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A novel design and experimental study of a cryogenic loop heat pipe with high heat transfer capability

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Abstract

A cryogenic loop heat pipe (CLHP) has been developed for future aerospace applications at TIPC (Technical Institute of Physics and Chemistry). This article presents a novel design of a cryogenic loop heat pipe and corresponding test system. The CLHP studied in this work has demonstrated to be able to operate in liquid-nitrogen temperature range using nitrogen as working fluid and to transfer large amount of heat over long distance with very small temperature difference. This device has been tested at three different orientations with respect to the relative position of the liquid line and the vapor line. The experimental results show that the CLHP can have a heat transfer capability of up to 12 W under horizontal and adverse gravity orientations and up to 20 W in liquid-nitrogen temperature range under gravity-assisted orientation.

Keywords: Cryogenic loop heat pipe; Liquid-nitrogen temperature; Capillary pressure; Heat transfer capability

1. Introduction

Loop heat pipes are effective two-phase heat transfer devices and can transport several orders of heat load than traditional single-phase techniques. Due to their great heat transport efficiency, these devices are emerging as the baseline design of thermal control systems for future spacecrafts [1,2]. A detailed analysis of the LHP working principles and its operation characteristics can be found in [3,4]. Furthermore, with the development of cryocooler technology and cryocooler-based applications such as space exploration, it is required to use cryocoolers to cool the optical instruments operating at a temperature range below 100 K, and the ambient loop heat pipe which operating temperature is around 273 K (such as ammonia LHP) will not meet this requirement. For the above reasons, it is necessary to develop the cryogenic LHP which can operate at liquid-nitrogen temperature range and even lower cryogenic temperature range to provide effective thermal link and vibration isolation between cryogenic cooling sources and cryogenic components. Some loop heat pipes used for cryogenic applications can be found in [5–9], and there are other kinds of cryogenic heat pipes reported in literatures, such as thermosyphons [10], wick-based heat pipes [11–13] and cryogenic capillary-pumped loops [14].

The main difference between cryogenic LHP and ambient LHP which uses ammonia as working fluid is as follows: as the CLHP operates at very low temperature range, it must use cryogenic substance such as nitrogen to implement its operation. However, the surface tension of cryogenic substance is relatively low and its pressure drop in the transportation lines is relatively large. Moreover, the dimension of a cryogenic LHP is much smaller than that of an ambient LHP. As a result, the startup of CLHP is more difficult than ambient LHP, and its heat transfer capability is relatively low. So, on the one hand,

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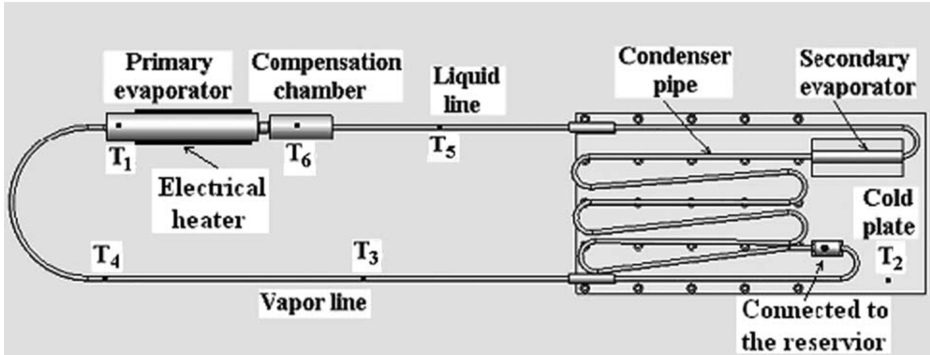

Fig. 1. The configuration of the CLHP.

CLHP needs to have a pressure reduction reservoir to insure its ability to operate against pressure under room temperature. On the other hand, how to cool the primary evaporator from room temperature to its operating temperature is an important question during the startup of a CLHP.

