

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



The Recent Research of Loop Heat Pipe

Chunsheng Guo

Abstract

The loop heat pipe was first studied for the difficult temperature control conditions under aerospace conditions. The loop heat pipe is composed of evaporator, reservoir, capillary wick, vapor/liquid line, and condenser. Different working fluids, different liquid filling amounts, different capillary wicks, different sizes, and different cooling methods will have an important impact on the performance of the loop heat pipe. Therefore, if the loop heat pipe wants to have good heat transfer efficiency, it is imperative to discuss good processing steps and processing techniques. When the loop heat pipe is running, the capillary wick is heated, the liquid in the capillary wick is heated and vaporized, and the gas passes through the vapor line to enter the condenser for condensation. After the condensation, the liquid flows back into the reservoir and the inside of the capillary wick through the liquid line. How to ensure the forward operation of the gas at the evaporator to reduce the reverse leakage heat during this cycle, how to ensure the condenser condensation efficiency is sufficient, etc. are all issues to be considered. This chapter describes in detail the processing and optimization methods for each part, and prepares a loop heat pipe that can work normally.

Keywords: nickel-ammonia loop heat pipe, capillary wick, heating power, temperature fluctuation

1. Introduction

The loop heat pipe is a variant of the ordinary heat pipe, and is a two-phase flow loop type heat pipe, which is a unidirectional heat conduction element similar to a diode. The working medium is mainly composed of a gas phase and a liquid phase in the steam pipe and the liquid pipe respectively. The form of the cycle, complete the transfer of heat. The design idea of the world's first LHP system was proposed by scientists in 1971. Then Soviet scientists Maydanik and Gerasimov successfully developed the world's first LHP system in 1972, after the Soviet Union and the United States. Research institutions are beginning to study loop heat pipes. The loop heat pipe is a high-efficiency loop heat transfer device with two-phase separation heat transfer. Since the structure of the loop heat pipe is more complicated than the ordinary heat pipe, it can adapt to more different working environments. The loop heat pipe has many advantages such as high heat transfer performance, long-distance heat transfer, small heat transfer temperature difference, and flexible installation. Therefore, in recent years, it has been widely used in aerospace heat dissipation, electronic products heat dissipation, anti-gravity ground heat transfer working environment and other fields.

Loop heat pipe was a new kind of two phase flow heat equipment, it used capillary suction force drive the working medium to complete the cycle of working medium inside the heat pipe flow and by using phase change of working medium two-phase flow to transfer heat [1]. Loop heat pipe had many advantages, such as large heat transmission, transmission distance, high heat transfer efficiency, antigravity features was strong, etc. [2]. Loop heat pipe was first applied in aerospace field, with the constant improvement of the loop heat pipe technology, it gradually be applied to every other civilian areas, especially in electronic cooling field [3].

The most important characteristic of loop heat pipe was its resistance to gravity characteristic. Baumann [4] made a theoretical analysis first for the influence of loop heat pipe resistance to gravity, but fails to provide the experimental data to support. Zhang [5] studied the loop heat pipe in start-up and heat transfer performance under antigravity work condition, found the loop heat pipe started up under the condition of antigravity liquid reflux need to overcome additional pressure drop loss gravity bringing, and in outside loop resistance increased obviously. When vapor trough exist vapor, start-up time and temperature increase, loop heat pipe appeared complex compound startup phenomenon. Anti-gravity work increased the working temperature of the loop heat pipe system, reduced the automatic temperature control range, and leaded to vapor produced in the evaporator was more likely to overheat and overall system thermal resistance increased at the same time. In order to match the cooling parts, the evaporators were often made into plates [1]. Research team of Chinese Academy of Sciences institute of physics [6] carried out the establishment of the numerical model of the plate LHP evaporator and the heat transfer model, then they analyzed the heat transfer mechanism inside the evaporator. Mitomi [7] designed three kinds of length loop heat pipe with the length were 2, 5, 10 m. Loop heat pipe working medium was ethanol and capillary core was made by polytetrafluoroethylene porous material. They analyzed the normal working performance and carried out numerical simulation, and found that three pipes could work under the same starting power. South China University of Technology Developers [8] had studied the influence of heat leakage, the initiation characteristics and optimized the evaporator, reservoir and condenser. Beijing Aerospace University and Institute of Space Studied [9, 10] studied the whole loop heat pipe system, including the evaporator and capillary core structure optimization effect on the performance of the loop heat pipe, the influence of reservoir auxiliary cooling and the evaporator auxiliary heat on loop heat pipe performance, performance test of loop heat pipe in microgravity environment, the influence of quantity of quality filling on the performance of the loop heat pipe. In practical application, there could be multiple sources of heat and multiple sources. The number of evaporators, condensers and accumulators is not fixed. Jentung Ku [11] tests the multi-evaporator loop heat pipe with 50 W power in a vacuum environment, and the performance is stable.

2. Capillary core preparation

Capillary core is an important component in loop heat pipe. Porosity, permeability, pore size distribution and capillary suction ability are the key parameters to reflect the performance of capillary core. In order to improve the ability of anti-gravity operation and long-distance operation of the loop heat pipe, it is necessary for the capillary core to have the characteristics of high permeability and high capillary suction ability. As the core device in the loop heat pipe, the capillary core transmits heat in the evaporator and provides enough capillary force to drive the working fluid cycle. At the same time, the vapor should be transferred to the vapor pipe in time to prevent the phenomenon of suction. Wolf indicates that LHP has gravity heat pipe

and capillary pump heat pipe. It has the advantages of anti-gravity, long distance operation, no external power source, high stability, passive energy transportation and so on. Capillary core, as the core component of loop heat pipe, provides the necessary power for the forward operation of heat pipe. At present, the main types of capillary core are: grooved capillary core, metal mesh capillary core, ceramic capillary core and metal powder sintered capillary core. At present, most metal powder sintered capillary cores are made of copper and nickel. These capillary cores are widely used in loop heat pipes because of their good thermal properties and liquid compatibility.

On the basis of previous studies, double pore capillaries were prepared by molten salt pore making technique. Compared with the addition of volatile pore-making agent, NaCl, with 99.5% purity and carbonyl nickel powder as capillary core material has the advantages of easy removal and uniform void distribution. The main parameters of capillary core, such as porosity, permeability, thermal conductivity, pore distribution and capillary suction ability, were measured according to the ratio of pore-forming agent and the pressure of cold pressing molding. The effect of the ratio of pore-making agent and the pressure of cold pressing on the properties of capillary core was obtained.

2.1 Preparation process of capillary core

Nickel powder was selected as raw material and NaCl as pore-making agent to prepare double pore capillary core. The main steps were powder ratio, cold pressing, sintering and cleaning. The specific steps were as follows: the preparation process was shown in **Figure 1**.

1. Powder ratio: In this paper, 2 μm nickel powder with 99.5% purity of NaCl was selected as the material to prepare the double aperture capillary core. Firstly, the NaCl particles were ground by ball mill (the positive and negative rotation time was 45 min, the interval time was 5 min, the total milling time was 6 h), and the total milling time was 6 h, the positive and negative rotation time was 45 min, the interval time was 5 min, and the total milling time was 6 h. The particle size of NaCl was mainly distributed in 200–400 mesh after ball milling. There were very few NaCl particles below 400 mesh. The NaCl powder with diameter of 48 μm (300–400 mesh) was screened by vibrating screen, and then the nickel powder and NaCl powder were mixed evenly by ball mill, and then put into drying. The box was dried.

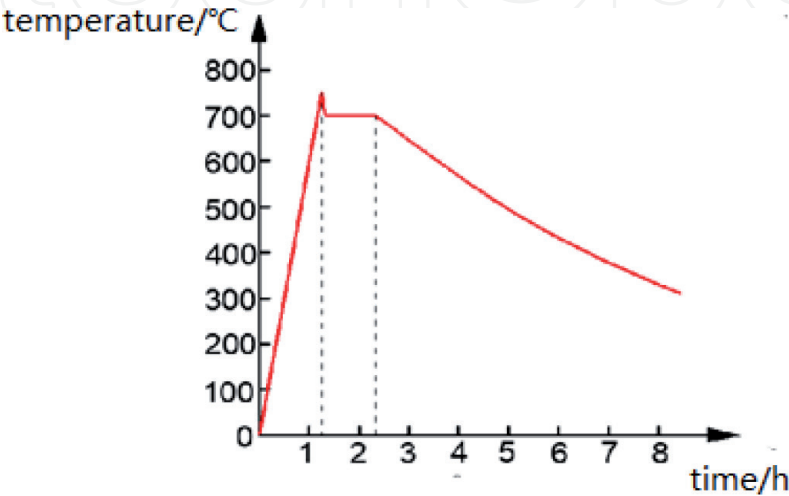


Figure 1.
Sintering temperature curve of nickel based capillary core.

2. Cold pressing molding. The powder was compacted by a press (the target pressure was 30, 40, 50, 60 KN, and the booster speed was 200 N/s).
3. The capillary core is sintered. The vacuum hot pressing sintering furnace selected in the experiment is ZT-40-20Y, combined with multiple sintering experiments and the temperature curve drawn in the previous literatures is shown in **Figure 2**.
4. Ultrasonic cleaning. After sintering, the NaCl particles in the capillary core need to be dissolved by ultrasonic cleaning to form a void and obtain a dual pore structure. The SEM of biporous wick is shown in **Figure 3**.

2.2 Capillary core parameter testing

2.2.1 Porosity and permeability

Porosity is the most direct index of porous structure of capillary core. The internal pores of capillary core are divided into connected pores, semi-connected pores, closed pores. The porosity of capillary core prepared by salt solution technique is mainly affected by the proportion and size of pore-forming agent.

