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Research paper

Experimental investigation on the start-up performance of a novel flat loop heat pipe with dual evaporators

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ABSTRACT

Thermal management for multiple heat sources has been becoming increasingly important, especially under high heat flux conditions. As a passive heat transfer device, loop heat pipes (LHP) with multiple evaporators does not consume extra energy, demonstrating a great potential in thermal management. This paper proposed a flat plate LHP with dual evaporators for the first time. Two flat plate evaporators were adopted, and both of them had their own porous wick, compensation chamber (CC) and vapor line. The condensed liquid converged, then moved along the main liquid line. The CC of two evaporators was joined by a tube, which can ensure the sharing of the returning liquid. To verify the performance of novel flat plate LHP, the start-up test was investigated under different heat load arrangements, involving only a single evaporate was applied heat load, two evaporators were applied with the equal or unequal heat load. Meanwhile, the operation stability was determined by testing the performance with the successionally variable heat load. This system has been shown to operate successfully at heating source temperature below 100 °C with heat load ranging from 10 W–10 W to 130 W–130 W (corresponding to the maximum heat flux of 13.52 W/cm^2).

1. Introduction

The battery pack is one of the key components of electric vehicles and the thermal management of which will significantly affect the safety of vehicles. The battery packs packaged into vehicles become multiple adjacent heat sources generating more and more heat per unit volume. The higher operating temperature of the battery packs will decrease their reliability and longevity (Liu et al., 2022), causing that the safety of batteries faces serious challenges. The batteries thermal runaway has become a common risk, so the thermal management of batteries seriously restricts the development of electric vehicles (Wu et al., 2019). In addition, the data center faced potential safety hazards, caused by the electronic equipment local overheating. Thus, efficient thermal management of multiple heat sources should be applied in the date center to ensure its safe operation. Depending on the heat-transfer medium, the thermal management of batteries can be divided into four methods, including air cooling, liquid cooling, phase-change material cooling, and heat pipe cooling.

The heat pipe (Jiang and Qu, 2019) and vapor chambers (Lu et al., 2019) could effectively conduct good thermal management through two-phase change heat transfer. Nonetheless, they cannot stratify heat dissipation requirements due to the limit of transferring high heat flux over a long distance. Thus, in system design, the loop heat pipe (LHP) is superior to the heat pipe and passive operation mode and considered to be a promising cooling method. LHPs can provide very small thermal resistance between heating sources and heat sinks, and their evaporator and condenser are joined by a smooth tube. A typical LHP mainly consists of an evaporator, a condenser and vapor/liquid transport lines (Maydanik, 2005). Maydanik et al. (Heat Pipe, 1974) first experimentally tested the LHP with a cylindrical evaporator in 1972, using water as the working fluid. With that, more LHPs with a cylindrical evaporator (Pastukhov et al., 1999) or flat evaporator (Liu et al., 2011, 2012; He et al., 2016b) were investigated to explore the heat transfer performance. Compared to the cylindrical evaporator, the flat evaporators have a flat heat-absorbing surface directly contacting most the heating sources. Thus, various kinds of miniature flat plate LHPs were designed to solve thermal problems (Chernysheva et al., 2014; He et al., 2020; Singh et al., 2007), meanwhile completely passive LHP does not consume extra energy during its operation. Zhou et al. (2019) employed the LHP as the thermal management system of high-end ultra-slim laptop computers, accounting for 20% of the energy consumption of current cooling methods.

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With the development of the LHP technology, a ramified LHP that consisted of multi-evaporators and one condenser appeared for solving multiple heat sources with high heat flux (Gregori et al., 2006). Compared to the typical LHPs, the design of thermal control systems with ramified LHPs is more compact reducing the wright of the entire device. On one hand, the LHP with multi-evaporators could dissipate waste heat from separated heating sources or a large heating surface. On the other hand, the LHP with multi-condensers had a more flexible arrangement of condensers. Thus, the ramified LHPs were easily integrated with complicated heating occasions. At present, some ramified LHP prototypes (Maidanik et al., 1992; Bienert et al., 1997; Yun et al., 1999; Goncharov et al., 2000) had been developed, demonstrating the feasibility.