This paper presents a novel design of a CLHP configuration and corresponding test system to solve the above mentioned problems: (1) The CLHP uses a simply manufactured axial-grooved short pipe as the secondary evaporator to accelerate the temperature decrease rate of the primary evaporator before startup. (2) The pressure reduction reservoir connects with the CLHP through a long fine pipe on the cold side (at one point on the condenser pipe line), as shown in Fig. 1. (3) A little amount of stainless steel screen mesh is placed in the compensation chamber to try to avoid the reverse flow during startup and to get more stable operating performance as well as higher heat transfer capability. Experimental tests of the CLHP using nitrogen as the working fluid have been performed under different orientations in a thermal vacuum vessel. The experimental results have demonstrated that this CLHP can operate in liquid-nitrogen temperature range with constant heat sink temperature of about 78 K and has the highest heat transfer capability of up to 12 W under horizontal and adverse gravity orientations and up to 20 W under gravity-assisted orientation in liquid-nitrogen temperature range. The objective of this investigation is to present the CLHP capability on managing a certain amount of heat loads, considering the thermal control in cryogenic conditions.

2. Configuration and test system of the cryogenic LHP

Basically, the cryogenic LHP used in this work has the configuration of Fig. 1. The CLHP consists of a primary evaporator, a compensation chamber, a serpentine condenser, a secondary evaporator, two transportation lines and a pressure reduction reservoir. The serpentine condenser is made of a long copper pipe with the length of 1.2 m and the outer diameter of 3 mm. This configuration has two transport lines for vapor-phase and liquid-phase, respectively. These lines are stainless steel thin-walled pipes with the inner diameter of 2 mm and the heat transfer distance is about 200 mm. The primary evaporator is integrated with the compensation chamber to guarantee the permanent liquid wetting of the primary wick. The secondary evaporator is actually a short pipe with axial grooves on its internal surface. The pressure reduction reservoir is placed out of the vacuum vessel and connected to the condenser through a long pipe with the inner diameter of 1.5 mm. Some configuration parameters are listed in Table 1.

Fig. 2 shows a schematic diagram of the test system and the experimental apparatus. The primary evaporator and

Table 1
Significant parameters of the cryogenic LHP with nitrogen as working fluid

Primary evaporator	
Total length	100 mm
Active length	85 mm
OD	20 mm
Material	Stainless steel
Secondary evaporator	
Length	50 mm
OD	8 mm
Material	Brass
Primary wick	
Material	Sintered powder stainless steel
Pore size	8–12 μm
Permeability	$>5 \times 10^{-14}$ m^2
Porosity	>0.2
Liquid line	
OD/ID	3 mm/2 mm
Length	170 mm
Vapor line	
OD/ID	3 mm/2 mm
Length	470 mm
Condenser	
OD/ID	3 mm/2 mm
Length	1200 mm
Compensation chamber	
Length	40 mm
OD/ID	18 mm/13 mm

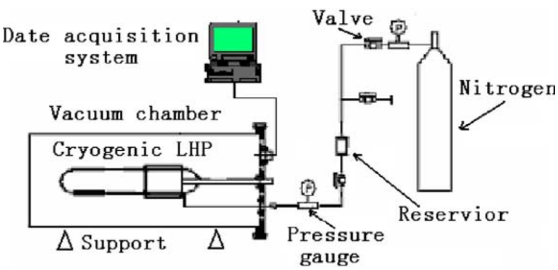

Fig. 2. Experiment setup of the CLHP.

the two transportation lines were wrapped in multi-layer insulation consisting of more than 10 layers of aluminum-coated terylene film. The cryogenic LHP including the cooling system was surrounded with a copper shield which was also wrapped in multi-layer insulation. The whole heat pipe assembly is placed in a vacuum vessel which can stand horizontally on two supports. As a result, the liquid line can be adjusted over or below the vapor line while the primary evaporator placed horizontally at all times by rotating the vacuum vessel around its axis so that to investigate the effects of gravity on the startup and operation of the CLHP. In the experiment, liquid nitrogen is directly used to cool a copper plate with the thickness of 20 mm, so the copper plate can serve as a heat sink for the serpentine condenser. On the contrary, an electrical resistance heater of 45 Ω attached to outer surface of the primary evaporator is connected to a DC power supply with accuracy of ±1.0% to provide the heat load to be transferred. In the same way, an electrical resistance heater of 20 Ω was attached to the outer surface of the secondary evaporator. The temperatures along the CLHP are measured with PT-100 resistance temperature sensors (deviation of ±0.5 K at 78 K) and the thermometer locations are given in Fig. 1. In the application, T_1 is the temperature of the primary evaporator, T_2 is the temperature of cold plate, T_3 and T_4 are temperatures along the vapor line, T_5 is the temperature of the middle of the liquid line and T_6 is the temperature of the compensation chamber. The temperature data obtained in each experiment can be automatically acquired by the Labview software, providing a real-time temperature variation graph of each thermometer. The charging pressure of the cryogenic LHP can be read through the pressure gauge. In the following experiment, the working fluid inventory is 0.016 kg approximately.

