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Development of biporous wicks for flat-plate loop heat pipe

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ABSTRACT

Two different methods, cold pressing sintering and loose powder sintering, are adopted to fabricate the biporous nickel wicks for loop heat pipes (LHPs) in the present study. Porosity of the wicks is measured by Archimedes method and radius and distribution of pores is observed by Scanning Electronic Microscope (SEM), and permeability of wicks is calculated by empirical equation. The effect of different sintering method, proportion of pore former, and sintering temperature on the wicks is investigated experimentally. Result shows that wicks are successfully fabricated, the optimal wicks are found to be sintered at 700 °C, using cold pressing sintering method, with pore former content 30% by volume; these wicks could reach the porosity of 77.40%, the permeability of $3.15 \times 10^{-13}\ m^2$, and have sufficient mechanical strength to meet the machining requirements. The effect of lathing and wire electro discharge machining on surface pores of wick is analyzed by SEM. In order to verify the performance of the biporous wick, a flat plate type of LHP is designed, fabricated and tested in this paper, and the results presents that the LHP can startup and run reliably under different heat loads.

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1. Introduction

The film evaporation in the porous media is a very efficient way for heat transfer, which is widely used in the two phase heat exchanger, such as capillary pumped loop (CPL), loop heat pipe (LHP). Due to its high heat transfer capacity and other merits, researchers have done many studies [1–3]. Along with the increasing cooling demands of the electronic devices, this heat dissipating technology is becoming more and more important.

LHP was first invented in the former Soviet Union in 1974 and CPL was first invented in the NASA Lewis Space Flight Center in 1966. The main difference between CPL and LHP is the location of the reservoir. The CPL reservoir is located remotely from the evaporator, while the LHP reservoir is coupled to the evaporator. Due to the different structures of reservoir, the operation performance of CPL and LHP may present differences. Wolf et al. [4] point out that LHPs combine the advantage of both conventional heat pipes and CPL. Moreover, LHPs possess the following advantages: self-priming, no power input; no moving part, passive heat transport system, high reliability; ability to operate against gravity.

As shown in Fig. 1, LHP system consists of evaporator, condenser, vapor transport line, and liquid transport line. LHP absorbs the heat and vaporizes the working fluid in the evaporator. Vapor is then transported to the cold region through the vapor transport line. In condenser, vapor is condensed into liquid, which is slightly subcooled; the liquid is then transported back to the hot region through the liquid transport line. It can be seen that the capillary force supplied by wick is the main power source of the whole system; therefore, the wick is the most important part in the LHP system and the structure of wick is one of key determining factor of the LHP's performance. Since wicks affect LHP fundamentally, they are the most crucial components to fabricate in LHP. Liu et al. [5–13] have conducted widely investigation for CPL and LHP both numerically and experimentally, including heat and mass transfer in evaporator and condenser as well as system performance test. Their investigation results present that the performances of the system are related with the characteristics of evaporator and condenser as well as system configuration. Moreover, Liu et al. [5,6] point that the CPL with a porous wick in the condenser can reduce even eliminate the pressure or temperature oscillations if the parameter of the condenser is reasonable. Liu et al. [8] have also conducted the investigation for the impact of working fluid to system operation.

The performance of wicks is determined by pore sizes and porosity: with finer pore, the wick can provide LHP with higher capillary force; with higher porosity, the permeability of wick is larger, which means less resistance for fluid flowing in the wick. However, too fine pores will cause the permeability plummets, leading hydraulic resistance increase sharply. Therefore, wicks with fine pore need higher porosity, which also could provide the wick low thermal conductivity to reduce the heat leaks to the liquid chamber.