In recent years, many scholars have investigated the multiple evaporators LHP with cylindrical type of evaporators. Ku et al. systematically investigated operating characteristics of the LHP with two evaporators and two condensers, including capillary limit (Nagano and Ku, 2006; Ku and Birur, 2002) and operating temperature control (Ku and Birur, 2001a,b). Additionally, a lot of experiments about start-up, different sink conditions, and CC temperature at different heat load arrangements were tested (Ku and Birur, 2001c), and summarized the performance characteristics of the multi-evaporator LHP. The related research about multi-evaporator LHPs were reviewed before 2012 (Ku et al., 2012). A mathematical model for a multi-evaporator/condenser LHP was developed by Gregori et al. (2006) using a software mathematical tool EcosimPro, and simulation results of steady and transient states were obtained. Chang et al. (2019) visualized the LHP with two evaporators and one condenser in the different gravitational heads, and the vapor–liquid distribution was observed in the evaporate core, CC and condenser, finding that nucleate boiling existed in the unpowered evaporator core in the gravity-capillary mode. Qu et al. (2018) summarized the research and development of multi-evaporator LHP over the past 20 years in terms of design theory, set-up and steady-state operational performance and mathematical model. Amhar and Putra (2020) designed a symmetric dual-cylindrical-evaporator LHP and utilized three-way *T* port valves on LHP to adjust a loop whether using one evaporator or two evaporators. Qu et al. (2021b) designed an asymmetric dual-cylindrical-evaporator LHP and established a steady-state heat transfer model (Qu et al., 2021a). The interaction between two evaporators on the startup performance is analyzed. It shows that the early-started evaporator obstructs the late-started evaporator when the vapor fails to flow into the late-started evaporator before its startup. The previous work provided a good theoretical basis for subsequent development with multi-evaporator and multi-condensers. But the interaction of vapor in separate evaporators could deteriorate the heat transfer performance.

In contrast to the use of multiple evaporators, the structure change of the single evaporator LHP has been used to satisfy the cooling of multi-heat sources. Pastukhov and Maydanik (2018) used the LHP with one evaporator, one condenser and three tubular heat exchanges located on the vapor line and liquid line to realize thermal management of multiple heat sources. He et al. (2018) and Xiao et al. (2020) designed the LHP with a large squared evaporator to cool a large heating surface or multiple heat sources. For cooling near electronic devices, a flat plate LHPs with bifacial evaporator (He et al., 2016a) was developed, which compensation chamber shared by two heating surfaces.

However, existing studies about LHPs with multiple evaporators mentioned above mostly pays attention to the cylindrical type of evaporators, but LHPs with flat plate type of evaporator are rarely involved. At the same time, the drawbacks of vapor interacting in the multi-evaporator LHP needed to be addressed.

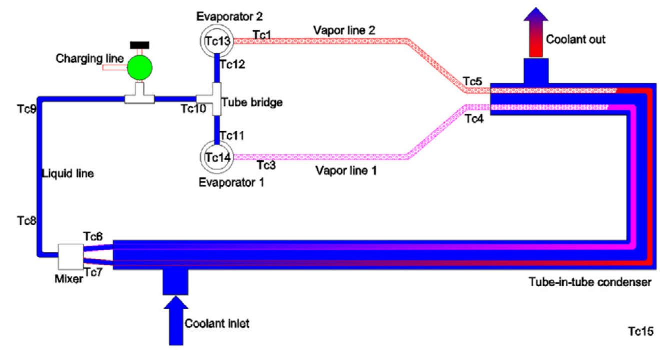

Fig. 1. Diagram of the LHP with dual evaporators and one condenser and the arrangement of thermocouples.

In this paper, a novel flat plate LHP with dual evaporators was proposed for the first time. The proposed LHP inherited the advantage of the flat plate LHP that was easily attached to the surface of heating elements, and at the same time two evaporators could dissipate heat from separate heating sources. The main objectives of this research are not only to design and fabricate the novel dual evaporator loop heat pipe, but also to conduct the performance test under different working conditions so as to verify the potential application.

2. LHP system design and experimental setup

The flat plate LHP with dual evaporators can utilize a set of heat transfer device to dissipate heat from two separate heat sources, and at the same time retain all the advantages of the LHP. In this paper, the distinct feature of the novel LHP system is that each evaporator is equipped with its own vapor transport line, and its compensation chambers are joined by a tube, as shown in Fig. 1. Two evaporators have the same geometric parameters. In the evaporator, the generated vapor passes through their own vapor transport lines to the condenser. The generated vapor in the evaporator is transported to the condenser through their own vapor transport lines. The vapor is condensed into liquid in the condenser. The liquid is firstly converged in the mixer, and then delivered to each CC by the main liquid transport line. The core idea of this design is to avoid the direct interference of vapor from two evaporators, but still to reserve the advantages of the flat plate LHP with dual evaporators. The parameters of the LHP components were depicted in Table 1. The evaporators and transport lines were made of stainless steel, and two sintered nickel wicks with the porosity of 71.4% and 70.2% were separately installed in the corresponding evaporator. The double pipe condenser was employed, and the water circulated between the external tube and the inner tube. Two copper rods with three heaters embedded worked as simulated heat sources, which were regulated by a voltage regulator and recorded by a wattmeter with an accuracy of 0.5%. For precisely monitoring the temperature change of the operating LHP, 15 thermocouples were arranged along with the LHP testing system and shown in Fig. 1, specifically including two K-type thermocouples testing the temperature of two simulated heat sources and 13 T-type thermocouples testing the temperature of LHP. The accuracy of thermocouples is ±0.5°C, and the temperature data were monitored by a data acquisition system "Keithley 2700".