3. Experiment results and discussion

3.1. The cooling process from room temperature before startup of the CLHP

Cryogenic loop heat pipe operates in liquid-nitrogen temperature range or even lower temperature range, so it must use cryogenic substance which critical temperature is much lower than room temperature such as nitrogen to implement its operation. Therefore, how to cool down the CLHP from super-critical condition to operating condition is an important question encountered in the study of CLHP. Moreover, the appearance of the concept of loop heat pipe is to solve the problem of transferring heat over long distance, so the transportation lines usually are flexible thin-walled stainless steel pipes. As a result, it will take long time to cool the primary evaporator from room temperature to the operating temperature by conduction with only the condenser connected directly with the heat sink. For the above reasons, it is necessary to use a secondary evaporator to shorten the temperature decrease process of the whole loop before the startup of a CLHP. As show in Fig. 1, the secondary evaporator is placed near the condenser in order to solve the problem mentioned above.

Fig. 3 presents the temperature decrease process of the whole loop before the startup. In this experiment, gravity was used to shorten the cooling process of the CLHP from room temperature. At the beginning, the whole CLHP was placed at the same horizontal plane, and before using liquid nitrogen to cool down the copper plate, the liquid line was adjusted to be 3.5 cm below the vapor line by rotating the vacuum vessel around its axis. Therefore, condensate will be forced to flow into the primary evaporator through

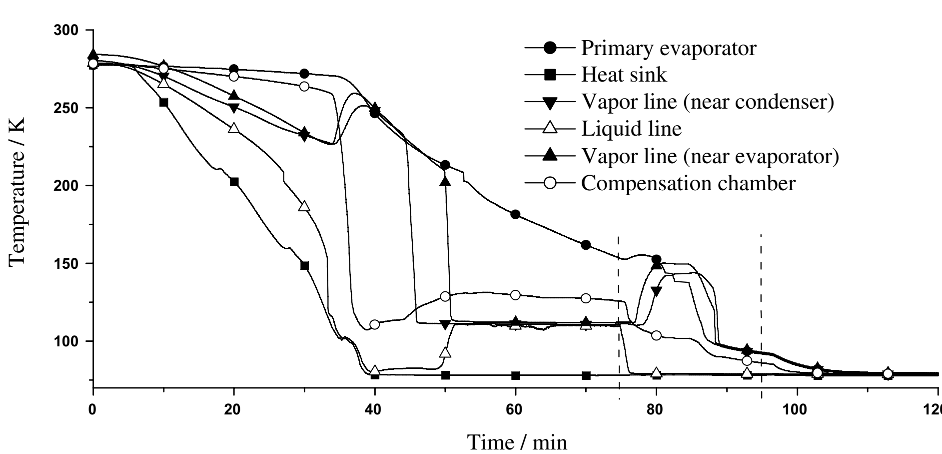

Fig. 3. The temperature decrease process of the CLHP before startup.

the liquid line by the effect of gravity when the condensate forms in the condenser pipe.

As seen from Fig. 3, after the cold plate was cooled by liquid nitrogen for about 40 min, its temperature (T_2) decreased to 78 K and remained at this value in the following experiment. In the beginning, as T_2 was gradually decreasing, the liquid line temperature (T_5) decreased more quickly than other thermometers. This is because the condensate formed in the condenser can easily go down into the liquid line due to the effect of gravity. At about 35 min, the temperature of the compensation chamber (T_6) started to decrease rapidly to 108 K in a few minutes. This also indicated that the condensate flow into the compensation chamber via the liquid line by effect of gravity. But soon after this decrease, T_6 began to increase to 128 K and maintain at this value when the primary temperature (T_1) decreased gradually during the period from 50 min to 75 min. During this period, T_5 also increased to and maintained at about 108 K. Therefore, from about 75 min to 95 min (as shown in Fig. 3 between the two dashed lines), heat power of 9 W was being applied on the secondary evaporator in order to accelerate the temperature decrease rate of T_1. Soon after the secondary evaporator was heated, T_5 began to decrease quickly from 108 K to 79 K in less than 1 min. And then, T_6 and T_1 also began to decrease more rapidly than before the secondary evaporator was heated. At about 110 min, T_1 balanced at 79.3 K, T_3 at 78.9 K, T_5 at 78.7 K and T_6 at 79.0 K.

