Frontiers in Heat and Mass Transfer (FHMT), 18, 24 (2022)
DOI: 10.5098/hmt.18.24

Global Digital Central
ISSN: 2151-8629

Frontiers in Heat and Mass Transfer

Available at www.ThermalFluidsCentral.org

RESEARCH PROGRESS AND PROSPECT OF HEAT PIPE CAPILLARY WICKS

Ningxiang Lu, Jinwang Li*, Yongkang Sun

College of Astronautics, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu Province, 211106, China

ABSTRACT

Heat pipe is a kind of high-efficiency heat transfer element which depends on the phase change of its internal working liquid. It has the characteristics of high heat conductivity and excellent average temperature performance. As the core component of heat pipe, capillary wicks play the role of transmitting working fluid and have a crucial impact on the heat transfer performance of heat pipe. In this paper, the research progress of capillary wicks in recent years is introduced from the aspects of structure, fabrication method, performance research, numerical analysis and so on. The current research results of capillary wicks are summarized, and the future research direction of capillary wicks is proposed. The preparation and performance of new capillary wicks, the improvement of its practical effect in heat pipe and the more accurate numerical simulation of capillary wicks are the important research directions in the future.

Keywords: *capillary wicks; heat pipe; preparation method; performance research; numerical analysis.*

1. INTRODUCTION

Heat pipe is a kind of high thermal conductivity heat transfer element which combines boiling and condensation. It can transfer heat from one place which is not easy to heat transfer to another which can effectively dissipate heat by using the phase change conversion of liquid evaporation and condensation, and no external power is needed in the whole process. Traditional heat pipe is a cylindrical vessel, which is composed of shell, capillary wicks and end cover. The container is pumped into negative pressure and filled with appropriate amount of working liquid, the capillary wicks close to the inner wall of the tube are filled with liquid and then sealed. One end of the heat pipe is the evaporation section, and the other end is the condensation section. The insulation section can be arranged in the middle of the two sections as required. When the evaporation section is heated, the working liquid in the capillary wicks absorbs the heat and evaporates into gas. The vapor pressure in the evaporation section is higher than the equilibrium gas pressure in the condensing section. The vapor flows rapidly to the condensation section. The gas condenses into liquid on the gas-liquid interface in the condensation section and releases a large amount of heat. The liquid flows back to the evaporation section along the porous material in the inner wall by capillary force, so that the high-efficiency heat transfer can be realized.

In the decades of rapid development of heat pipe, the demand of various working conditions has promoted the in-depth study on the principle of heat pipe and the design and development of new structures. Different types of heat pipes, such as siphon heat pipe, reciprocating heat pipe and pulsating heat pipe, have been derived to meet the needs of different occasions. Heat pipe is now widely used in aerospace, agriculture, industry, electronics and many other industries. Small heat pipe is widely used in heat dissipation of electronic components (Chen et al., 2016). Diallo et al. (2018) studied a solar loop heat pipe, which provided optimization ideas for space heating and domestic hot water generation. Lee et al. (2020) designed and tested a cryogenic loop heat pipe (CLHP) to transfer heat over a certain distance by the capillary forces generated from porous wicks without a mechanical power source, which can efficiently cool infrared detectors in a zero-gravity environment and in limited spaces. Loop heat pipe has made some technical achievements and successful applications in many fields with great demand for efficient heat transfer and reliable control, such as electronic equipment cooling, heat dissipation and heat management (Filippeschi, 2011; Pastukhov et al., 2003), solar energy (Basha et al., 2014; He et al., 2014), waste heat utilization (Pastukhov and Maydanik, 2013; Zaghdoudi et al., 2013). The shape of flat heat pipe is very conducive to the heat diffusion of centralized heat source. It is often used in electronic equipment to dissipate heat and reduce heat flux (Zaghdoudi et al., 2013; Chaudhry et al., 2012; Singh et al., 2021).