For the flat plate LHP with dual evaporators, operating behavior was influenced by the distribution of the working fluid between two evaporators. Different ways of heat load imposed on the evaporator needed to be considered, such as heat load only on a single evaporator, and heat load on two evaporators.

Table 1
Structure parameters of the LHP components (Unit: mm).

Evaporator	Heating diameter × Thickness Height	49 × 1 15	
Nickel wick 1	Porosity	71.4%	
Nickel wick 2	Porosity	70.5%	
Vapor line 1	Inner diameter × Length	4 × 250	
Vapor line 1	Inner diameter × Length	4 × 255	
Liquid line	Inner diameter × Length	4 × 625	
Condenser	Inner tube 1	Inner diameter × Length	4 × 750
	Inner tube 2	Inner diameter × Length	4 × 760
	Double pipe	Inner diameter × Length	34 × 760
Tube bridge	Inner diameter × length	4 × 100	

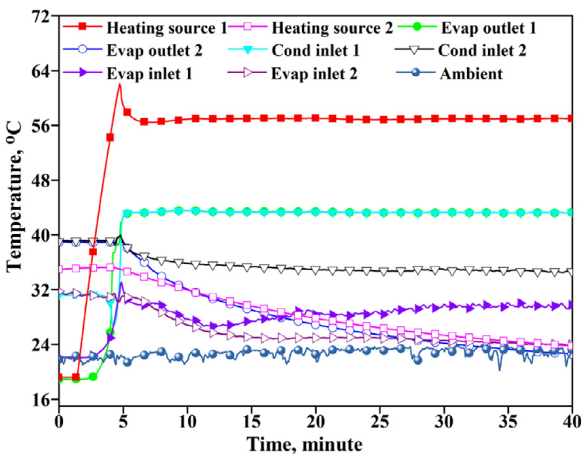

Fig. 2. Start-up with 50 W–0 W.

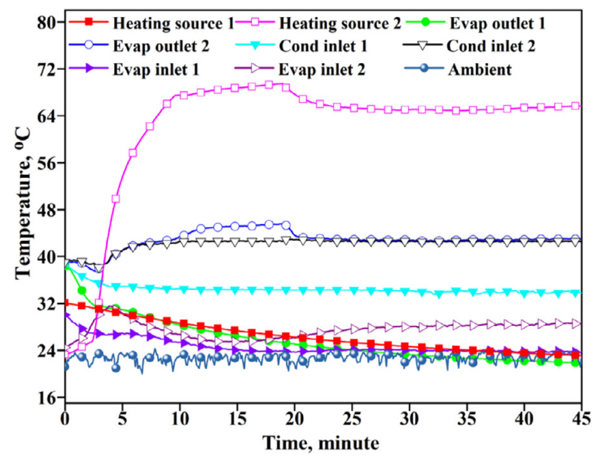

Fig. 3. Start-up with 0 W–50 W.

Therefore, the charging ratio of the working fluid used was very important. Two modes of constant heat conduction and variable heat conduction were considered during the operating process. For constant heat conduction mode, the amount of working fluid could be calculated as following equations when heat load was imposed on a single evaporator or double evaporators:

$$\alpha_{\text{single}} = 1 - \frac{(V_l + V_{vc} + 1/2 \bullet V_{cond})}{V_{total}} \quad (1)$$

$$\alpha_{\text{double}} = 1 - \frac{(V_{l1} + V_{vc1} + V_{l2} + V_{vc2} + 1/2 \bullet (V_{cond1} + V_{cond2}))}{V_{total}} \quad (2)$$

For variable heat conduction mode, amount of working fluid could be calculated as following equations when heat load was imposed on single evaporator or double evaporators:

$$\alpha'_{\text{single}} = 1 - \frac{(V_l + V_{vc})}{V_{total}} \quad (3)$$

$$\alpha'_{\text{double}} = 1 - \frac{(V_{l1} + V_{vc1} + V_{l2} + V_{vc2})}{V_{total}} \quad (4)$$

where, α_{single} and α_{double} are the filling ratio for LHP with single and double evaporators respectively, V_l represents the volume of the liquid line, V_{vc} represents the volume of CC, V_{total} represents the total volume of the LHP.