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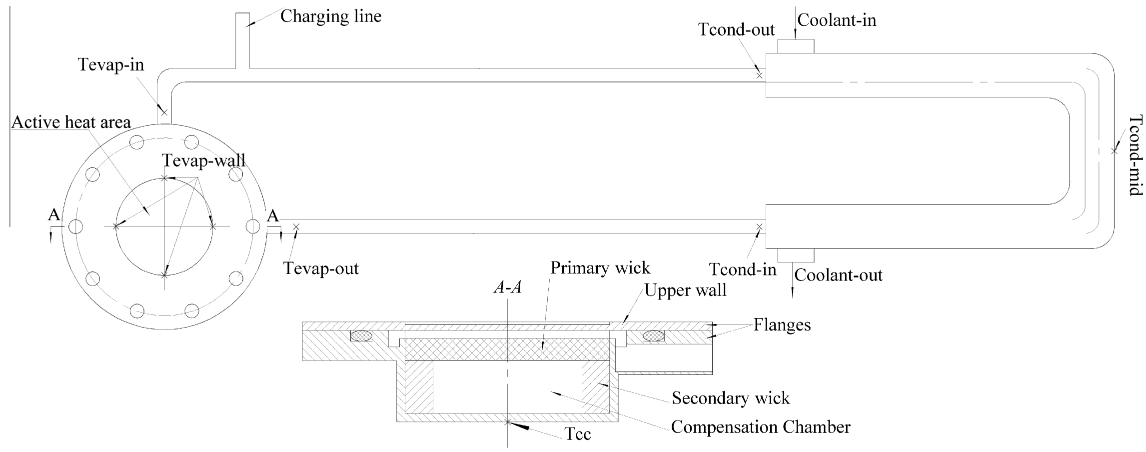


Fig. 1. Scheme of LHP and the temperature measuring point.

Typically, the porous wick structure is groove type, mesh type and sintered type [14,15]. Mishra et al. [16] carry out experimental trials to fabricate wicks with high porosity, using carbonyl nickel powder as raw material. After optimization, cylindrical wick (L/D ratio: 10) with porosity of 64%, average pore size of 5 μm and a permeability of 1×10^{-13} m^2 could be realized, they also analyze the effect of wire electro discharge machining on surface pore using Scanning Electron Microscopy. Shih and Hourng [17] study the capillary-induced fluid motions in an isotropic powder-embeded porous matrix by Monte-Carlo simulation method, the concept of random walk and a two-block hexagonal network model are employed to accomplish the simulation procedures. Xin et al. [18] fabricate wicks by sintering the mixture of nickel powders and copper powders (with nickel to copper ratio of 9:1) under temperature of 650 °C for 30 min, and the wicks can reach the porosity of 70%, the permeability of 10^{-13} m^2, and mean pore radius of 0.54 μm; Li et al. [19] investigate capillary pumping performance of porous wicks through experiment, the result shows that capillary pumping amount changing curve of porous wick can be described with an exponential increase equation, and capillary pumping rate is found to increase with the increasing porosities of the porous wicks; Santos et al. [20] fabricate ceramic porous wick for LHP, and the ceramic porous wick has 50% of porosity, 1–3 μm of pore radius distribution and a permeability of about 3.5×10^{-14} m^2. For a limited operation temperature of 100 °C, the LHPs are able to transfer up to 25 W and 15 W using acetone and water, respectively, at steady state condition; Eduardo et al. [21] use carbonyl nickel powder, atomized nickel powder and a powder of both to make tubular wicks, and find that the mixture is selected as the best raw material, and pore size in the range of 2–24 μm and porosity about 50% is measured.

In high heat flux condition, the vapor and liquid flow rate are equally large in the evaporator. Due to the fine pore, monoporous wicks will produce high hydraulic resistance, which is one of the most important reasons causing dryout in evaporator. The best monoporous wicks have critical heat flux at 300 W/cm^2 [22]. Therefore, some scholars propose biporous wick system [23,24]. As shown in Fig. 2, the two different kinds of pores can allow the wick to achieve a better performance through separation of liquid and vapor: the large pore can reduce liquid hydraulic resistance effectively, moreover, large pore also provide extra area for liquid film to evaporate, and the fine pore can maintain the system with sufficient capillary force. Experiments are carried out and show that the biporous wicks are very effective: Semenic and Catton [22] test the performance of both monoporous wicks and biporous wicks, and find that best biporous wick has critical heat flux at 990 W/cm^2, and the bidispersed wicks used in the experiment are manufactured by Advanced Cooling Technology. Cao et al. [25] fabricate biporous wicks with copper powder, and large/small pore-diameter ratios are 200/80 μm, 400/80 μm, 800/80 μm, they also investigate heat and mass transfer in the wicks. Yeh et al. [26] add pore former into filamentary nickel powder to manufacture biporous wick, study the effect of sintering temperature, particle size of pore former, and the pore former content on heat transfer performance of wicks, and find that particle size and pore former and the pore former content are the significant factors.