Capillary wicks are the core component of heat pipe, which have vital impact on the heat transfer performance of heat pipe. Capillary wicks provide working fluid circulation power, liquid evaporation interface and realize liquid supply. High performance capillary wicks are the guarantee of high performance of heat pipe evaporator. Capillary wicks have three main functions: 1) providing a channel for the liquid at the condensation end to return to the evaporation end; 2) providing a channel for heat conduction between the inner wall and the liquid (steam); 3) providing the pores necessary for the capillary pressure of liquid gas. High performance capillary wicks should have the following characteristics: 1) good heat conduction effect, i.e. small radial thermal resistance; 2) low pressure loss of reflux liquid and high permeability; 3) large enough capillary suction pressure or small effective pore diameter; 4) good process repeatability and reliability, simple manufacture and low price. The performance of capillary wicks generally depends on its material, manufacturing technology and technical level. Most of the existing research is to improve the comprehensive performance of capillary wicks by changing the manufacturing process and internal structure, etc.

This paper introduces the research status of capillary wicks, such as manufacturing method, structure, performance research and numerical calculation, summarizes the current application situation and prospects the future research direction.

* *Corresponding author. Email:* ljw@nuaa.edu.cn

2. THE STRUCTURE OF CAPILLARY WICKS

According to the complexity of porous structure, wicks in heat pipe can be divided into single structure capillary wicks and composite structure capillary wicks. The single structure capillary wicks are simple to manufacture and low in cost which mainly include main channel capillary wicks, mesh capillary wicks, metal sintered capillary wicks, etc. Composite capillary wicks are formed by the combination of two or more single capillary wicks, which usually have different pore sizes on the same surface. Small pore size is used to improve capillary pressure, and large pore diameter is used to provide high permeability. Compared with single structure capillary wicks, composite capillary wicks can meet more complex performance requirements, and can be used to balance a variety of requirements in different working conditions. Common composite capillary wicks include wire mesh and micro groove composite capillary wicks, channel and powder sintered capillary wicks, porous composite capillary wicks and so on.

2.1 Single structure capillary wicks

① Wire mesh capillary wick

The wire mesh capillary wick is the most common and commonly used one of the single structure capillary wicks. It is made of a variety of metal wires braided into a mesh or rolled by the formed wire mesh. The layers are interlaced with each other. The advantages of this structure are simple structure, simple manufacturing method, lower cost, thinner thickness and higher flexibility compared with other structures, but the disadvantage is that the flow resistance of liquid working fluid is greatly affected by the tightness of wire mesh, and the gap between layers will increase the thermal resistance, which will affect the heat transfer performance of heat pipe.

In order to solve the problem of the influence of the gap between the layers of the wire mesh capillary wick on the thermal resistance of heat pipe, there are two kinds of optimization methods at present: ① Adopting the high-precision diffusion welding technology without relative movement to prepare capillary wicks, which has the advantages of high welding accuracy and small solder joint, and its disadvantages are that the welding surface and welding technology are required high and the production efficiency is low due to the complexity of the technology; ② For the multi-layer capillary structure in the same heat pipe, selecting mesh capillary structure with different mesh size for each layer. The mesh structure with larger mesh is adopted for the working fluid flow interface to reduce the flow resistance, and the smaller grid is used for the reflux part to increase the capillary pressure, which is beneficial to the reflux. That is, a double gradient is set inside the capillary wick to realize the bidirectional demand of suction and reflux and reduce the heat resistance of heat pipe at the same time. Su et al. (2008) established a set of capillary pump loop heat pipe and its performance test system, and tested three different kinds of wire mesh capillary wicks. The results show that the composite wire mesh capillary wicks can improve the permeability of capillary wicks without reducing the capillary force, so as to improve the performance of heat pipe.