Archimedes drainage method for porosity measurement, capillary core wet weight m_{wet} , drying thoroughly weighing capillary core dry weight m_{dry} , and measured the outer diameter of cylindrical capillary core r and length L , densities of deionized water. Porosity ε

$$\varepsilon = \frac{m_{wet} - m_{dry}}{V \cdot \rho} \times 100\% \quad (1)$$

According to the gas resistance test table shown in **Figure 4**, the experimental device uses compressed air as the air source, and the compressed air in the air compressor enters from the left side air compressor joint. In order to ensure the accuracy of the experiment and improve the service time of the platform, a filter and a steady pressure tank are connected after the air enters the pipeline. The gas flow through the experimental section is controlled by the mass flow-meter and the mass flow controller after the air passes through the unidirectional valve after the steady pressure. The capillary core is installed in the experiment section, and the pressure difference between the two sides of the capillary core is detected by pressure differential transmitter. At the end of the experiment, the gas was emptied into the air through the buffer tank.

The flow in this experiment is the flow inside the tube, the maximum flow rate is 30 L/min, the length of stainless steel tube is 300 mm, the inner diameter of stainless steel pipe is 20 mm, and the Reynolds number is

$$Re = \frac{\rho v d}{\mu} \quad (2)$$

The calculated Reynolds number is 176.9. The experimental fluid flow is laminar flow, which accords with the applicable condition of Darcy formula. The length of stainless steel tube is 15 times the length of capillary core. The working fluid in the pipe can be developed fully and the inlet effect can be reduced effectively. The thickness of stainless steel tube wall 1 mm is much smaller than the diameter of capillary core. This experimental device can accurately measure the permeability of porous media K. A number of empty tube experiments were carried out before the experiment to eliminate the pressure drop caused by friction on the pipe wall.

According to the results of many experiments by French scientist Darcy, permeability K can be measured experimentally by formula (3).

$$q_v = \frac{KA\Delta P}{\mu H} \tag{3}$$

q_v is the flow rate in the experiment (m^3/s), K is the permeability of the sample (m^2), A is the cross-sectional area of the sample (m^2), H is the length of the sample (m), ΔP is

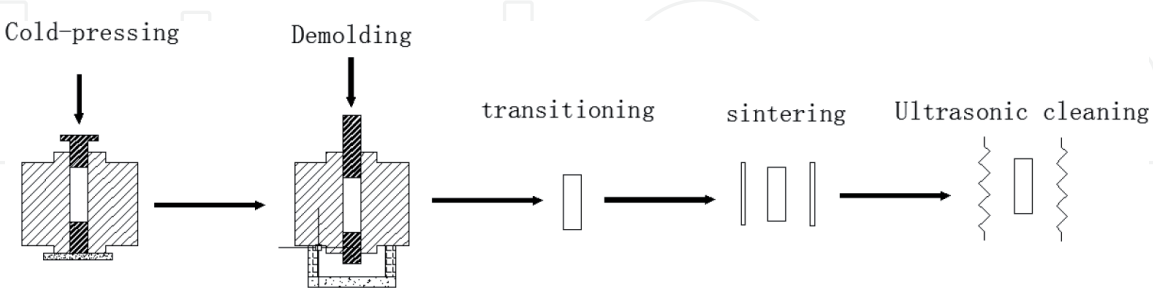


Figure 2.
Flow chart of capillary core preparation.

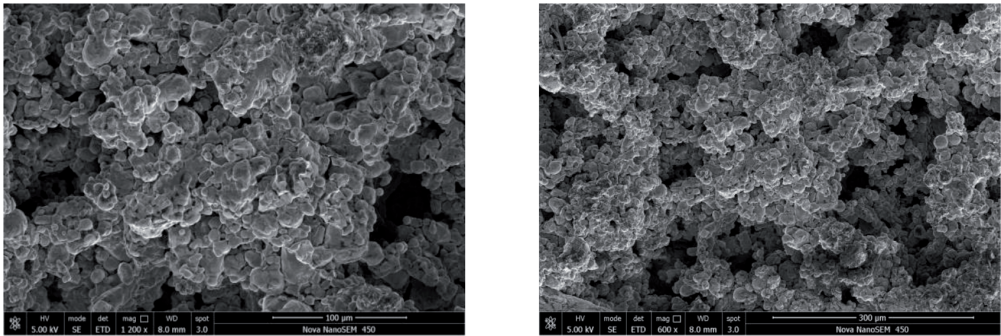


Figure 3.
50 kN cold pressure 20% NaCl mass fraction capillary core surface 1200 and 600 times scanning electron microscope.

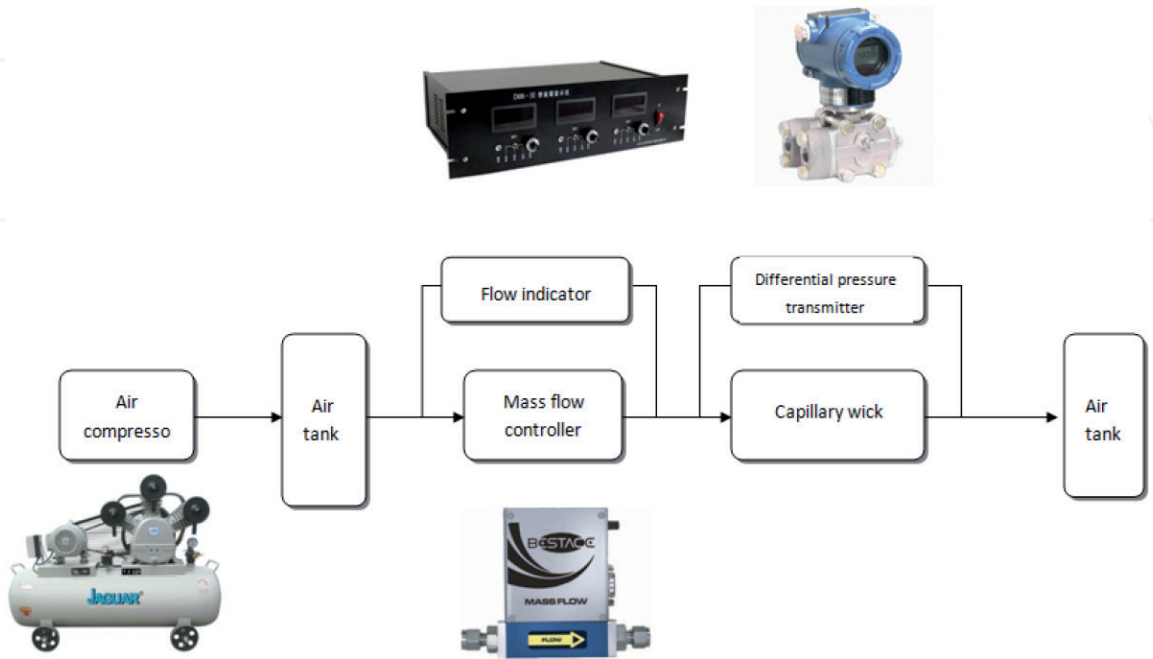


Figure 4.
Schematic diagram of gas resistance test table.

the pressure difference at the two ends of the sample (Pa), μ is experimental fluid viscosity (Pa s). The schematic diagram of the experimental device is shown in **Figure 4**. The principle is that the air compressor acts as a gas source to provide the experimental fluid for the whole experimental device, and the capillary core is put into the experimental section by controlling the flow rate of the experimental fluid by the mass flowmeter (q_v). According to formula (3), the permeability of capillary core is calculated by observing the pressure difference between the two ends of the experimental section by the pressure differential transmitter.

According to the experimental part, **Figure 5** shows the porous wicks porosity and permeability curves of different NaCl proportion.

It can be seen from the figure that as the proportion of NaCl increases, the porosity and permeability increase gradually. The reasons of this phenomenon are:

1. As the proportion of NaCl increases, the volume of NaCl particles increases, and the total powder mass is equal during cold press forming, so the porosity increases as the proportion of NaCl increases.
2. During the cold pressing and sintering process, as the temperature rises, the gap between the nickel powder particles gradually decreases, and the gap between the nickel powder and the NaCl particles remains unchanged, so the proportion of the pore former increases, and the porous wick shrinks. The smaller the degree, the larger the porosity.
3. The particle size of NaCl particles is significantly larger than the particle size of nickel powder. After cleaning and desalting, the original NaCl particles occupy the pores, the flow resistance of the working medium in the pores decreases, and the permeability increases.

Figure 6 is porous wick porosity and permeability curve for 20% NaCl wt of different cold forming pressures. It can be seen from the figure that as the cold forming pressure increases, the porosity remains basically unchanged and the permeability gradually decreases. The reasons are:

1. As the cold forming pressure increases, the pore size between the nickel powder particles decreases, and the working fluid flow resistance becomes larger, so the permeability decreases.
2. The proportion of total NaCl in the porous wick is the same. The pores occupied by NaCl particles account for the main part of the biporous structure. The proportion of pores formed between the nickel powder particles during sintering is small, so the porosity remains basically unchanged.

2.2.2 Capillary suction experiment

The relationship between capillary force and permeability is complex, the relationship between capillary force and permeability is negative, and the increase of permeability is bound to decrease. The most direct method for observing capillary force is to observe the liquid level rising velocity and suction mass velocity in porous media. In this paper, the suction ability of capillary core is determined by observing the suction quality of capillary core.

The principle of the experiment is that the bottom of the capillary core is in contact with the liquid surface by controlling the lifting platform to ensure that only

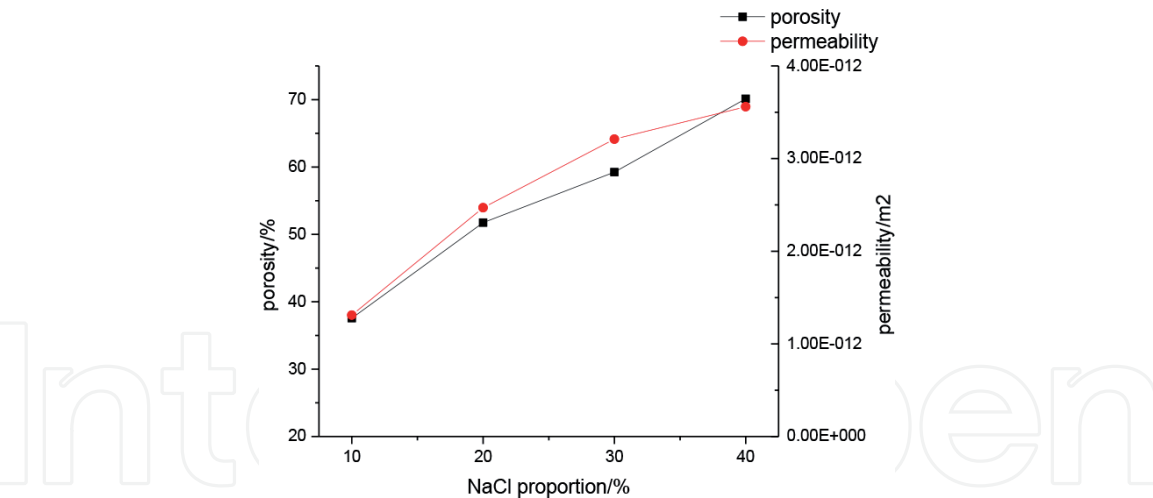


Figure 5.
Porosity and permeability curves of different NaCl proportion.