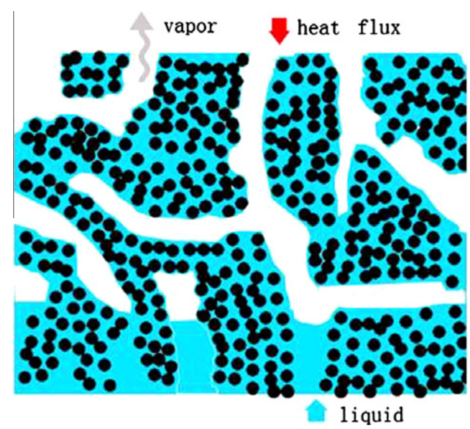


Fig. 2. schematic of biporous wick.

The main purpose of the present study is to manufacture biporous wicks with high porosity, ensuing LHP operate stably and reliably in high heat flux condition.

2. Experiment

2.1. Materials

Generally, materials used for sintering wicks include copper powders, nickel powders and stainless steel powders. In the present study, T255 nickel powders made by INCO [27] are chosen as raw material, its mean radius is 2.2–2.8 μm, and bulk density is 0.52–0.65 g/cm^3. As pore former, Sodium carbonate is mixed into nickel powder with volume ratio of 10%, 20%, and 30%, respectively.

2.2. Embryo

Both cold pressing sintering and loose powder sintering method are applied to make embryos. Schematic of cold pressing method is

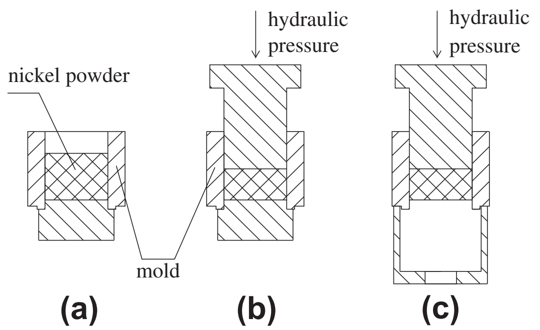


Fig. 3. Cold pressing method (a) loading (b) cold press (c) demold.

shown in Fig. 3. The mixture of nickel powder and pore former is filled into the steel mold and pressed by the punch; pressure value can be read from the pressure gauge. Meanwhile, the mixture is also filled into graphite mold for loose powder sintering.

2.3. Sintering

Sintering is a very complicated process. According to the literature [28]· porous material should be sintered at half melting point T_m as long as possible in order to get ideal cylindrical pore structure, however, porous wicks should have sufficient mechanical strength to meet the machining requirements, therefore, in the actual process, sintering temperature is always higher than $0.5T_m$. Different materials need different sintering atmosphere, as to nickel powder, it should be sintered at reducing atmosphere to restore the oxide on the surface of particle.

The mean radius of T255 nickel powder is quite small, so surf-activity is relatively large and sintering temperature is relatively low, generally 600–900 °C, lasting about 30–60 min. In order to prevent wicks stuck to the furnace during the sintering process, place a piece of graphite sheet in the furnace, and then put the embryos on the sheet. Due to high conductivity of graphite, wicks can be heated uniformly, thus avoiding deformation because of thermal stress. In the study, wicks are sintered at 700 °C and 800 °C for several times to investigate the impact of different sintering temperature on wicks.

3. Results and discussion

3.1. Porosity and permeability

Sintered wick is shown as Fig. 4. Put wicks into ultrasonic cleaner, and wash the wicks repeatedly to dissolve the pore former. When the pH value of water is 7, take out and dry the wicks.

Archimedes method [29] is used to measure the effective porosity. The procedures are as follows: first, measuring the dry weight m_1 of wick by the electronic scale, second, saturating the wicks by distilled water at 75 °C for 6 h, and then measuring the weight of saturated wicks in the air m_2 and in the water m_3, respectively. The effective porosity can be calculated as:

$$\varepsilon = \frac{m_2 - m_1}{m_2 - m_3} \quad (1)$$

The permeability of wicks is calculated according to Carman-Kozeny formula [29]:

$$k = \frac{d^2\varepsilon^3}{180(1-\varepsilon)^2} \quad (2)$$

where k is permeability of wicks (m^2), d is average powder diameter (m), and ε is the porosity of wicks.

Fig. 4. Picture of wick made by cold pressing–sintering method.