The calculated results were respectively 0.891 and 0.861 for the constant heat conduction while 0.732 and 0.621 for the variable heat conduction. Considering that the heat load was changed with operating conditions, the value of the charging ratio was determined at 0.7. In this experiment, the methanol was chosen to be the working fluid. Before charging the methanol into the LHP system, non-condensed gas was excluded through an oil diffusion pump. The amount of working fluid was 35.23 g (44.54 ml), which was charged when the internal pressure of the LHP system arrived at 2.5 × 10^{-4} Pa. In order to cut down the impact of heat exchange with the test environment, transport lines and simulated heat sources were wrapped with thermal insulation material. In the horizontal stance, the start-up process and successional operation with varying heat loads were tested at different heat load arrangements, and heat transfer characteristics of the flat plate LHP with dual evaporators were analyzed.

3. Discussion about experimental results

Start-up performance is an essential evaluation index for LHP heat transfer performance, which shows the working fluid normally circulates and can be regarded as a thermal bus for heat transfer. Compared to the LHP with one evaporator, the flat plate LHP with dual evaporators has more complex characteristics of flow and heat transfer. For the LHP with dual evaporators, start-up performance is influenced by heat load, heat sink temperature, ambient temperature and gravity, as well as by the distribution of the heat load between two evaporators and the total heat load imposed on two evaporators. Start-up processes have been experimentally investigated at different heat load arrangements, including start-up with only one evaporator, start-up with equal heat load and start-up with the unequal heat load. In addition, successional operation with variable heat load has been also tested.

3.1. Start-up with only one evaporator

In the system of the flat plate LHP with dual evaporators, the start-up with only one evaporator was when a single evaporator was heated while the other evaporator maintained an idle state. In the horizontal stance, start-up experiments with only one evaporator were carried out. Fig. 2 and Fig. 3 were start-up

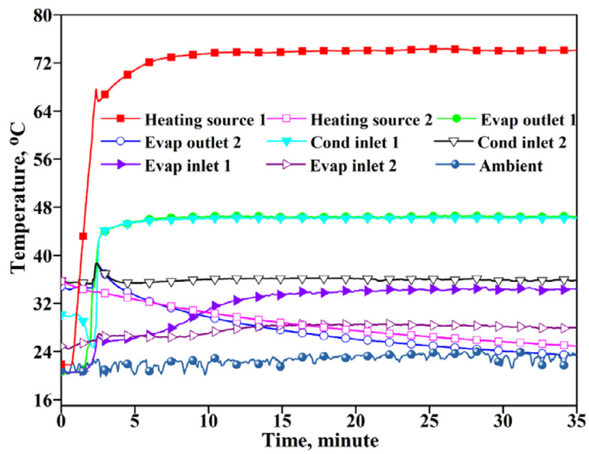

Fig. 4. Start-up with 100 W–0 W.

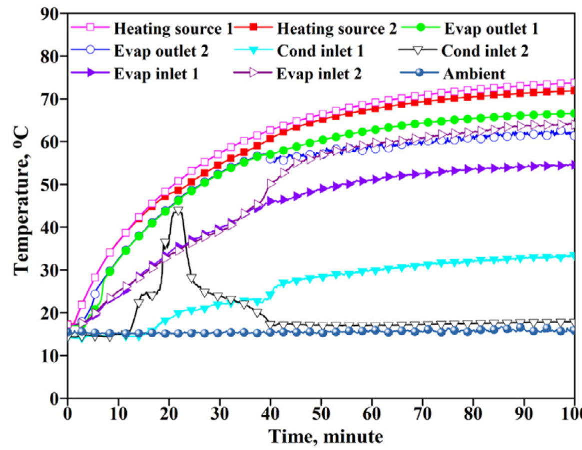

Fig. 5. Start-up with 10 W–10 W.

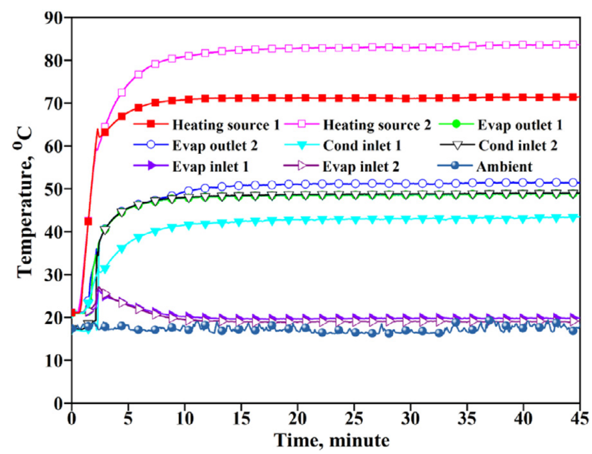

Fig. 6. Start-up with 100 W–100 W.

experiments of 50 W–0 W and 0 W–50 W, respectively, where the former was the value of heat load imposed on evaporator 1, and the latter was the value of heat load imposed on evaporator 2. The temperature of heating source 1, evaporator outlet 1 and condenser inlet 1 increased and eventually reached a steady state when a 50 W heat load was imposed on the evaporator 1. The working fluid in the loop corresponding to the evaporator 1 circulated normally, indicating that the start-up process with only one evaporator was successful. The temperature of featured points corresponding to the evaporator 2 tended to approach the ambient temperature, and evaporator 2 was in an idle state. When 0 W–50 W was provided with the LHP with dual evaporators, evaporator 2 worked normally and evaporator 1 did not. With heat load further increased to 100 W–0 W, the same situation occurred, as shown in Fig. 4.