3.2. The startup process of the CLHP under horizontal orientation (i.e. when the liquid line and the vapor line are on the same horizontal plane)

After the temperatures along the loop balanced at about 79 K for 15 min, the liquid line was adjusted to be on the same horizontal plane with the vapor line by rotating the vacuum vessel around its axis at about 125 min, so that the CLHP started to operate at horizontal orientation. An illustration of the rotating mechanism was shown in Fig. 4. As shown in Fig. 5, after the adjustment, the temperatures began to increase slowly. This does not mean the temperature cannot stabilize under this orientation. It is just because the operating temperature of the CLHP with no heat load on the primary evaporator under horizontal orientation is little higher than that under the gravity-assisted orientation. At about 160 min, a heat power of 0.5 W was applied on the primary evaporator. Soon after that, T_6 decreased gradually, which indicated that the

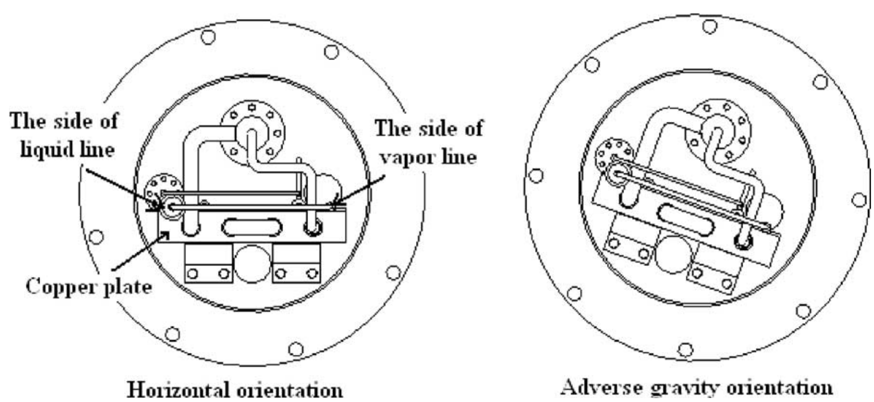

Fig. 4. Illustration of the rotating mechanism.

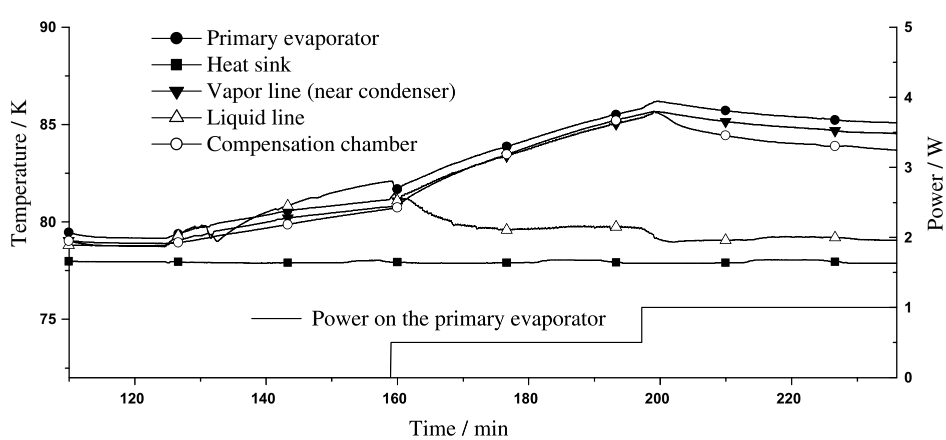

Fig. 5. The startup process of the CLHP under horizontal orientation.

working fluid began to circulate in the loop by the capillary pressure formed in the primary evaporator. After the heat input was increased to 1 W, T_1 started to decrease, which indicated the heat transfer resistance between the primary evaporator and the heat sink began to reduce.