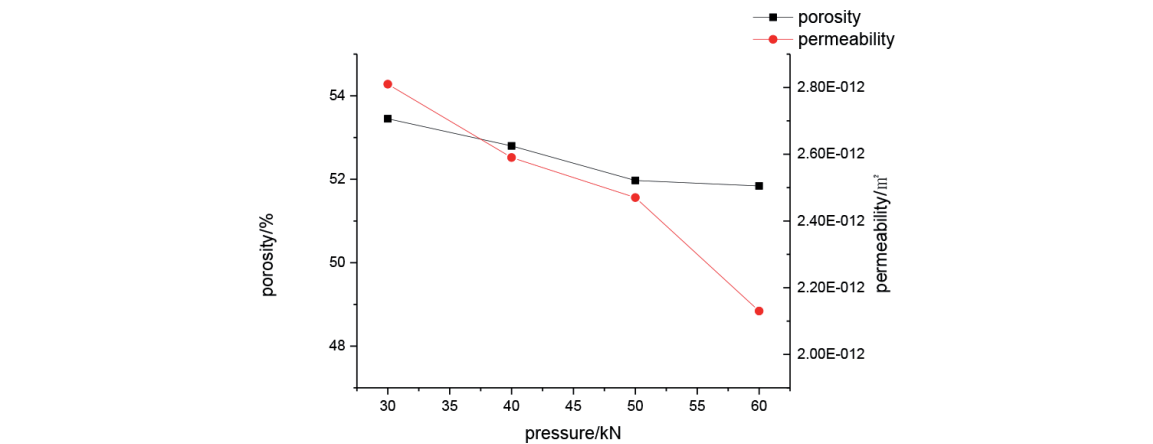


Figure 6.
Porosity and permeability curves of different cold pressing pressure.

the bottom of the capillary core exists the phenomenon of suction. The electronic analysis balance records the data and draws the suction curve.

As shown in **Figure 7**, the size of the capillary suction specimen is 100 mm in length and 20 mm in diameter. The suction fluid is deionized water, the bottom of the capillary core is in rigid contact with the deionized water surface through the motion control platform, and the quality of the working fluid inside the beaker is measured by the electronic analytical balance (accuracy is 0.0001 g). The reduced mass is the quality of capillary suction. In order to control the rising velocity of liquid level accurately, the minimum rising speed of motion control platform is 0.01 mm/s. In order to ensure the measuring accuracy and the total quality of suction fluid to reduce the influence of the inside wall of beaker on the suction process, the diameter of beaker is 40 mm. The height is 160 mm. **Figure 8** shows the physical model of capillary aspiration. The suction curve of different PFA agent ratio and different cold-forming pressure are shown in **Figure 9** and **Figure 10**.

Figure 11 (the number below the pore-forming agent ratio is the total number of pores in the range of 0–30 μm in the electron micrograph) is 80 times magnification of the surface of the porous wicks, and the surface pore size distribution is measured by image pro plus software, 10, 20, 30, 40%, respectively. It can be seen that most of the pore diameters are distributed at 2–4 μm (about 30%). It can be seen that the total pore size decreases in the range of 2–30 μm with the increase of the proportion of pore-forming agent, The reason is that the proportion of the

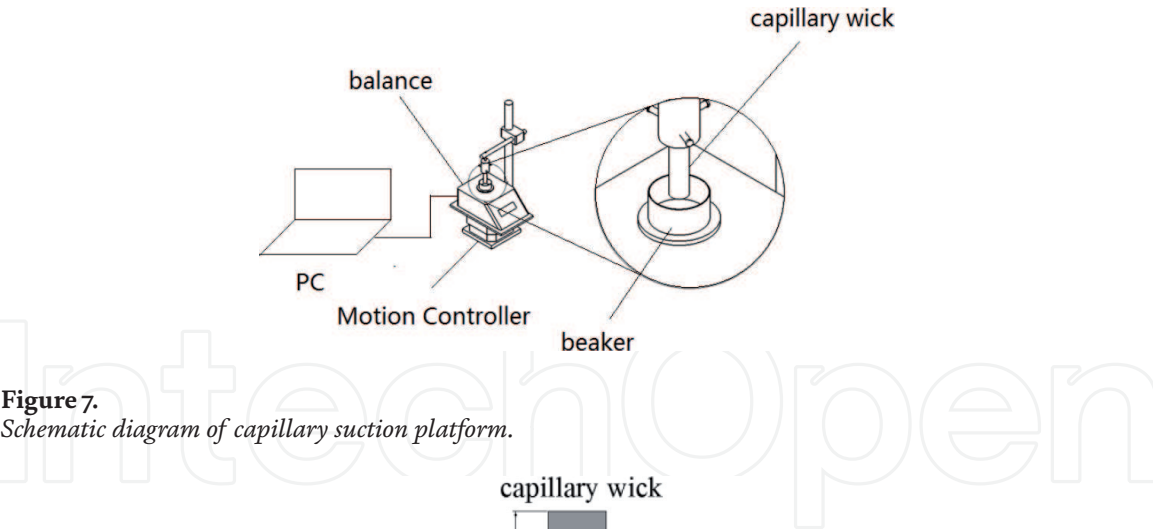


Figure 7.
Schematic diagram of capillary suction platform.

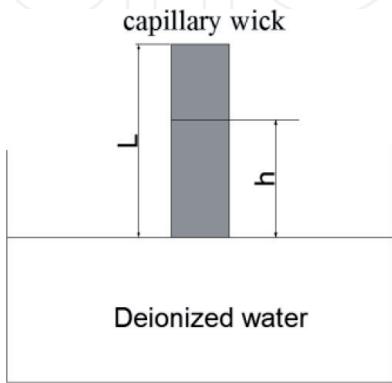


Figure 8.
Physical model of capillary aspiration.

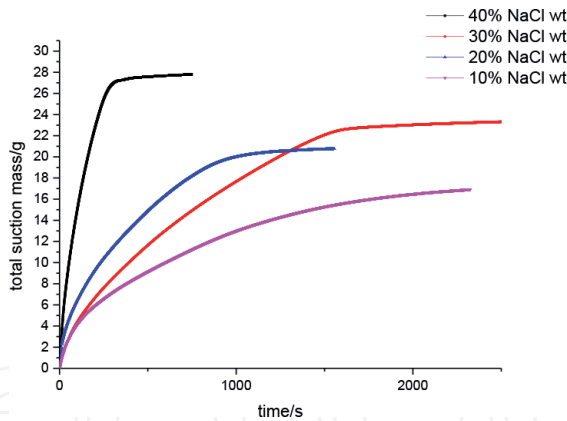


Figure 9.
The suction curve of different NaCl ratio.

pore-forming agent is increased, and the number of pore-forming agent particles in the same section is increased, and the pores of each size are adhered to each other, resulting in a decrease of the number of total pores.

As is shown in **Figure 10**, the capillary suction mass of the porous wick is proportional to the porosity, and the experimental results are in line with the derivation conclusion.

The capillary suction speed of the porous wick is proportional to the porosity and the average pore diameter. It can be seen from the figure that the porous wicks (40% NaCl wt) have the fastest capillary suction speed and the porous wicks (10% NaCl wt) have the slowest capillary suction speed. Porous wicks (20% NaCl wt) with a small diameter of pores more than porous wicks (30% NaCl wt), so the former has a higher suction speed than the latter.

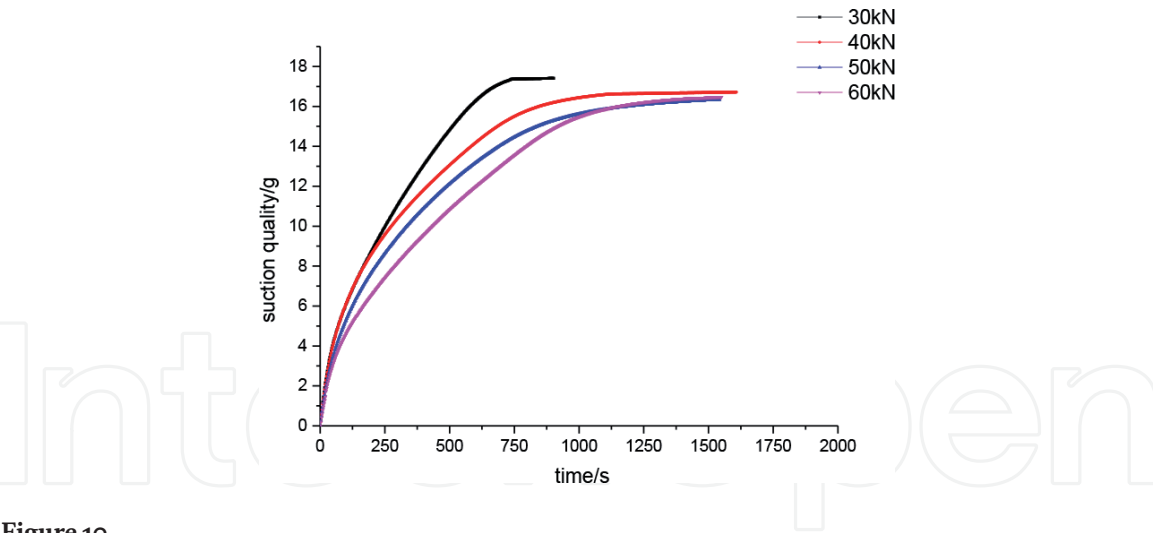


Figure 10.
The suction curve of different wicks with different cold pressure.