Both two evaporators had their own vapor line, avoiding direct mutual interference. When one evaporator was heated, the vapor appeared and passed through its corresponding vapor line into the condenser. The relative condenser inlet temperature increased and the heated evaporator inlet temperature decreases, which indicated that the working fluid inside the LHP was circulating positively and the LHP starts successfully. The condensed liquid flowed in the CC through the main liquid line. The heated evaporator inlet temperature was higher than the idle evaporator inlet temperature. This temperature difference resulted in mass and heat transfer between two evaporators. Therefore, part of the returned liquid and heat flowed to the idle evaporator. The idle evaporator only received a little heat from the other evaporator, which hardly affected the thermal behavior of the other evaporator. So the vapor line of the idle evaporator could be kept in its original state without being affected. Meanwhile, the characteristic point temperature of the idle evaporator had not changed significantly and always converged to the ambient temperature. Therefore, the start-up process with only one of the evaporators was similar to that of LHPs with a flat evaporator.

3.2. Start-up with equal heat load

Equal heat load was imposed on two evaporators to test the performance of the start-up with the equal heat load. The LHP with dual evaporators could start up from 10 W–10 W to 130 W–130 W with the temperature of the two heating sources below 100 °C. Fig. 5 was start-up process with 10 W–10 W, namely 10 W was imposed on each evaporator. The temperature of two heat sources gradually rose and eventually reached a steady state. The temperature of condenser inlet 2 first increased and then decreased close to the ambient temperature. No vapor entered into the vapor line 2 to the condenser, so the heat load on the evaporator 2 could not be dissipated out by the means of the condenser. However, Fig. 5 showed the temperature of the evaporator inlet 2 was higher than that of the evaporator inlet 1. It is implied that heat load on the evaporator 2 was transferred to the evaporator 1. When the relatively low total heat load was imposed, the working fluid would be redistributed between two evaporators. Heat load on the LHP with dual evaporators was dissipated by one of the two evaporators.

With the heat load on two evaporators increased to 100 W–100 W, the start-up process showed fast and stable like in Fig. 6. Both of heating sources reached the equilibrium state, but the temperature of heat source 1 was much lower than that of the heat source 2. For ensuring the identical performance of the two evaporators, the same manufacturing process was chosen for the sintering wick and the evaporator. However, it is difficult to maintain consistency in the actual sintered wick, resulting in the different performances. Additionally, the assembly of the wick was an interference fit, and it is possible that the faulty sealing will cause vapor to enter the CC, deteriorating the heat transfer performance. As well, the cover plate and wick ribs may result in the ineffective contact, which can lead to excessive contact thermal resistance, deteriorating the heat transfer performance. Therefore, with the same heat load on two evaporators, there may be differences in their heat transfer performance, resulting in the temperature difference at the two evaporators. Fig. 7 gave start-up process with 130 W–130 W, which was the same as the start-up process with 100 W–100 W. With the total heat load increased, the temperature difference between two heating sources gradually increased.

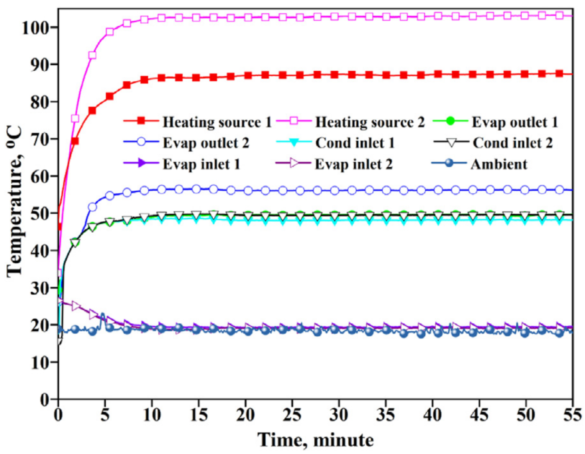

Fig. 7. Start-up with 130 W–130 W.