3.3. The heat transfer capability of the CLHP under different orientations

When the CLHP is under the horizontal orientation, the experimental results are shown in Figs. 6 and 7. As seen from Fig. 6, when the heat power of 12 W was applied on the primary evaporator, obviously the CLHP can operate successfully. At about 846 min, the heat power was increased to 14 W. After that, T_1, T_6 and T_5 started to increase rapidly, which meant this heat power was over the maximum value that the CLHP studied in this work can transfer under horizontal orientation. So the compensation chamber temperature and the primary evaporator temperature increased quickly due to the inadequate subcooled liquid retuned back to the compensation chamber. At about 855 min, T_1 increased to 155 K and T_6 to 110 K. But after the heat input to the primary evaporator was stopped, T_6 still increased, even though T_1 began to decrease slowly. Fig. 7 shows the temperature response of the CLHP to the sudden decrease of the heat input. When T_1 and T_6 increase to a certain value with the heat input of 12 W, the heat input was suddenly decreased to 3 W. After that, T_1 and T_6 decreased quickly, as shown in Fig. 7. Comparing Figs. 6 with 7, it is obvious that once the CLHP has deprimed, it will not be able to return back to normal operation automatically under the horizontal orientation. So the restart after the appearance of a deprime condition also need to be studied in the research of CLHP.

In the same way, the liquid line can be adjusted over or below the vapor line to make the CLHP operate under adverse gravity or gravity-assisted orientations. When the CLHP operates under adverse gravity orientation, the capillary pressure induced in the primary evaporator should overcome the effect of gravity while maintaining the working fluid circulation in the loop. Therefore, the heat transfer capability under this situation should less than that under horizontal orientation. But in this experimental work, the liquid line was only 3.5 cm over the vapor line. So the effect of gravity on the heat transfer capability of the CLHP was neglectable due to the much great capillary

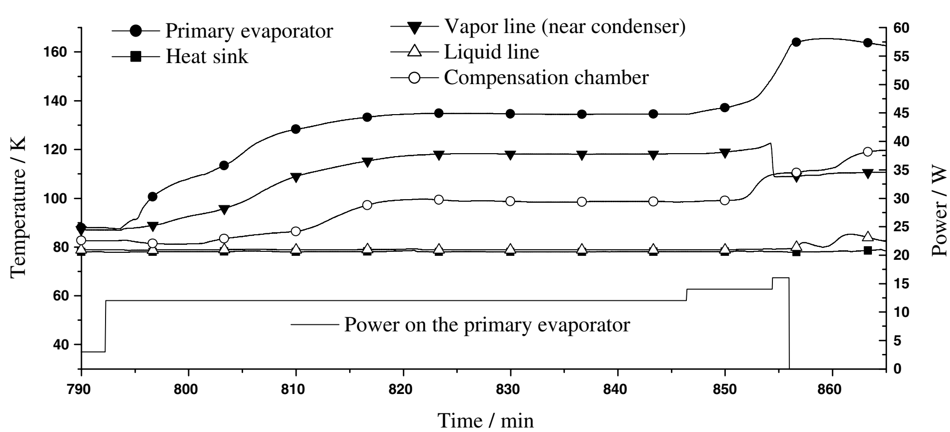

Fig. 6. The heat transfer capability of the CLHP under horizontal orientation.