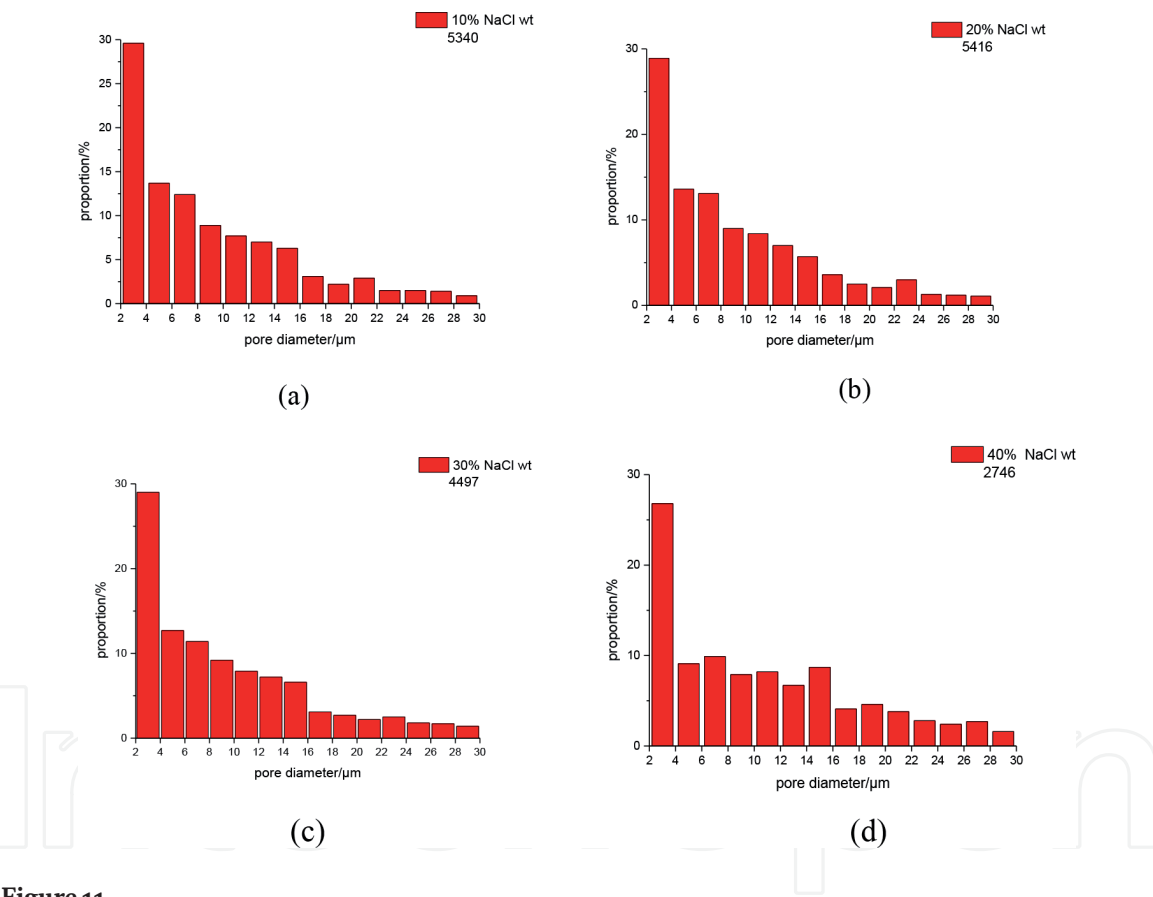


Figure 11.
Pore diameter distribution (a), (b), (c), and (d) are 10, 20, 30, and 40%, respectively.

As is shown in different cold forming pressures, suction speed porous wicks (30 kN) > porous wicks (40 kN) > porous wicks (50 kN) > porous wicks (60 kN), the suction quality is basically consistent but there are small differences, porous wick (30 kN) > porous wick (40 kN) > porous wick (50 kN) > porous wick (60 kN). It can be seen that as the cold pressure increases, the porosity and permeability both decrease. When the length of the porous wick is controlled, the internal structure of the porous wick pressed at 30 kN pressure is loose, the permeability is large, the suction resistance is small, so the suction speed is faster, the permeability decreases gradually with the increase of pressure, the suction speed decreases. As is shown in **Figure 12** small pores which produce larger capillary force decrease

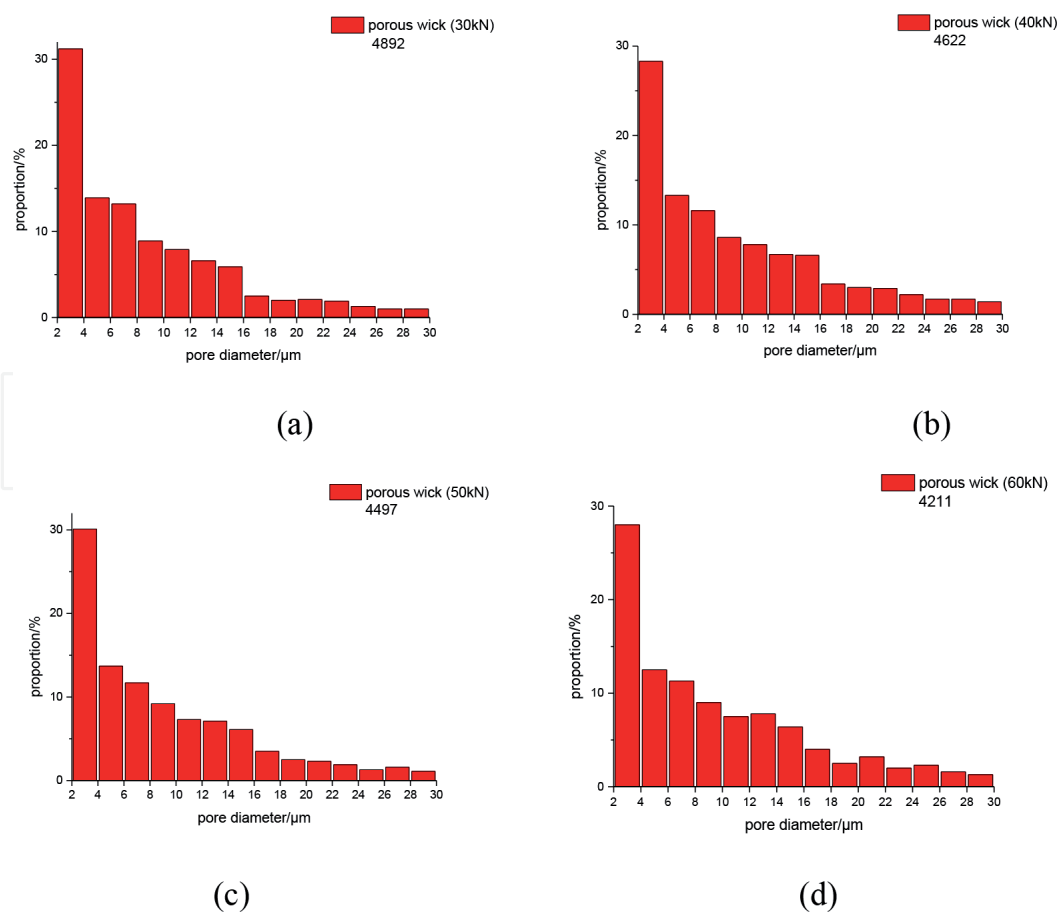


Figure 12.
Pore diameter distribution (a), (b), (c), and (d) are 30, 40, 50, and 60 kN, respectively.

with the increase of pressure, so the capillary suction speed is porous wicks (30 kN) > porous wicks (40 kN) > porous wicks (50 kN) > porous wicks (60 kN).

The total suction mass of the porous wicks with different cold forming pressures is porous wicks (30 kN) > porous wicks (40 kN) > porous wicks (50 kN) > porous wicks (60 kN), which is consistent with the porosity test results.

3. Structure design of loop heat pipe

3.1 Structural design of capillary cores

The structure size of capillary core has an important effect on the performance of loop heat pipe. For example, the length of capillary core has a significant effect on the heat transfer capacity of loop heat pipe. When the length of the capillary core is long, the synergy between the temperature and the flow field becomes longer with the increase of the length of the capillary core, but when the capillary core is too long, the flow resistance of the working fluid in the capillary core is further increased. It will result in less fluid flowing through the capillary core in unit time and affect the heat transfer rate of the loop heat pipe. The structural size of the capillary core was prepared with reference and in the second chapter of this paper. The final size of the capillary core was 100 mm in length and 20 mm in diameter. The 3D model of capillary wick is as shown in **Figure 13**.

The capillary core is not only a simple cylindrical structure, its structure is relatively complex, the outside is a vapor trough for the passage of vapor, and the internal storage tank for liquid working fluid. The curved liquid surface of vapor liquid



Figure 13.
 Schematic diagram of capillary core structure.

phase transition of the working fluid is in the capillary core, the liquid working fluid enters through the liquid channel, and the vaporization at the curved liquid level is derived from the vapor tank. The results show that the ratio of the depth to width of the capillary vapor channel is 1:1, and the effect is the best when the length of the groove is 75 mm, the depth and width are 2 mm, and the number of grooves is 6. In the third chapter, the capillary core suction ability of different inner diameter liquid storage channel is studied. The capillary core suction performance is the best when the inner diameter is 8 mm. The final structure of the evaporator and reservoir is shown in **Figure 15**.

3.2 Design of evaporator and liquid tank

Evaporator and liquid accumulator are the main components of loop heat pipe. Especially the evaporator, which contains capillary core, is the place where the liquid working fluid changes to the gas working medium in the loop heat pipe. However, the vapor generated in the capillary core must prevent its reverse flow into the liquid reservoir. In the evaporator, there is a liquid lead pipe in the capillary core, which is connected to the vapor pipeline, and the liquefied working fluid is directly introduced into the liquid channel inside the capillary core. The structure of the evaporator is shown in **Figure 14** below. Structural diagram of evaporator and liquid reservoir is shown in **Figure 15**.