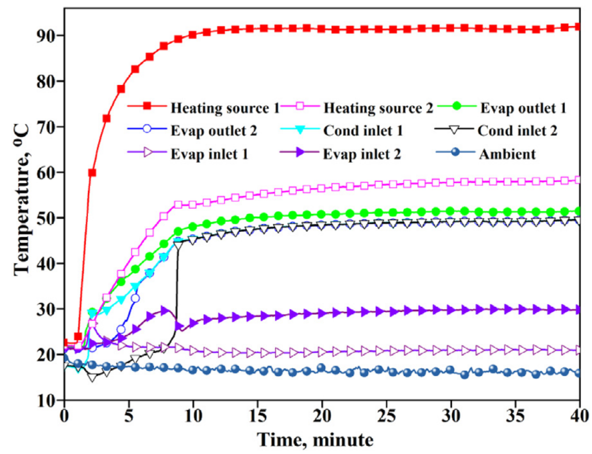

Fig. 9. Start-up with 130 W–20 W.

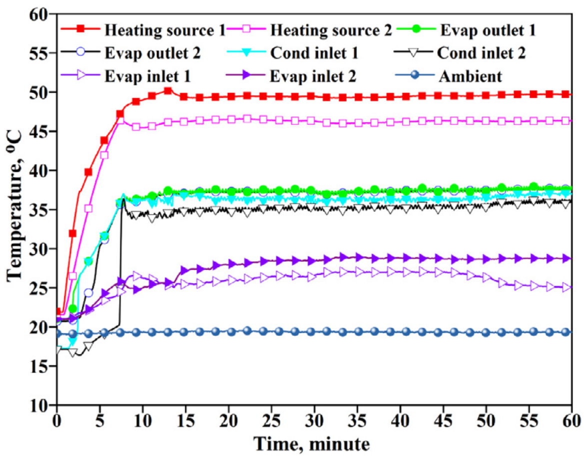

Fig. 8. Start-up with 30 W–20 W.

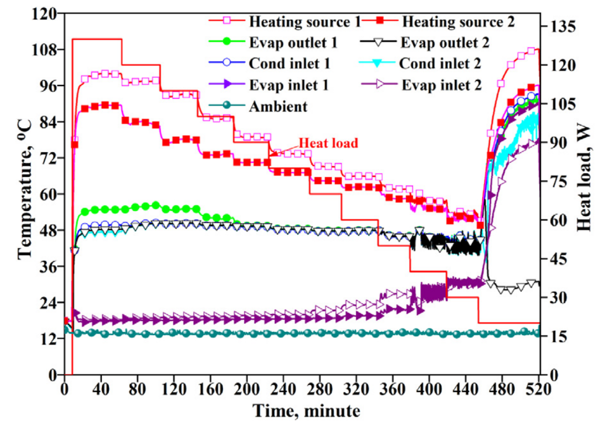

Fig. 10. Successional operation with equal heat load.

3.3. Start-up with unequal heat load

The operation with unequal heat load was the most common to the LHP with dual evaporators. The larger heat load difference between two evaporators, the more serious the mutual influence between the two evaporators. In this section, the start-up performance of the LHP with dual evaporators was discussed under the condition of unequal heat load. Fig. 8 and Fig. 9 showed the curves of the start-up process with 30 W–20 W and 130 W–20 W, respectively. Heat load was simultaneously imposed on two evaporators. The evaporator 1 started up firstly based on the analysis of the temperature change at the condenser inlet 1. Then the evaporator 2 postponed starting up, but eventually reached a steady state. This LHP system could start up successfully regardless of the large difference in heat load. With the heat load difference between two evaporators increased, the temperature difference between two heating sources also increased.

The amount of the generated vapor was determined by the capacity of the evaporator to absorb the heat load, affecting the frictional resistance along the loop. When the heat load imposed on the evaporator 1 was larger than that imposed on the evaporator 2, the temperature of heat source 1 and evaporator inlet 1 was higher than that of heating source 2 and evaporator 2. The temperature difference between evaporator inlet 1 and evaporator inlet 2 was the driving factor that heat flowed from the evaporator 1 to the evaporator 2. Namely, the evaporator provided with a lower heat load partially acted as the condenser. This character of the LHP with dual evaporators was called "heat load share". When the heat load difference increased, heat load share became more obvious.