For the research of wire mesh capillary wick, Chi et al. (2007) designed a micro capillary pump loop thermal control system, which adopts wire mesh laminated structure to ensure the unidirectional flow of working medium without external mechanical control. Aoki et al. (2012) flattened the cylindrical heat pipe with outer diameter of 6mm by flattening forming process, and obtained two kinds of copper wire mesh sintered capillary wick ultra-thin heat pipes with flattening thickness of 1mm and 0.7mm respectively. Their heat transfer performance and heat transfer limit were studied. Ma et al. (1980) tested the mesh capillary wick and detected the capillary force and permeability of different mesh wicks. Hu et al. (1999) conducted an experimental study on the heat transfer performance of flat plate heat pipe. The results show that in the boiling heat transfer process of evaporation section, the temperature fluctuation of metal mesh capillary wick surface is greater than that of smooth wall, and the temperature fluctuation of single-layer mesh is greater than that of multi-layer mesh.

② Channel capillary wick

The working principle of channel capillary wick is to use the effect of channel interface tension to make the liquid working medium return, so as to realize the function of capillary wick. There are two types of grooved capillary wicks: axial grooves and circumferential grooves, each has a variety of different cross-section shapes. The main advantage of this processing method is that the liquid in the groove is heated from the two sides and the bottom three directions, which improves the heat transfer efficiency and effectively reduces the thermal resistance of the heat pipe. Because of the clear geometrical appearance of the wick structure, it is more suitable for micro flow, micro phase change and micro scale heat transfer process.

The experimental method is usually used in the application research of channel capillary wick, and further theoretical and data support is often needed in the follow-up. Lataoui et al. (2010) measured the inclination angles and the limiting heat flux of axial grooved heat pipes by means of experiments. Fang et al. (2008), Li et al. (2008b) and Holley and Faghri (2005) separately studied the heat transfer performance of channel capillary wick heat pipe and the influence of the length and number of channels on heat transfer performance of heat pipe.

For the theoretical analysis of slotted wicks, there are three main research methods: empirical formula method, numerical analysis method and the combination of the two methods. The empirical formula method has small calculation amount and is suitable for engineering application, but it needs a lot of data support. The numerical analysis method can involve the detailed characteristics of the inner channel, and the calculation is more accurate. Chen et al. (2006) measured the heat transfer limit of Ω-shaped channel heat pipes by combining theory with experiment, and developed a calculation model suitable for Ω-shaped channel. Zhang et al. (2008) used empirical formula and numerical method to study the curvature radius and flow velocity of the Ω-shaped channel capillary wicks, calculated the heat transfer limit, and studied the geometric mechanism and thermal resistance of the Ω-shaped channel capillary wicks to improve the capillary heat transfer performance of the heat pipe. Kaya and Garcia (2007) investigated the effects of contact point, contact angle and interfacial shear stress on the channel capillary wicks by combining numerical analysis and empirical formula, and calculated the heat transfer limit of grooved heat pipe, which was verified by experiments. Suman (2008) used empirical formula and model to analyze the curvature radius, pressure loss and capillary pressure difference of grooved capillary wicks, and put forward a method to optimize the channel form of heat pipe.

③ Sintered capillary wick

Sintered metal capillary wicks mainly include metal powder sintered capillary wick and metal fiber sintered capillary wick. They mainly use solid-state sintering technology to sinter metal powder particles or metal fibers in vacuum or protective atmosphere at a certain sintering temperature and time, which is not easy to fall off and has porous structure.

This method is simple, and is one of the most commonly used manufacturing methods of capillary wicks. This kind of capillary wick has a high capillary suction force. Because of its good contact with the wall and small thermal resistance, it greatly reduces the radial thermal resistance and overcomes the disadvantage of poor repeatability of wire mesh capillary wick process. However, due to the high sintering density and poor permeability, the axial heat transfer capacity is still smaller than that of axial grooved tube wicks. In order to improve the poor permeability and high density of sintered capillary wicks, it is often used to add a certain proportion of pore forming agent in solid-state sintering to ensure a certain porosity. However, there are still some defects in the precision control of size, pore size and porosity, which need to be solved.