In the design of loop heat pipe evaporator and liquid accumulator, the most important thing is to ensure the positive heat conduction of the loop heat pipe, and the most important thing is to do the sealing work well. The seal of evaporator and liquid accumulator means that there is a certain pressure bearing capacity in isolation from the outside environment, and more important is to prevent the diffusion (heat leakage) of the gas working fluid from the evaporator to the liquid accumulator. The heat transfer within the loop heat pipe is not strictly unidirectional, but the heat transfer in the loop heat pipe is not strictly unidirectional. Most of the external heat input in the capillary core makes the working fluid gasification to participate in the loop heat pipe circulation, only a part of the heat into the liquid reservoir in the form of heat conduction, this part of the heat called is a heat leak. Heat leakage will lead to excessive temperature and abnormal increase of pressure of the liquid accumulator, which will affect the normal operation of the working fluid in the loop heat pipe.

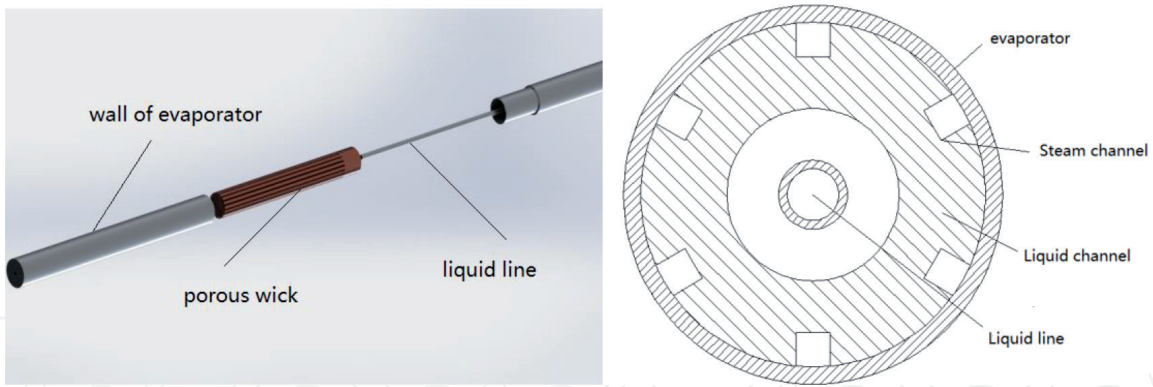


Figure 14.
Evaporator structure profile.

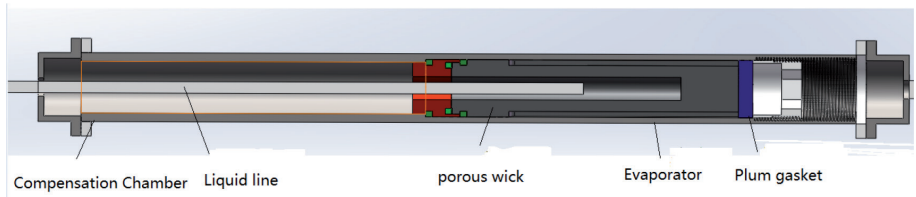


Figure 15.
Structural diagram of evaporator and liquid reservoir.

The heat leakage is mainly transmitted through the heat conductivity of the capillary core and the outer wall of the loop heat pipe, which is difficult to avoid. However, the heat leakage should be considered in the preparation of the loop heat pipe. Limit the adverse effects of heat leakage to a lower range of effects. If vapor enters the tank, it will cause the temperature and pressure of the tank to rise, which will lead to the failure of the heat pipe operation. When the vapor is running in the opposite direction, the heat transfer efficiency of the loop heat pipe will be seriously affected, which will cause the gas accumulation in the liquid accumulator and the capillary seriously. The thin core leads to the failure of forward heat and mass transfer in the loop heat pipe.

In order to prevent the reverse operation of vapor, an inner step stainless steel outer wall is designed for evaporator and liquid accumulator in order to reduce welding, and the capillary core is clamped in one direction, and a clasp structure is installed at the capillary core and step. There are three gaskets on the outer wall of the evaporator and liquid accumulator. Layer by layer protection reduces the reverse flow of heat vapor along the inner wall, improves the heat transfer energy of the return heat pipe, and simulates the failure of the heat pipe operation. Evaporator wall thickness as thin as possible to reduce thermal resistance to facilitate the capillary core to absorb external heat. At the vapor outlet, the capillary core is clamped by thread connection, and a plum flower gasket is installed between the bolt structure and the capillary core, and the vapor produced by the thermal reaction flows out of the pore between the pores of the plum flower gasket. This junction can be reused, just loosen the bolt structure to replace the capillary core. The specific size is obtained from the size of the capillary core. As shown in **Figure 15**.

3.3 Condenser optimization

In the loop heat pipe system, the condenser is responsible for the rapid transfer of heat from the evaporator to the outside world. After heated vaporization of the working medium in the evaporator, the hot vapor enters the condenser through the gas pipeline, and the heat is exchanged with the outside in the condenser to

dissipate heat towards the outside world, and the vapor moves towards the liquid storage device after the condenser becomes a liquid. Therefore, the condenser must have sufficient undercooling to ensure that the working fluid can be completely condensed into liquid. At present, the cooling methods of various equipment are water cooling or air cooling. It is found that the vapor in the evaporator is usually difficult to be condensed into liquid due to the lack of cooling power. So there are a lot of heat pipes in the loop. Adopt water cooling. In order to further improve the cooling temperature, alcohol is chosen as the cooling medium.

The loop heat pipe condenser prepared in this paper is shown in **Figure 16**. The condenser adopts a cylindrical tube structure with an inlet and an outlet to circulate low temperature alcohol or cold water, and the cylinder pipe is a cooling pipe. Considering the overall size of the loop heat pipe, the length of the condenser is set to 200 mm. However, the heat transfer length of 200 mm is insufficient and the vapor in the condenser is cooled completely into a liquid. Faced with this situation, there are usually two solutions: one is to put fins on the outside of the pipe, the other is to make the pipe into a coil. After the experiment, it was found that the efficiency of the first scheme was also insufficient when the first scheme was running at high power. Therefore, the coiled tube alcohol cooling was used in the end. However, as the final cooling scheme, we should pay attention to the length of coil should not be too long, too long pipe length will lead to excessive resistance in operation of the working fluid, which will affect the forward operation of the loop heat pipe.

3.4 Loop heat pipe assembly

The connection between evaporator and condenser in heat pipe is vapor pipeline and liquid pipeline. In order to reduce the flow resistance of the medium, the more smooth the inner, the better. In this paper, stainless steel tube is selected and the inner polishing is done. The vapor liquid phase change process is involved in the operation of the loop heat pipe, and the sealing property is very high. Therefore, stainless steel is used in all parts of the loop heat pipe, and the connection between each part is argon arc welding. All stainless steel components (including liquid accumulators and evaporators) should be cleaned according to the stainless steel cleaning method before final use to improve the performance of the loop heat pipe. The loop heat pipe also needs to be equipped with a new belt valve. The working fluid filling mouth of the door is filled and sealed with heat pipe working fluid. After welding the loop heat pipe, it is necessary to pick up the leakage of the system, inflate the system with air compressor from the filling port, and place the system

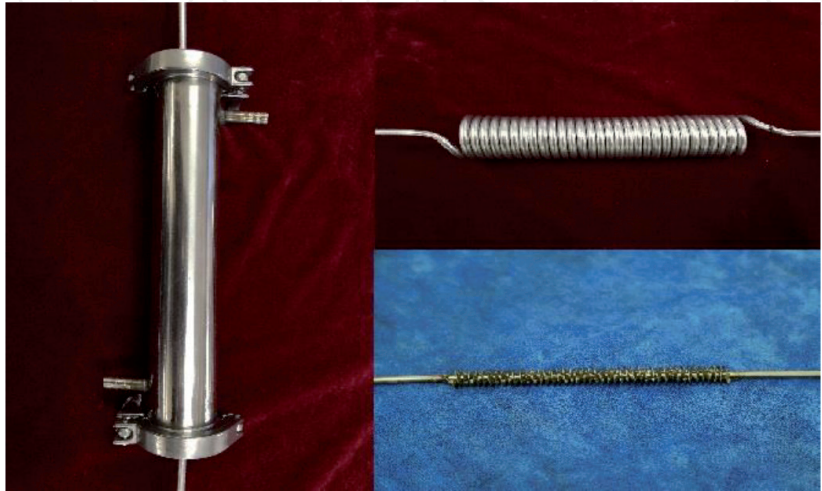


Figure 16.
Condenser structure (including two heat dissipation modes).

in water. If there is no bubble, the system is sealed completely, and if there is air bubble, the leakage point of welding should be rewelded. In order to reduce the difficulty of welding and to facilitate the performance experiment in the future, the loop heat pipe is made into a rectangle, 1000 mm in length and 300 mm in width, in order to match the heat transfer test bed designed later.

The structure and dimensions of the heat pipe are described in **Figure 17** and **Table 1**.