3.4. Successional operation with variable heat load

Successional operation with variable heat load was a common method for evaluating the stability of the LHP. For the LHP with dual evaporators, heat load imposed on two evaporators was simultaneously altered to test the operating performance of the system. Based on conditions that were often encountered in engineering applications, some tests, including successional operation with equal heat load/one fixed and one varied/alternative heat load, were conducted. Fig. 10 gave the curve of successional operation with equal heat load, it was changed from 130 W–130 W to 20 W–20 W in the interval of 10 W for each evaporator. Under the condition of equal heat load, the proposed LHP could operate stably in every stage. When the heat load was reduced, the temperature difference between the two heating sources gradually decreased. In the range between 130 W–130 W and 100 W–100 W, the temperature of evaporator outlet 1 was higher than the temperature of evaporator outlet 1, which resulted from the different heat transfer capacities of two evaporators. The temperature of evaporator inlet 2 was increasingly higher than the temperature of evaporator inlet 1, implying that a section of heat load on the evaporator 2 was conducted to the evaporator 1 through the tube bridge. When the heat load was decreased to 40 W–40 W, temperature oscillations occurred at the inlets of

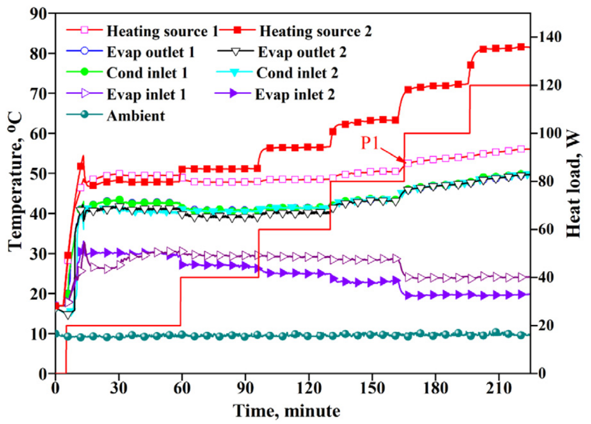

Fig. 11. Successional operation with heat load on evaporator 2 fixed at 20 W and evaporator 1 changed.

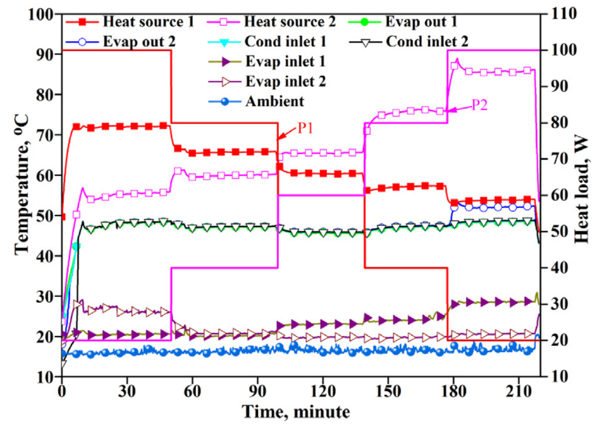

Fig. 12. Successional operation with the total heat load fixed at 120 W.

two evaporators and the condenser, but the temperature of the two heating sources showed stable. The tube bridge provided a direct thermal-hydraulic connection with two evaporators. As the heat load decreased, the state of the working fluid in two CCs reached unanimity. The low heat load broke the balance, leading to temperature oscillations of evaporator inlet 1 and evaporator inlet 2. Depending on the second case of the using performance of LHP (Liu et al., 2022) condition of serviceability, characteristic only of the LHP (Liu et al., 2022), the evaporator inlet temperature influenced the evaporator outlet temperature. As the heat load decreased further to 20 W–20 W, the temperature rapidly rose at all featured points except for condenser inlet 2, which was similar to the start-up process with 10 W–10 W. The evaporator 2 did not work normally, and worked as the condenser.

Fig. 11 was the curve of successional operation with evaporator 2 fixed at 20 W and evaporator 1 provided variable heat load. 20 W–20 W was firstly imposed on two evaporators, and the heat load on the evaporator 1 was altered in the step of 20 W. In the first stage, temperature overshoot of heating source 1 and evaporator inlet 2 was observed. The temperature of evaporator inlet 2 firstly increased and then decreased, but the temperature of evaporator inlet 1 showed stable. As the heat load imposed on the evaporator 1 increased, the temperature of heating source 1 was increasingly higher than the temperature of heating source 2, but the temperature of evaporator inlet 1 was lower than that of the evaporator inlet 2. This temperature difference forced heat to flow from evaporator 1 to evaporator 2. It was implied that the evaporator with a lower heat load played the role of the condenser in the system of the LHP with dual evaporators.

Fig. 12 was the curve of the operating process that the total heat load was maintained at 120 W and the heat load on two evaporators was alternatively changed. It was seen that the temperature of both heating sources changed with heat load, and quickly reached a corresponding stable state. With the total heat load maintained at 120 W, heat transferred by the LHP system did not change much. Thus, the temperature of evaporator outlet 1, evaporator outlet 2, condenser inlet 1 and condenser inlet 2 almost kept the same pace. When the heat load on the evaporator 2 reached 120 W, the temperature of evaporator outlet 2 deviated from the other featured points by 4 °C. With the heat load on the evaporator 1 decreased, the temperature of evaporator inlet 1 was gradually higher than the temperature of evaporator inlet 2, indicating that the evaporator 1 worked as the condenser at this time.