It can be seen from Fig. 5 that wicks made by the mixture have much higher porosity than those made by pure nickel powder. This is because these two kinds of powders are different in mechanism of the pore formation: as to pure nickel powder, each pore is surrounded by 4–6 particles to form 26–50% porosity [28], so the porosity is only depended on particle size, particle distribution and particle shape. While the pore made by pore former is generated after pore former is dissolved or evaporated, porosity is depended on type, size, and content of pore former, and has little to do with size and shape of matrix powder. Therefore adding pore former can improve porosity greatly. It also can be seen from the figure that at the same pressure, the wicks made by mixture also have larger porosity than those made by pure nickel powder. In fact, this is very desirable in the fabrication of wicks, in the actual process, wicks are required to have sufficient mechanical strength in order to machine and assemble, so the embryos are often cold-pressed under certain pressure. If there is no pore former, the porosity will be relatively lower. As to the loose powder sintering,

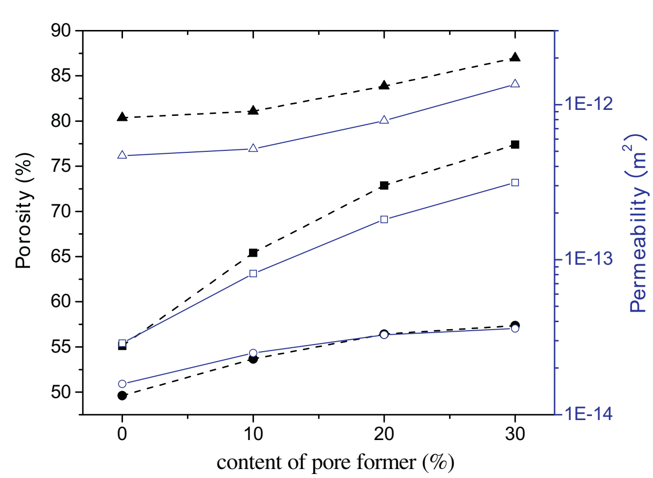


Fig. 5. Porosity and permeability of wicks made by different methods.

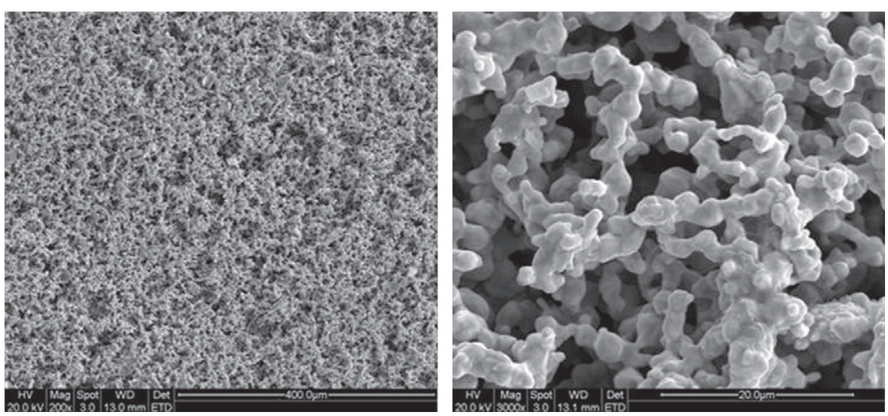
the porosity of these wicks is very high no matter adding pore former or not. At the pore former content of 30%, the porosity is as high as 86.99%, but the structure of all loose powder sintered wicks is too soft to meet the mechanical requirement. The porosities of all wicks sintered at 800 °C are relatively lower than those sintered at 700 °C. Moreover, the wicks sintered at 800 °C are stuck on the graphite sheet, and there are slight warp and crack on the surface of some wicks. Meanwhile, since 800 °C is close to the melting point of sodium carbonate, some sodium carbonate particles are found on the graphite sheet after sintering process.

3.2. Radius

FEI Quanta 200 Scanning Electronic Microscope (SEM) is used to observe the pore size and distribution. Fig. 6 is the SEM picture of wick made by pure nickel powder, it can be seen that the pore distribution is uniform. Figs. 7 and 8 are the SEM pictures of wicks made by cold pressing sintering and loosen powder sintering. Compared with Fig. 6, there are some pores made by pore former. From Figs. 7–9, there are three kinds of pores: the first one is made by pore former, and mean radius is about 60 μm; the second one is the gap between nickel powders, mean radius is less than 1 μm; the third one is pore generated by numbers of nickel powder agglomeration, mean radius is about 5 μm. As shown is Fig. 2, when LHP operates in the high heat flux condition, the vapor will selectively occupy the large pores, forming vapor channels in large pore. The inversed meniscus in the wicks includes two parts: the one in the large pores, and the one in the small pores. Actually, the vapor channels in the large pores provide additional area for liquid film to evaporation. Moreover, the existences of large pores make it easier for vapor to secede from wick and flow into the vapor transport line. The latter two types of pores are relatively small, which can provide LHP with enough capillary force. Meanwhile, duo to the pore former, the inner connectivity of wick is improved, which is very essential for wicks used in LHP.