3.5 Vacuum and perfusion of loop heat pipes

In addition to the capillary core properties, the internal working fluid perfusion of the loop heat pipe has the greatest influence on the performance of the loop heat pipe. There are two factors that influence the perfusion effect: one is the quality of perfusion, the other is the degree of vacuum during perfusion, that is, the purity of the injected working fluid. First of all, the heat pipe is filled with flux, when the charge is too small, it will cause the heat pipe to be burned out in the liquid storage device of the heat pipe evaporator, and the heat pipe will fail. When the charge is too much, there will be a lot of liquid working fluid in the condenser, which will cause excessive resistance along the path and hinder the forward operation of the heat pipe. It is inevitable to mix air and other non-condensable gases when pouring working fluid into the loop heat pipe. The research of Beihang [84DIAN85] finds Danghuan when there are non-condensable gases such as nitrogen in the heat pipe, it will lead to the difficulty of starting the loop heat pipe, the high temperature of the evaporator and

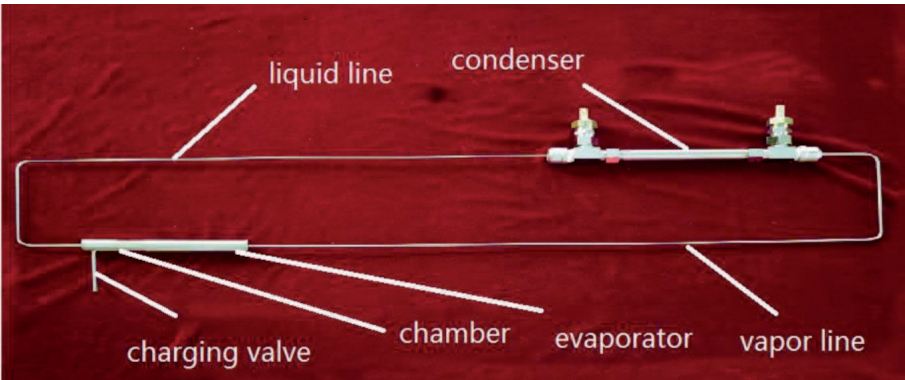


Figure 17.
Loop heat pipe structure diagram.

Loop heat pipe component	Dimension parameter(mm)
Evaporator (Dout/Din/L)	26/20/150
Reservoir (Dout/Din/L)	26/18/120
Capillary core (D/L)	20/100
Capillary vapor groove (L/W/H)	80/2/2
Capillary core liquid channel (Din/L)	8/80
Vapor line (Dout/Din/L)	6.35/3.89/1200
Liquid line (Dout/Din/L)	6.35/3.89/1200
Condenser pipeline (Dout/Din/L)	6.35/3.89/2000
Loop heat pipe appearance (L/W)	1000/300

Table 1.
Size diagram of loop heat pipe.

the decrease of the heat transfer efficiency. It is also found that the non-condensable gas will greatly reduce the service life of the loop heat pipe. Therefore, it is necessary to maintain a vacuum environment during perfusion. We should pay attention to the leakage of the loop heat pipe and the leakage of the working fluid during the simulation of the perfusion according to the way mentioned in this paper.

3.6 Vacuum infusion

Loop heat pipe perfusion is divided into two important steps: first, vacuum, and secondly, perfusion. Therefore, a loop heat pipe perfusion platform integrating vacuum pumping and perfusion is established in this paper. Based on dual functions, the pipeline must have two routes. The first is the perfusion pipeline, which is used to introduce liquid ammonia into the loop heat pipe. The perfusion line is shown in **Figure 18** above.

The pipeline is designed from top to bottom, the top is a liquid ammonia bottle, and the bottom is connected with a loop heat pipe. The loop heat pipe outlet is a pressure reducing valve to monitor the liquid ammonia outlet and the pressure in the pipeline. Then there are two condensing units to try to prevent liquid ammonia from liquefaction. Ensure the accuracy of subsequent flowmeter measurements and prevent too much gas in the pipeline from fluctuating the flow rate. The flowmeter is used to detect the amount of heat in the heat pipe. Continue after a one-way valve to prevent working fluid backflow. One-way valve is a flow valve. The pressure reducing valve can control the flow velocity of the working fluid in the pipeline to control the filling speed. The flow valve is followed by the valve and the loop heat pipe.

The exhaust line also consists of two parts, one is the air in the perfusion line and the other is the air in the heat pipe of the loop, as shown in **Figure 19**. The design scheme of the main line of the heat pipe pumping vacuum perfusion test rig is shown in **Figure 22**. The valve which combines the pouring pipe and the vacuum pumping pipe to control the pipe passage condition is designed as shown in **Figure 20**.

The designed pipe is placed vertically, the aluminum alloy frame is arranged, and the flowmeter display device is designed to monitor the quality of the working fluid that has been poured in the heat pipe. During perfusion, the heat pipe accumulator should be placed in a lower temperature environment than the perfusion tube condenser. This is because it is difficult for liquid ammonia to flow into a loop heat pipe simply because of the gravity effect, so that the temperature in the heat pipe is lowered so that the pressure inside the loop heat pipe remains relatively low all the time. The flow of liquid ammonia in the pipeline is promoted by the pressure of different positions in the pipeline. The vacuum pumping system designed

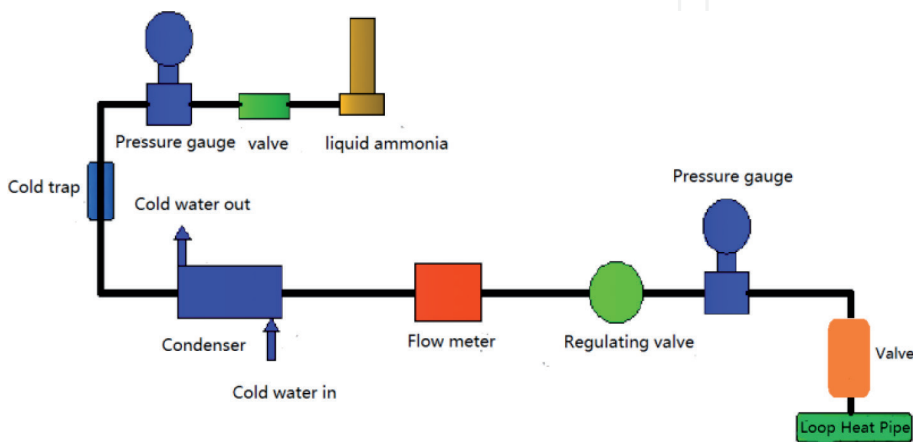


Figure 18.
Perfusion pipeline diagram.

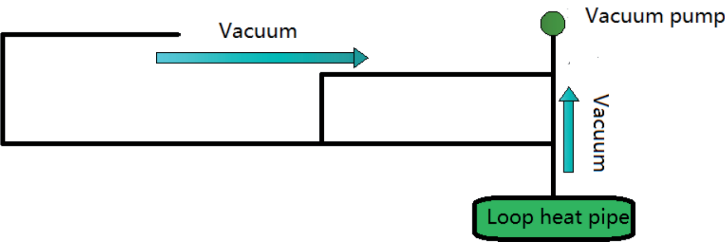


Figure 19.
Drawing of vacuum line.

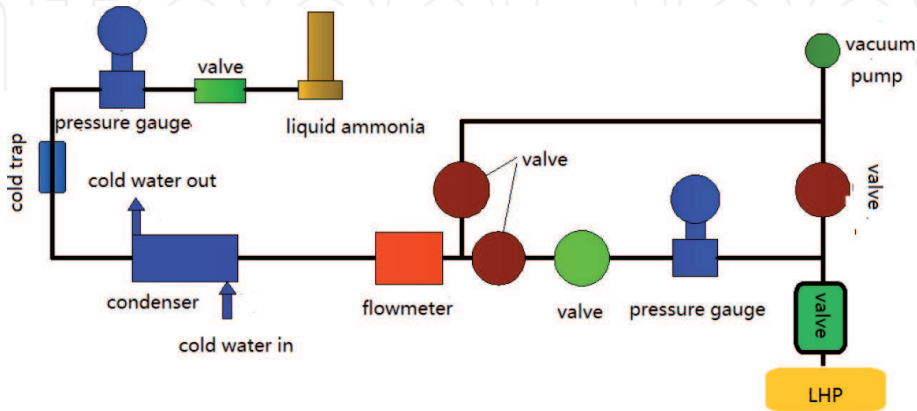


Figure 20.
Schematic diagram of vacuum perfusion pipeline.



Figure 21.
Loop heat pipe vacuum perfusion test bench.

in this paper uses Edward molecular pump to pump the vacuum in the pipeline. In the vacuum process, the pressure in the pipeline can be lowered by 6×10^{-2} Pa. The device diagram is shown in **Figure 21**.

4. Heat transfer experiment of loop heat pipe

In this paper, the heat transfer test bench of loop heat pipe is built, including heating module, cooling module, temperature collecting module, etc. The performance of loop heat pipe is studied experimentally. The loop heat pipe test platform consists of three modules: heating module, cooling module and temperature collecting module. Heating module has two sets, one is controlled power heating,

the other is constant temperature heating. The output power is controlled by puss power supply, and the loop heat pipe evaporator is heated by resistance wire. Constant temperature heating using cast copper heating block. There are grooves on the surface of cast copper heating block for heating loop heat pipe evaporator. The cast copper heating block is controlled by PID and the temperature is monitored by internal thermocouple. This heating method can only guarantee the outer wall temperature of the loop heat pipe evaporator without knowing the heating power of the loop heat pipe. According to the situation, these two heating methods should be used.

The experimental platform needs a cooling module to condensate the loop heat pipe condenser. The condenser is connected to the DC20-20 type low temperature constant temperature tank, and the flow velocity of the constant temperature tank is 20 L/min. The lowest temperature can be -20°C , so this tank can be filled with alcohol as a cooling agent.

The data acquisition module is used to collect the local temperature of the heat transfer experiment of the loop heat pipe, and the performance of the loop heat pipe is analyzed by the variation of each temperature. The data collector uses Fluke2638A to collect data, and Fluke2638A has three chucks, each of which has 20 channels, which can collect 60 temperature points at the same time. K-type Ω thermocouple is used to collect temperature transmission data to data collector. The thermocouple is made of TT-K-36 type Ω temperature measuring line, and MES thermocouple welding machine is used to weld the temperature measurement line. The temperature range of the thermocouple was $-200\text{--}260^{\circ}\text{C}$, and the measurement error was $\pm 0.5^{\circ}\text{C}$. In order to ensure the detection accuracy, each K thermocouple is connected to the data collector channel and the ice water is mixed to zero.

The distribution of thermocouple is shown in **Figure 22**, (1) is the outlet temperature of liquid pipeline, (2) is the inlet temperature of the liquid reservoir, (3) is the inlet temperature of the evaporator, (4) is the temperature at the heating point, (5) is the inlet temperature of the vapor pipe, (6) is the intermediate temperature of the vapor pipe, (7) and (8) are the temperature at the inlet and outlet of the condenser, and (9) are the temperature in the middle of the liquid pipeline. In addition, the condenser inlet and outlet temperatures need to be measured.