Successional operation with variable heat load demonstrated that the LHP with dual evaporators could be used to deal with different cooling occasions. With the heat load changed, two evaporators affected each other and had the features of heat load share.

4. Performance analysis of the evaporator

For the LHP with dual evaporators, the LHP thermal resistance was very difficult to evaluate due to the complex heat transfer route, but the evaporator thermal resistance might be obtained by the following equation:

$$R_{ei} = \frac{T_{ei} - T_{backi}}{Q_i} \tag{5}$$

where R_{ei} was the ith evaporator thermal resistance, T_{ei} was the temperature of heating source, T_{backi} was the temperature of the ith evaporator back, and Q_i was heat load on the ith evaporator ($i = 1, 2$).

Fig. 13 showed the evaporator thermal resistance varied with heat load in successional operation under equal heat load. It could be seen that R_{e2} was higher than R_{e1} under the equal heat load, except for 30 W. As the heat load rose from 40 W to 110 W, the difference reached the largest value at 110 W. The heat transfer capacity of the evaporator 2 was weaker than that of the evaporator 1. Thus, part of the heat from the evaporator 2 was transferred to the evaporator 1 through the tube bridge when heat load on the evaporator 1 was equal to or larger than the heat load on the evaporator 1. Of course, the evaporator 1 would help the evaporator 1 dissipate part of the heat when the heat load on the evaporator was lower than the heat load on the evaporator 2. Two evaporators had different heat transfer capacities that resulted in a redistribution of the total heat load on the LHP with dual evaporators, called heat load share. The uncertainly of the evaporator thermal resistance can be calculated by

$$\frac{\delta R_{ei}}{R_{ei}} = \sqrt{\left(\frac{\delta t}{t}\right)^2 + \left(\frac{\delta Q}{Q}\right)^2} \tag{6}$$

$$\delta t = \sqrt{(\delta T_{ei})^2 + (\delta T_{backi})^2} \tag{7}$$

$$t = T_{ei} - T_{backi} \tag{8}$$

Through uncertainty analysis of measuring instrument accuracies, the maximum uncertainty of the evaporator thermal resistance was ± 3.55% at a heat load of 20 W and the minimum uncertainty was ± 0.57% at a heat load of 130 W.

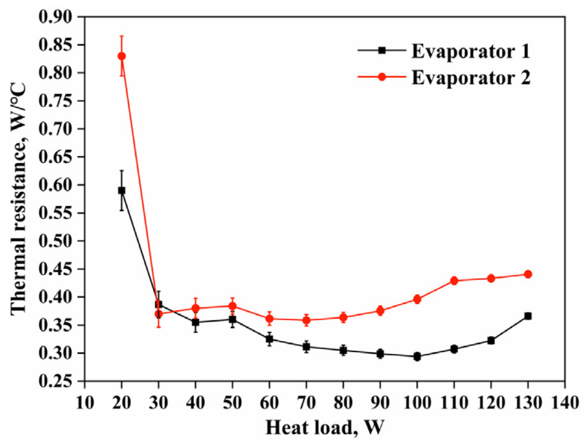

Fig. 13. The dependence of evaporator thermal resistance on heat load.

5. Conclusions

In this study, a flat plate LHP with dual evaporators was developed, and its thermal performance was tested in the horizontal stance. With the temperature of both of heating sources below 100 °C, this LHP system could start up successfully and control temperature stably within the set heat load range, and successional operation with the heat load cycle showed good performance. A single evaporator could transfer the maximum heat load of 130 W, corresponding to a heat flux of 13.52 W/cm^2. At the same time, the additional feature, heat load share, of the LHP with dual evaporators was found during the tests. The different evaporator thermal resistance led to different heat transfer capacities of two evaporators, and the total heat load on the LHP system was redistributed based on operating conditions. It was found that the operating performance was affected by the total heat load on the LHP system, as well as by the distribution of the heat load between two evaporators. The LHP with dual evaporators can dissipate heat from two separate heating sources, and has a simple structure. Compared to the current cooling methods, the LHP with dual evaporators provides high heat transfer capacity without extra energy, and has great potential to solve thermal issues that need to collect heat from multiple heating sources.

CRediT authorship contribution statement

Song He: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Zhengyuan Ma:** Methodology, Investigation, Validation, Writing – review & editing, Data curation. **Weizhong Deng:** Methodology, Software. **ZiKang Zhang:** Methodology, Software, Data curation. **Ziqi Guo:** Software, Data curation. **Wei Liu:** Resources, Supervision, Project administration, Funding acquisition. **Zhichun Liu:** Conceptualization, Resources, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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