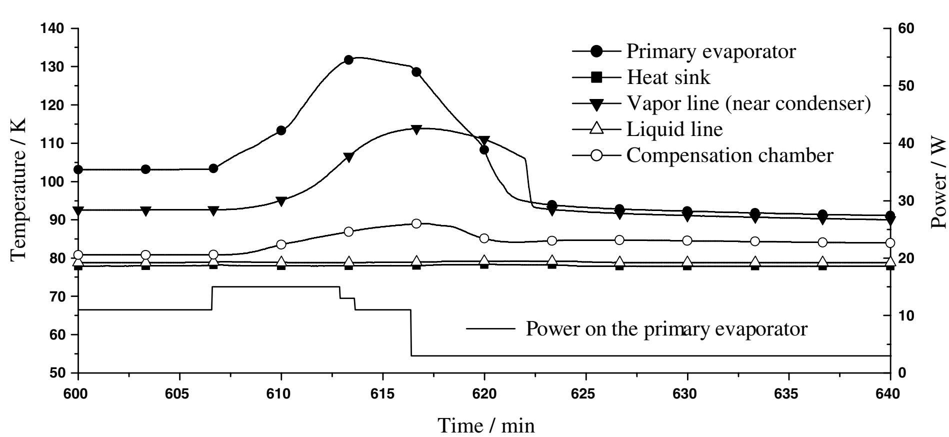

Fig. 7. The temperature response of the CLHP to the sudden change of heat input.

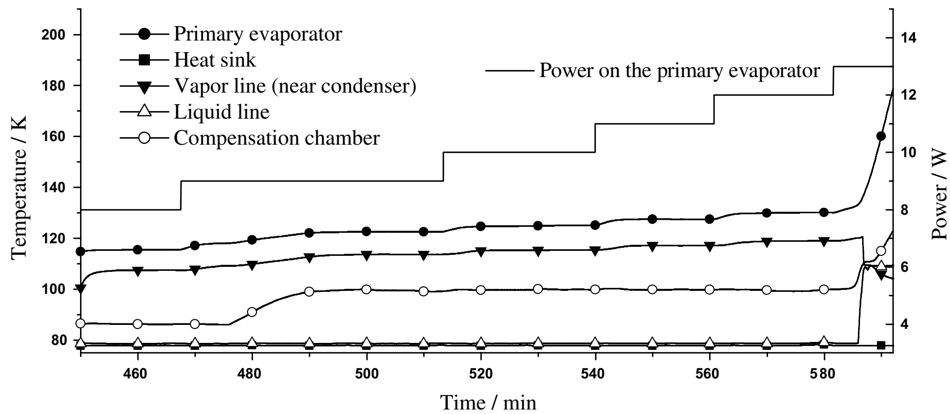

Fig. 8. The heat transfer capability of the CLHP under adverse gravity orientation.

pressure in the primary evaporator. As seen from Fig. 8, when the liquid line was 3.5 cm over the vapor line, which meant the CLHP operated under adverse gravity orientation, the heat transfer capability can still be up to 12 W. When the heat input applied on the primary evaporator increased to 13 W, the temperature of the liquid line began to increase rapidly and the temperature of the vapor line decreased suddenly, which indicated that the capillary pressure produced in the primary evaporator was not able to maintain the working fluid circulation in the loop resulting in the sudden increase of the compensation chamber and the primary evaporator temperatures. This was an obvious deprime condition observed under adverse gravity condition. Fig. 9 shows the experimental data when the CLHP operated under gravity-assisted orientation, i.e. the liquid line was about 3.5 cm below the vapor line. In this situation, the heat transfer capability of the CLHP can be up to 20 W in liquid-nitrogen temperature range, although its actual heat transfer limitation was much higher than this value under this orientation which meant the CLHP can operate successfully with the primary evaporator temperature over 126 K.

3.4. The heat transfer resistance of the CLHP under horizontal orientation

The following experimental results about the thermal resistance of the CLHP being studied in this paper can fully demonstrate the concept and advantage of CLHP over the equivalent solid copper rod (i.e. its diameter and length are the same with the transportation lines) which theoretical thermal resistance is about 30 K/W. The calculation process is as follows: considering the heat conduction by two shunt-wound solid copper rods (one with length of 170 mm and diameter of 3 mm, the other with length of 470 mm and diameter of 3 mm), the theoretical thermal resistance of this heat transfer road can be calculated using the following expression (the conductance of cooper is 590 W/(m K) at 80 K): $R = \delta/kA$, where δ is the length of the rod, k is the conductance of copper and A is the cross area of the rod.