4.1 Study on start-up characteristics of loop heat pipe

Eva 1 is the temperature of evaporator, *eva 2* is another temperature of evaporator, *s line 1* is the temperature of vapor line near the evaporator, *s line 2* is the temperature of vapor line near the condenser, *conin* is the temperature of the condenser inlet, *conout* is the temperature of the condenser outlet, *waterin* is the temperature

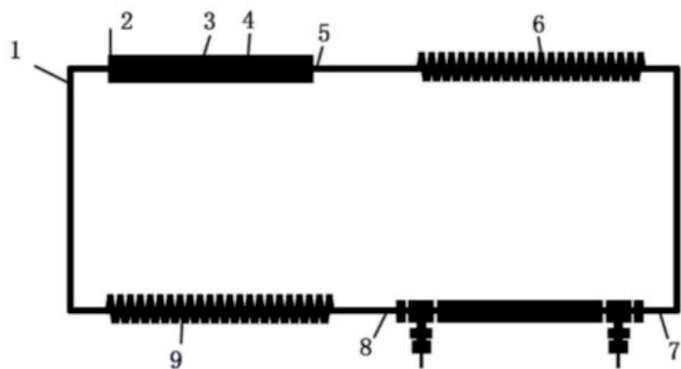


Figure 22.
Location of thermocouple distribution.

of water of the condenser inlet, *waterout* is the temperature of water of the condenser outlet, *l line 1* is the temperature of the liquid line near condenser, *l line 2* is the temperature of the liquid line near chamber, *CC 1* is the temperature of chamber, *CC 2* is another temperature of chamber, *steamout* is the temperature of vapor in the outlet of evaporator.

The startup of LHP can be divided into the following four processes: (1) after the evaporator is heated, the heat is transferred to the working fluid and vaporized. Because of the barrier of the capillary core sintering structure, the vapor can only enter into the vapor pipe through the vapor trough; (2) the vapor enters the condenser to cool through the vapor pipe, (3) after condensing into the liquid in the condenser, the liquid working fluid is pumped back into the liquid storage room because of the capillary force of the capillary core; (4) the working fluid of the reflux flows back into the evaporator through the permeability of the capillary core. In this paper, it is found that the minimum starting power of the loop heat pipe is 5 W.

Figure 23 shows the starting heat transfer characteristics of the loop heat pipe at 5 W startup. It can be seen from the diagram that the loop heat pipe operates steadily after a period of time (3500 s), and the temperature of each part remains constant. In the early stage of the experiment, the evaporator and vapor line begin to rise steadily, the internal working fluid of the loop heat pipe evaporator absorbs the external heat, the internal working fluid reaches the saturation temperature and begins to vaporize, and the vapor enters the vapor pipeline, which leads the internal temperature of the pipeline to increase. Vapor passes through the vapor line and enters the condenser, so the inlet temperature of the condenser jumps. Through the condenser enough gas refrigerants are condensed into the liquid line, so the liquid tube is filled with liquid. The line temperature is low. After that, the liquid working fluid is reflowing back to the liquid accumulator and evaporator under the action of the capillary core to complete the forward circulation of the loop heat pipe. At the initial stage of starting the loop heat pipe, there was a small fluctuation in the temperature at the evaporator. The temperature first decreased and then increased. This was caused by the liquid working fluid began to condensate and reflux, and it also marked the formal start of the loop heat pipe. The starting time of the loop heat pipe is 1000 s.

4.2 Study on heat transfer characteristics of loop heat pipe

The threshold value for the initial start-up of the loop heat pipe is 5 W. When the heating power of the loop heat pipe evaporator is increased, the temperature of each part of the loop heat pipe is different. In order to further understand the heat transfer performance of the loop heat pipe prepared in this paper, the heating power of the loop evaporator is gradually increased, and the relationship between the temperature of each part of the loop heat pipe and the heating power is discussed. In this paper, the heat transfer experiment of loop heat pipe with different heating power has been carried out from 5 to 1 W interval. The experimental scheme is carried out according to the above experimental scheme. The external cold source temperature is -5°C when the heat transfer is heated by the transverse power heating method. The temperature curve of heating power 8W and 10W with -5°C heat sink is as shown in **Figures 24 and 25**.

With the increase of evaporator power, the loop heat pipe can continue to operate normally, and its operation law is similar to that of each part of the heat pipe heated at 5 W. The temperature inside the evaporator and vapor line rises first and then remains stable. The inlet temperature of the condenser is also stable after rising sharply at the beginning, and the temperature difference between the inlet of the condenser and the inlet of the condenser has been maintained, indicating that the loop heat pipe has been in a positive operating state. The experimental results

show that the liquid line temperature of the loop heat pipe is approximately the same under different heating power, which indicates that the working fluid can be condensed completely into liquid through the condenser when the loop heat pipe is running, and is lower than the saturation temperature under the current pressure. The temperature curve and thermal resistance of different heating power are shown in **Figures 26 and 27**.

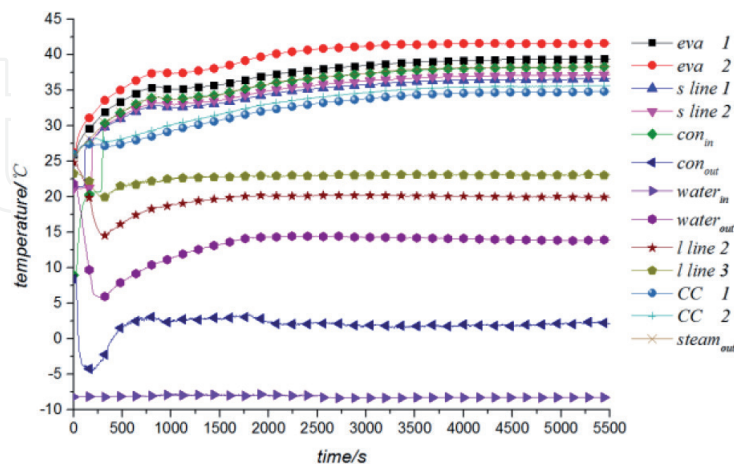


Figure 23.
5 W heating power loop heat pipe temperature curve.

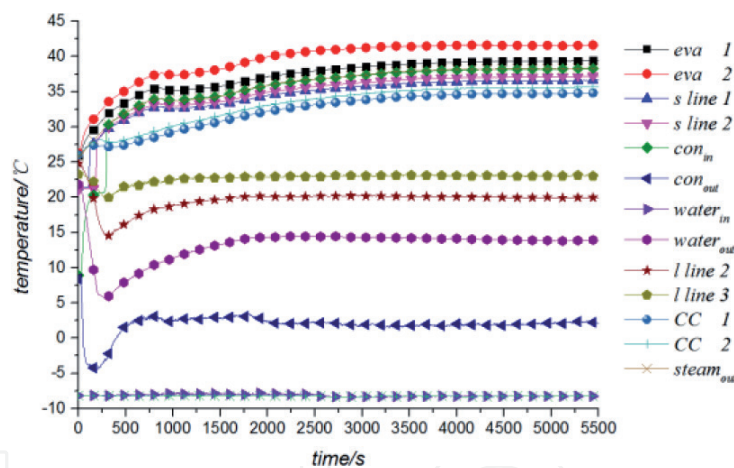


Figure 24.
8 W heating power loop heat pipe temperature curve (-5°C heat sink).

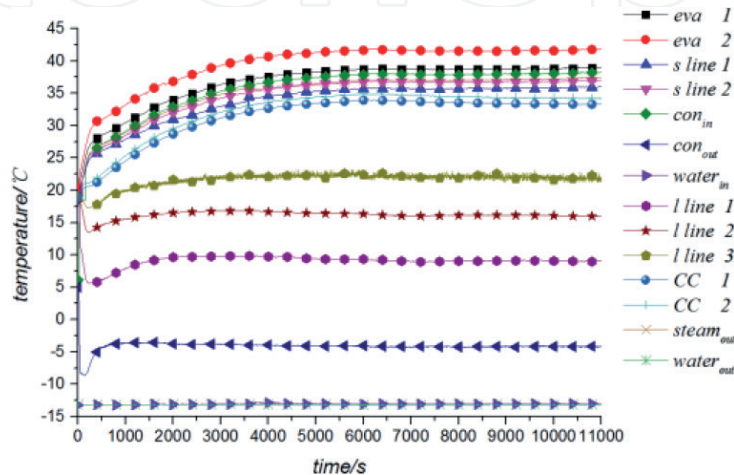


Figure 25.
10 W heating power loop heat pipe temperature curve (-5°C heat sink).

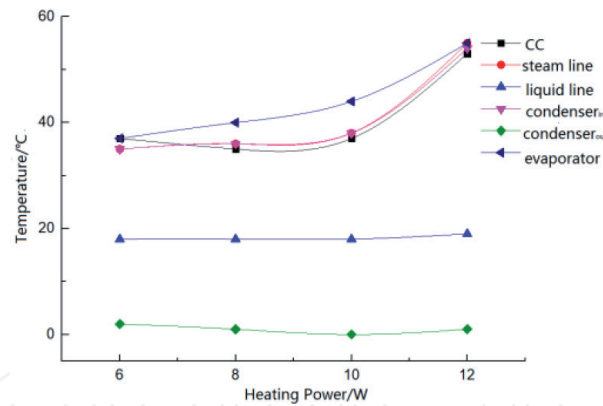


Figure 26.
Curve of temperature change with heating power.

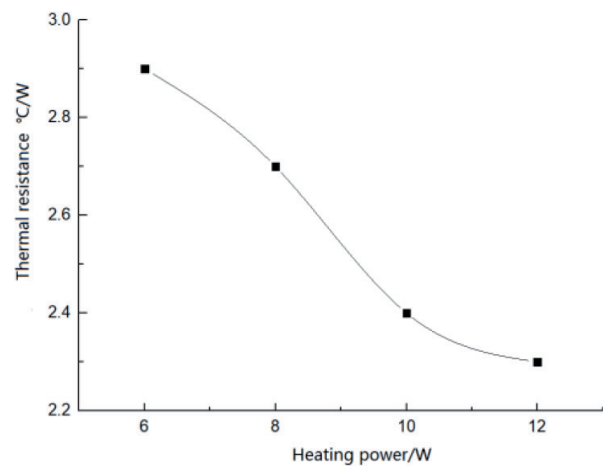


Figure 27.
Relationship between heating power and thermal resistance.