3.3. Machining

In order to meet the precise geometrical requirement of flat plate loop heat pipe, wicks often need to be machined, which typically includes lathing and wire electric discharge machining (wire-EDM). It can be seen form Fig. 9 that the effect of lathing on the wicks is not confined to the machined surface, the machined surface is tore and most of pores on the surface is blocked completely, which is undesirable in LHP. As to wire-EDM, the affect region is only the machined surface. It can be seen from Fig. 10 that the pores under the machining face are intact, and melted nickel on the surface can be removed by acid solution. In summary, wire-EDM is a better method in machining wicks, which can lead to less pore closure compared with lathing, but both above methods can arise the problem of pore closure, as a result, to keep the good capacity of the wick, it is recommended that do not machine the heat or suck surface of wick.



(a) 200 magnitude (b) 3000 magnitude

Fig. 6. SEM picture of wick (pure nickel powder, cold pressed, 700 °C).

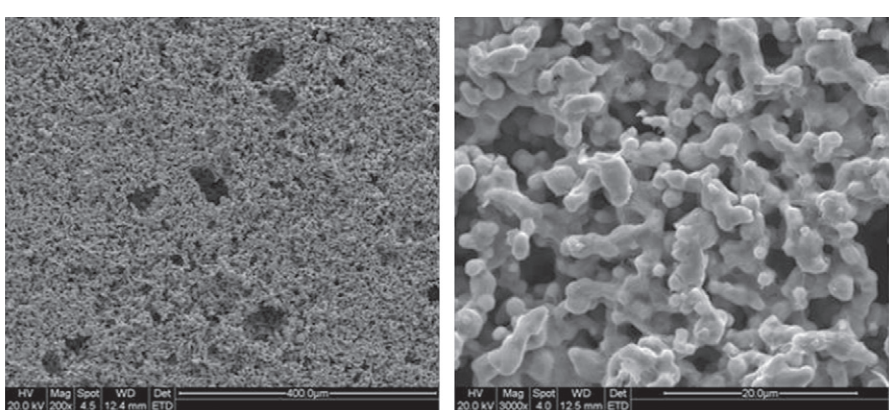


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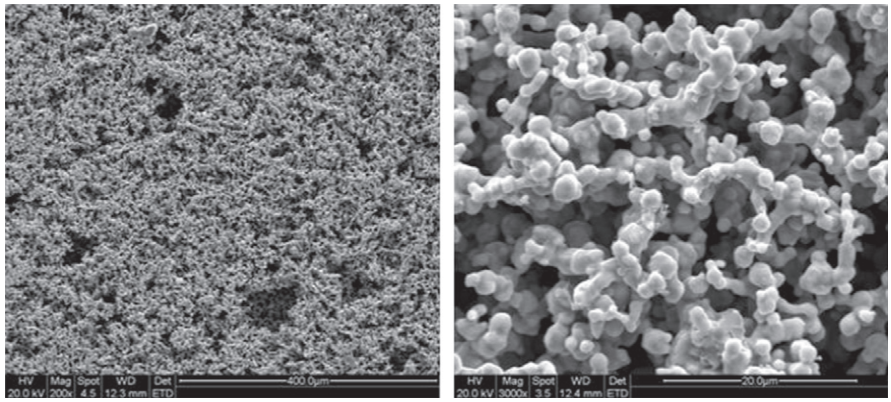
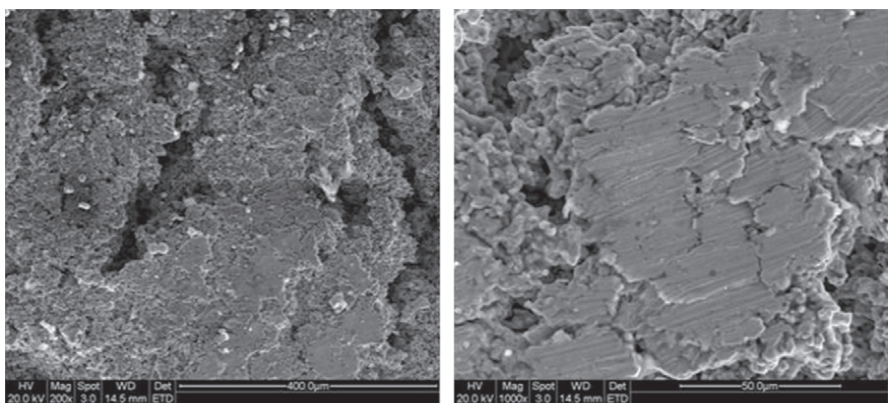
Fig. 7. SEM picture of wick (30% pore former content, cold pressed, 700 °C).