Fig. 10 presents the heat-load dependence of the thermal resistance (i.e. the temperature difference between the primary evaporator and the heat sink divides the heat input) of the CLHP under horizontal orientation, and also gives

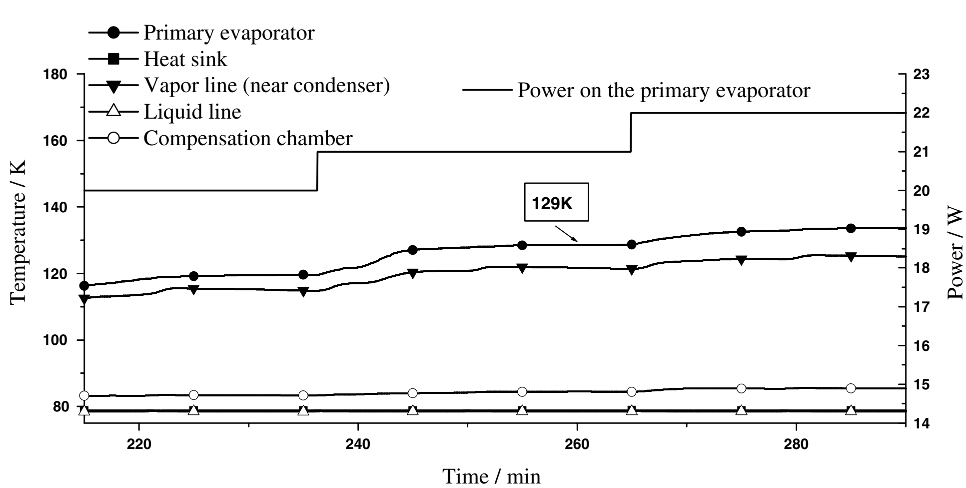

Fig. 9. Heat transfer capability of the CLHP under gravity-assisted orientation.

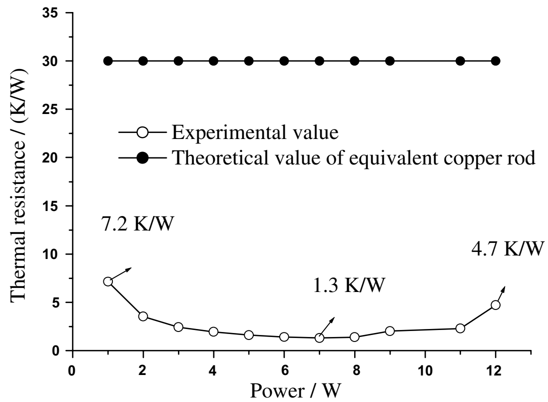

Fig. 10. The thermal resistance of the CLHP under horizontal orientation.

the comparison of the thermal resistance of the CLHP to that of an equivalent solid copper rod. It can be seen obviously from Fig. 10, the thermal resistance of the CLHP is much smaller than that of the equivalent copper rod, which indicates that the CLHP studied in this paper have an excellent heat transfer performance. When the heat input varies from 3 W to 11 W, the thermal resistance of the CLHP is relatively small and almost the same. The thermal resistance of the CLHP has a smallest value of 1.3 K/W when the heat load is 7 W.

4. Conclusions

It can be seen from experimental results that the CLHP studied in this paper, using nitrogen as working fluid, can operate at liquid-nitrogen temperature range with the constant heat sink temperature of 78 K, and has an excellent heat transfer performance over equivalent solid copper rod. Based on the above mentioned experiments, the results of the testing can be summarized as follows:

1. The CLHP studied in this paper has relatively simple configuration, and can transfer heat effectively over considerable distance with very small temperature difference.
2. Heating the secondary evaporator can accelerate the temperature decrease rate of the primary evaporator before the startup of the CLHP under gravity-assisted orientation.
3. The CLHP has a heat transfer capability of up to 12 W under horizontal and adverse gravity orientations and up to 20 W in liquid-nitrogen temperature range under gravity-assisted orientation.
4. When the heat load varies from 3 W to 11 W, the thermal resistance of the CLHP is much smaller than that of the equivalent copper rod under horizontal orientation.
5. The pore size of the primary wick used in this work is only 8–12 μm, so the heat transfer capability can be increased greatly if the wick with pore size of 1–3 μm is used. Furthermore, the CLHP performance can be also improved by using other cryogenic fluids such as oxygen and by decreasing the temperature of the heat sink.

Therefore, the CLHP studied in this work has a great perspective in cryogenic application, and is also a potential device for future aerospace application. However, further investigations are still required.

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