The temperature variation of loop heat pipe is different with different heating power. As is shown that the higher the heating power, the higher the temperature of the evaporator, the higher the internal pressure, and the faster the temperature of the evaporator increases with the increase of heating power, so the heating power of the loop heat pipe should not be too large. Prevent the internal pressure from exceeding the pressure limit of the loop heat pipe. With the increase of the evaporator temperature, the temperature of the vapor pipeline entering the gaseous medium also becomes higher, which leads to the continuous increase of the vapor pipeline temperature to the inlet temperature of the condenser. In this paper, the low temperature alcohol is used as the external heat sink in the experiment, and the loop heat pipe is condensed. The working fluid in the condenser can be condensed completely, so even though the external heating conditions are different, the outlet temperature of the condenser remains basically unchanged at about 0°C. The experimental results show that the temperature of the loop heat pipe liquid accumulator increases rapidly with the increase of heating power, which is due to the fact that the evaporator tube wall and the liquid storage tube wall are made from the same stainless steel jacket. The heat from the outer wall of the evaporator is transferred to the outer wall of the liquid storage device by heat conduction, which results in the increase of the temperature of the external wall of the liquid storage device. The increase of external wall temperature may lead to excessive internal temperature and high pressure, which may hinder the forward operation of the loop heat pipe. So in subsequent studies, How to reduce the heat leakage from evaporator to liquid accumulator will be an important and difficult problem.

The heat transfer efficiency of loop heat pipe is usually measured by its overall thermal resistance. The total thermal resistance (R_{total}) of the loop is expressed as follows: the difference between the average temperature of the evaporator and the average temperature of the condenser is used to compare the heating power of the upper loop heat pipe with the difference between the average temperature of the evaporator and the average temperature of the condenser.

$$R_{total} = \frac{T_{ev} - T_{cool}}{Q_{load}} = \frac{T_{ev}^{in} + T_{ev}^{out} - T_{cool}^{in} - T_{cool}^{out}}{2Q_{load}} \tag{4}$$

The experimental results show that the thermal resistance of the loop heat pipe becomes smaller and the overall heat transfer performance of the loop heat pipe becomes more and more excellent when the heating power is increasing, that is to say, the thermal conductivity of the loop heat pipe is getting better and better. However, the heat resistance of the loop heat pipe has a minimum value. The heat transfer efficiency of the loop heat pipe is the highest when the loop heat pipe works under this condition, but at the same time the temperature inside the evaporator is also very high, and the heat transfer limit of the loop heat pipe reaches its heat transfer limit.

The experimental results show that when the external condensation temperature is insufficient, the heat absorbed by the loop heat pipe evaporator cannot be transferred out, which leads to the high pressure inside the loop heat pipe. The capillary force provided by the capillary core cannot overcome the resistance in the loop heat pipe normally and the suction of the working fluid leads to the failure of the loop heat pipe operation. However, when the condenser and the external heat exchange is sufficient, the evaporator can transfer the heat completely, and the different undercooling degree has no great influence on the steady state of the loop heat pipe. As is shown in curves of heat sink temperature of -10°C at -15°C under heating power of 10 W of the loop heat pipe. It can be seen that the temperature distribution of loop heat pipe evaporator, liquid accumulator, vapor line and liquid line are basically the same at different external heat sink temperatures. The temperature at the outlet of the condenser is affected by the external heat sink of the condenser. The lower the external heat sink temperature, the lower the temperature of the condenser, and the difference of the temperature at the outlet of the condenser is exactly the difference of the external heat sink. The external heat sink temperature also affects the time required for the loop heat pipe to reach stable operation. It can be seen from the diagram that the lower the external heat sink

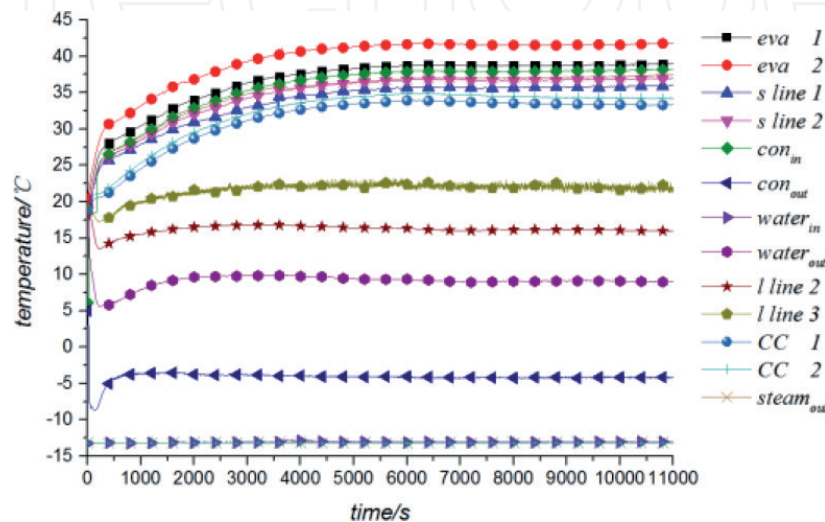


Figure 28.
Temperature curve of heating power loop heat pipe (-10°C heat sink).

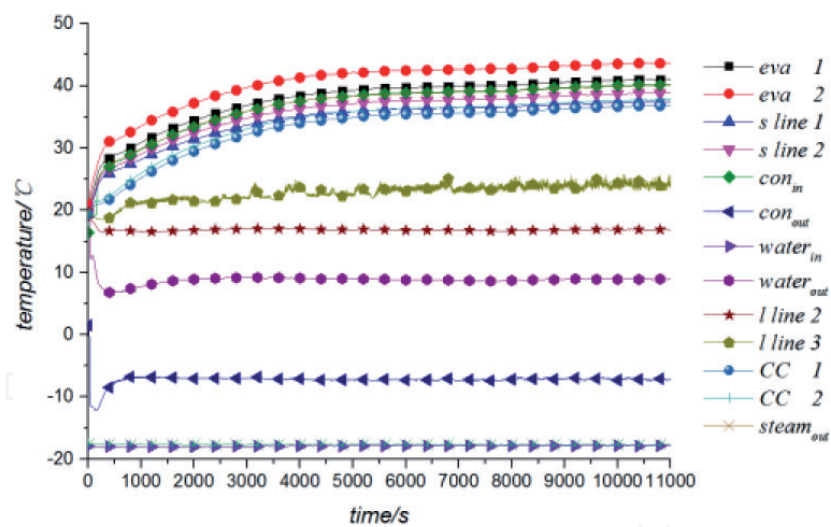


Figure 29.
Temperature curve of heating power loop heat pipe (-15°C heat sink).

temperature, the longer the loop heat pipe operation will be stable. The temperature curve of different heat sink (-10°C and -15°C) are shown in **Figures 28** and **29**.

5. Conclusion

1. With the increase of mass of NaCl, the suction speed and total suction mass increase, it can be concluded that the pore-forming agent (NaCl) will significantly improve capillary core performance, which is crucial for the loop heat pipe.
2. In select range, the cold forming pressure has little influence on the performance of the capillary cores.
3. The loop heat pipe which uses the novel capillary cores can start up successfully on 5 W. Besides the heat sink will influence the time that the LHP operate stably. The lower the temperature of the external heat sink, the longer the loop heat pipe will run stably.

Author details

Chunsheng Guo
School of Mechanical, Electrical and Information Engineering, Shandong University,
Weihai, China

*Address all correspondence to: guo@sdu.edu.cn

IntechOpen

© 2019 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.



References

- [1] Maydanik YF, Chernyshevana MA, Pastukhov VG. Review: Loop heat pipes with flat evaporators. *Applied Thermal Engineering*. 2014;**67**:294-307
- [2] Maydanik YF. Loop heat pipe. *Applied Thermal Engineering*. 2005;**25**:635-657
- [3] Huang BJ, Hsu PC. A thermoelectric generator using loop heat pipe and design match for maximum-power generation. *Applied Thermal Engineering*. 2015;**91**:1082-1091
- [4] Baumann J, Cullimore B. Non-condensable gas, mass, and adverse tilt effects on the start-up of loop heat pipes. *The International Journal of Automotive Engineering*. 1999;**1**:2036-2048
- [5] Zhang HX, Lin GP, Ding Z, Shao XG, Sudakov RG, Maydanik YF. The experimental study of loop heat pipe start-up characteristics. *Journal of Science China's Scientific E Series: Engineering Science*. 2005;**35**:1720-1730
- [6] Yan T, Zhao YN, Liang J, Liu F. Investigation on optimal working fluid inventory of a cryogenic loop heat pipe. *International Journal of Heat and Mass Transfer*. 2013;**66**:334-337
- [7] Mitomi M, Nagano H. Long-distance loop heat pipe for effective utilization of energy. *International Journal of Heat and Mass Transfer*. 2014;**77**:777-784
- [8] Tang Y, Deng D, Huang G, Wan Z, Lu L. Effect of fabrication parameters on capillary performance of composite wicks for two-phase heat transfer devices. *Energy Conversion and Management*. 2013;**66**:66-76
- [9] Bai L, Lin G, Zhang H, Miao J, Wen D. Operating characteristics of a miniature cryogenic loop heat pipe. *International Journal of Heat and Mass Transfer*. 2012;**55**:8093-8099
- [10] Du C, Bai L, Lin G, Zhang H, Miao J, Wen D. Determination of charged pressure of working fluid and its effect on the operation of a miniature CLHP. *International Journal of Heat and Mass Transfer*. 2013;**63**:454-462
- [11] Ku J, Ottenstein L, Douglas D, et al. Multi-Evaporator Miniature Loop Heat Pipe for Small Spacecraft Thermal Control, Part 1: New Technologies and Validation Approach[C]. In: 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition Orlando, Florida. 2010;**6**:2010-1493