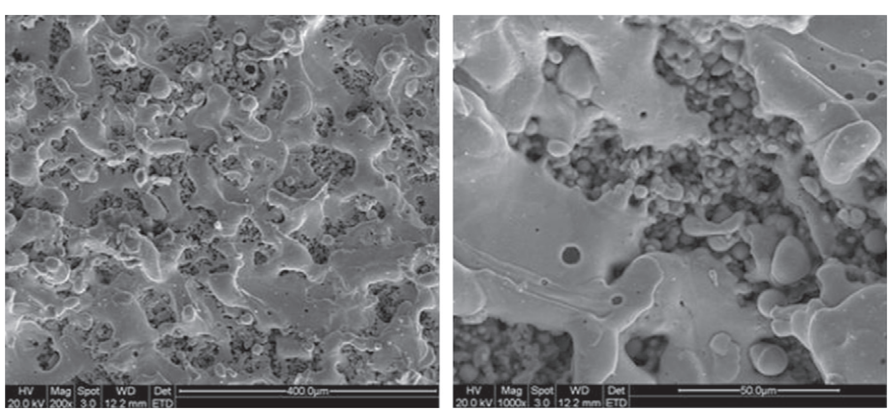
(a) 200 magnitude (b) 3000 magnitude

Fig. 8. SEM picture of wick (30% pore former content, loosen sintered, 700 °C).



(a) 200 magnitude (b)1000 magnitude

Fig. 9. SEM picture of wick being lathed.



(a) 200 magnitude (b)1000 magnitude

Fig. 10. SEM picture of wick being wire-EDM cut.

3.4. LHP experiment

In order to verify the performance of heat and mass transfer, a flat type of miniature LHP system was designed, fabricated and tested. The system in the present study consists of four subsystems: LHP system, heating system, ambience temperature control system, and data acquisition system. Fig. 1 shows the flat-plate LHP system, which is composed by an evaporator, an water cooling type condenser, a vapor line and a liquid line. The main structural characteristics of LHP are shown on Table 1. The evaporator, condenser and vapor/liquid lines are all made from pure copper. For charging, the loop is firstly evacuated to 3.0×10^{-4} Pa and then filled with methanol (99.5% purity). Twelve T-type thermocouples with ±0.2 °C accuracy are used to measure temperature at different locations of the LHP and the ambient air. All the instruments are connected to the Keithley-2700 data acquisition system which

Table 1
Main design parameters of LHP.

Evaporator	Upper wall	Thickness (mm)	1.5
		Rib width (mm)	1
		Groove width (mm)	1
		Number of ribs	19
	Compensation chamber	Diameter O/I (mm)	74/36.9
		Height (mm)	15
		Thickness (mm)	1.5
	Primary wick (nickel)	Diameter/height (mm)	36.9/3.94
		Porosity	69.4%
	Secondary wick (stainless steel mesh)	Diameter O/I (mm)	36.9/26.9
		Height (mm)	8.06
Condenser		Diameter (O/I) (mm)	16/15
		Length (mm)	620
Vapor line		Diameter O/I (mm)	5/4
		Length (mm)	300
Liquid line		Diameter O/I (mm)	5/4
		Length (mm)	360

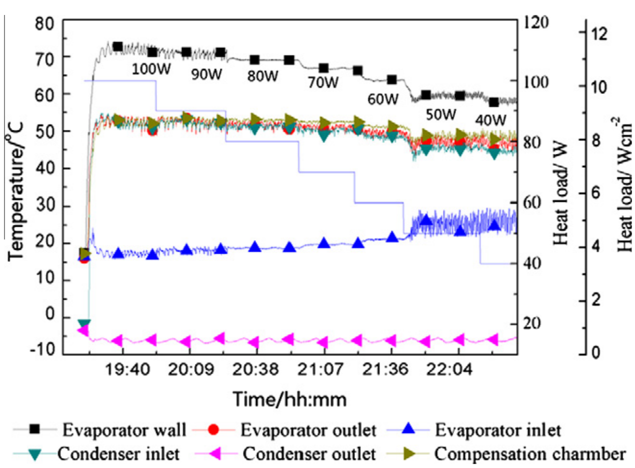


Fig. 11. Temperature of LHP under different heat load.

