation of a liquid plug and promotes the upward escape of bubbles. The liquid plug in the upper horizontal pipeline breaks in advance at filling ratio = 50%. Furthermore, the high pressure vapour escapes from the rear end of the liquid plug. The driving force acting on the liquid plug changes from the thrust of the vapor plug into the shear force of vapor flow. The aforementioned results in a sharp decrease in the velocity of the liquid plug for $X \geq 200$ mm. When filling ratio = 70%, vertical vibration causes several small vapor plugs in the TPLT test, fig. 10. This results in the low pressure of a single vapor plug, low liquid plug speed, and an early deceleration.

When P = 20 W, the flow velocity in a static TPLT is significantly higher than that in the vertical vibration one, fig. 11(b). However, flow velocities in these two TPLT are very similar to the velocities obtained for P = 40 W, fig. 11(c). According to the conducted analysis, due to the low heating power, operates intermittent operation occurs when P = 20 W. Since the non-condensable gas inside the TPLT is excluded, the number of vaporized nuclei in a no-operating TPLT is relatively small. Therefore, a higher superheat is required for boiling. Consequently, an intense boiling will occur in the evaporation section, which will promote the rapid flow of the liquid plug. However, vertical vibration will increase the number of vaporized nuclei in the liquid and cause unstable liquid in the evaporation section of a TPLT. Boiling occurs in the evaporation section at low superheat values, thus resulting in a lower flow velocity in a vibration TPLT when compared to a static case. When P = 40 W, the intermittent operation phenomenon disappears, the liquid in the evaporation section continues to boil and be disturbed, and the effect of vibration on the boiling phenomenon is significantly reduced. Therefore, flow velocities in these two TPLTs are very similar.

Conclusions

In this paper, visualization experiments on a TPLT were performed under the condition of vertical acceleration of 30 m/s^2 and vibration frequency of 35 Hz. By comparing the two-phase flow type and flow velocity in TPLT with the static state, the effect of vertical vibration on the TPLT flow process is analyzed. The following conclusions can be drawn.

- Vertical vibration promotes the rupture of the liquid plug, reduces the size of the vapor plug, inhibits the formation of plug flow, and promotes the transformation of plug flow to either annular flow or wavy flow. Furthermore, liquid flow from the evaporation section to the condensation section is restrained, resulting in deterioration of liquid-phase heat transfer performance of a TPLT.
- When liquid flows from the evaporation section to the condensation section, its velocity first increases and then decreases. Vertical vibration does not alter the distribution law of

liquid flow velocity in the TPLT. Lastly, liquid flow velocity at low heating power is higher than that at high heating power due to start-up overheating.

- Vertical vibration weakens the overheating phenomenon during TPLT start-up and decreases the liquid flow velocity when compared to the static TPLT case. However, with an increase in the heating power, the effect of vertical vibration on liquid flow velocity is reduced due to the continuous disturbance of the working medium in the TPLT.

Acknowledgment

The financial support of Guangdong Basic and Applied Basic Research Foundation (2020A1515111099) is gratefully acknowledged.

References

[1] Zhang, H., *et al*. Numerical Investigation of a CO_2 Loop Thermosyphon in an Integrated Air Conditioning System for Free Cooling of Data Centers, *Applied Thermal Engineering. 126* (2017), Nov., pp. 1134-1140
[2] Chen, C. X., *et al.*Characterisation of a Controllable Loop Thermosyphon for Precise Temperature Management, *Applied Thermal Engineering, 185* (2021), 116444
[3] Li, F. J., *et al.* Experimental Investigation of an R600a Two-Phase Loop Thermosiphon to Cool a Motorized Spindle Shaft, *Int. Communications in Heat and Mass Transfer, 97* (2018), Oct., pp. 9-16
[4] Shuang, Z., *et al*. Experimental and Theoretical Analysis of a Closed Loop Two-Phase Thermosiphon Under Various States for Latent Heat Storage, *Energy Reports, 6* (2020), Suppl. 7, pp. 1-7
[5] Swart, R. T. D., Thermal-Hydraulic Simulation and Evaluation of a Natural Circulation Thermosyphon Loop for a Reactor Cavity Cooling System of a Hightemperature Reactor, *Nuclear Engineering and Technology, 52* (2020), 2, pp. 271-278
[6] Shao, S. Q., *et al*. Experimental Investigation on a Loop Thermosyphon with Evaporative Condenser for Free Cooling of Data Centers, *Energy, 185* (2019), Oct., pp. 829-836
[7] Yin, X., *et al*. Experimental Investigation of Two-Phase Thermosyphon Loop for Passive Containment Cooling, *Applied Thermal Engineering, 184* (2021), 116403
[8] Wang, Y. F., *et al*. A Combined CFD/Visualized Investigation of Two-Phase Heat and Mass Transfer Inside a Horizontal Loop Thermosiphon, *International Journal of Heat and Mass Transfer, 112* (2017), Sept., pp. 607-619
[9] Li, F. J., *et al*. Visualization Research on a Pentane Loop Thermosyphon for Shaft Cooling, *Heat and Mass Transfer*, *58* (2021),3, pp. 1-10
[10] Alaei, A. M., A New Designed Heat Pipe: An Experimental Study of the Thermal Performance in the Presence of Low-Frequency Vibrations, *Heat and Mass Transfer, 48* (2011), 4, pp. 719-723
[11] Chen, R. H., *et al*. The Influence of Longitudinal Vibrations on the Heat Transfer Performance of Inclined Heat Pipes, *Advances in Mechanical Engineering, 7* (2015), 2, pp. 1-13
[12] Arkady, V. S., Resonant Vibration Heat Transfer Coefficient Increase of Short Low-Temperature Heat Pipes, *International Journal of Heat and Mass Transfer, 158* (2020), 119764
[13] Neil, F. H., *et al*. Longitudinal Vibration Effects on a Copper/Water Heat Pipe's Capillary Limit, *Journal of Thermophysics & Heat Transfer, 10* (1996), 1, pp. 90-96
[14] Sugimoto, K., *et al*. Flow Visualization of Refrigerant in a Self-Vibration Heat Pipe by Neutron Radiography, *Nuclear Instruments & Methods in Physics Research, 605* (2009), 2, pp. 200-208

Paper submitted: October 23, 2021
Paper revised: December 27, 2021
Paper accepted: January 3, 2022