helps to monitor and record test data from the LHP prototype. In order to test the thermal performance of the LHP, a heat load simulator in the form of copper block with two embedded cartridge heater and active area of diameter of 36 mm is used. For the purpose of minimizing heat loss to the ambient, the heat load simulator is thermally insulated using 10 mm thickness nano-adiabatic material with conductivity of 0.012 W/m K. The temperatures of two sides of the heat insulation material are measured during the experiment. According to the calculation, the absolute error of the heat load is less than 0.3%.

Figs. 11 and 12 show the experimental results. It can be obtained that the biporous wick can allow the LHP operate reliably at a wide range of heat load, from 40 W to 100 W. When heat load is applied to the evaporator, part of the applied heat can be transferred to liquid core or compensation chamber, which is so called heat leak. For LHP with cylindrical evaporator, the leaking heat is transferred in radial direction of wick from heat surface to chamber [30]. But for LHP with flat-plate evaporator, the heat leak problem is more serious than that of LHP with cylindrical evaporator, since the former is easier to transfer more heat from the heating wall to compensation chamber (CC) than the later. If the transferred heat

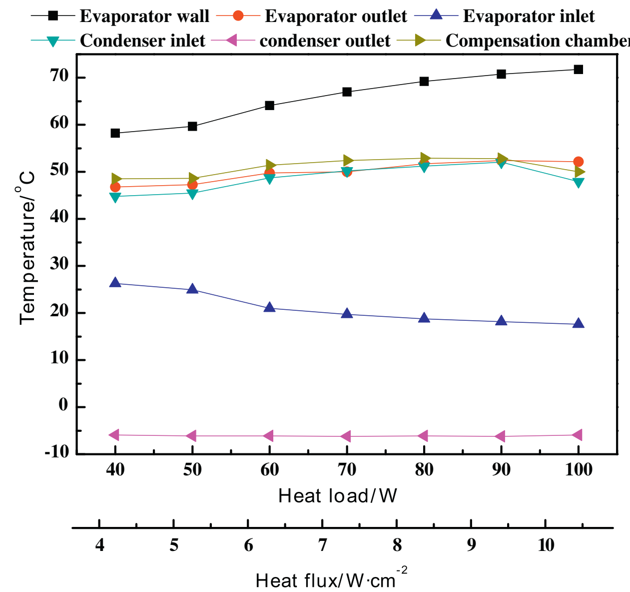


Fig. 12. Steady temperature of LHP under different heat load.

is larger enough to reduce the subcooling of the returning fluid, bubbles will generate in the CC, which can reduce cycling quantity or block working fluid flow back to CC, or even lead to dryout in the wick. The back conduction in the flat plate evaporator have a great impact on operation of the LHP, especially on the startup process. Therefore it is one of key characteristics of LHP that whether LHP can start up successfully. Under the heat load of 100 W (heat flux of 10.4 W/cm^2), LHP can start up very quickly, and the temperature of evaporator wall is less than 75 °C. With decrease of heat load, the LHP still operates stably. From the results, it can be observed that the flat-plate LHP can startup and run successfully without dryout, which means the LHP have a good startup characteristic. When the heat load is lower than 50 W, there are temperature oscillations with large amplitude at the evaporator inlet, this is because the flow rate of subcooled liquid is low, and vapor-liquid two-phase region exists in the evaporator inlet, its complexity leads to temperature oscillation.

4. Conclusion

The biporous wicks are successfully manufactured by mixture of nickel powder and pore former with two different ways: cold pressing sintering and loosen powder sintering method. There are some findings as follows:

(1) 700 °C is an appropriate temperature for sintering nickel powder.
(2) The wick made by cold pressing, sintered at 700 °C can meet the requirement of LHP in terms of radius, porosity, permeability and strength.
(3) The biporous wick can allow LHP system run stably and reliably.
(4) The LHP with biporous wick can dissipate heat load effectively and stably.

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