At present, the research on sintered capillary wick is mainly aimed at improving its capillary performance and optimizing its size and structure, which has the disadvantages of high compactness and low accuracy. In order to improve the pumping characteristics of loop heat pipe capillary wicks, Wang et al. (2016) and He et al. (2018) separately sintered copper based multi hollow capillary wicks materials with high porosity by using Na_2CO_3 and NaCl as pore forming agent. The optimal

Frontiers in Heat and Mass Transfer (FHMT), 18, 24 (2022)
DOI: 10.5098/hmt.18.24 Global Digital Central
ISSN: 2151-8629

matching relationship between pore forming agent and particle diameter was derived, and the experimental correlation between corresponding proportions was deduced. The research results show that the permeability and suction properties of the capillary wick are not only determined by the porosity, but also by the pore structure of the material. The capillary wick with higher porosity, smaller average equivalent pore size and more concentrated pore size distribution has better capillary suction performance. Wang (2014) prepared a new type of sintered porous capillary wick for loop heat pipe with high aspect ratio and internal thread structure by powder metallurgy method using carbonyl nickel powder as raw material. The effects of sintering temperature, sintering time and charge density on the porosity, shrinkage, pore size distribution, micro morphology, permeability and capillary pressure of the wick were studied. The internal thread structure and processing technology of the outer surface of the porous capillary wick were optimized. Ling et al. (2018) prepared porous copper fiber sintered wicks with uniform and gradient porosity by low-temperature solid-state sintering, and studied the effects of fiber morphology, working solution, porosity and their distribution on the pumping performance of porous copper fiber sintered capillary wicks. Deng et al. (2013) tested the capillary properties of four kinds of sintered capillary wicks by infrared thermal imaging method. The results show that the permeability and capillary properties of copper powder sintered capillary wicks are better than those of nickel powder sintered capillary wicks. Fig. 1 shows the scanning electron microscope images of sintered copper wicks: (a) spherical copper; and (b) irregular copper.

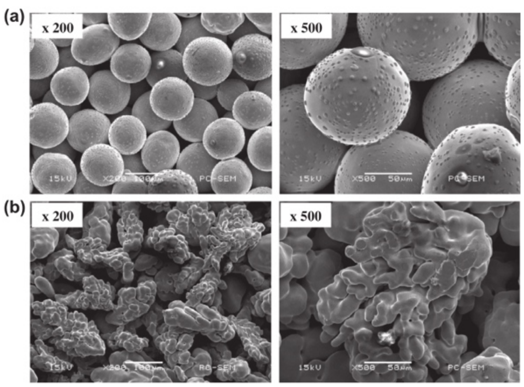


Fig. 1 SEM images of sintered copper wicks: (a) spherical copper; and (b) irregular copper (Deng et al., 2013)

2.2 Composite structure capillary wicks

The actual working conditions often require the capillary pressure and permeability to meet the process requirements at the same time, and there are also more precise requirements for the size and structure of the capillary wicks, but it is difficult for a single structure capillary wick to meet two or more requirements at the same time. The composite structure capillary wick combines two or more single structure capillary wicks, and has the advantages of multiple single structure capillary wicks. Making full use of their advantages can better meet the needs of production, which is an important direction of capillary wick development. Common composite capillary wicks include wire mesh and micro groove composite capillary wick, channel and powder sintered capillary wick, porous composite capillary wick and so on.

① Wire mesh and micro groove composite capillary wicks

The combination of wire mesh and channel capillary wick can reduce the thermal resistance and improve the heat transfer performance of capillary wick. Hwang et al. (2007) machined some grooves on the common sintered wick, and analyzed and studied them. It was found that the porous groove wick can increase the surface area of working fluid evaporation and the channel for working fluid reflux. The shape of groove and the size of internal gas channel greatly affect the heat transfer performance of heat pipe. Kaya (2009) designed a single trunk heat pipe with composite structure of micro groove and wire mesh, as shown in Fig. 2. Kaya discussed the effects of the generation of bubbles in the evaporation section and the collapse of bubbles in the condensation section on the performance of the heat pipe in a single trunk heat pipe, and found that the main heat pipe can start up faster when there is an exhaust hole in the main heat pipe.

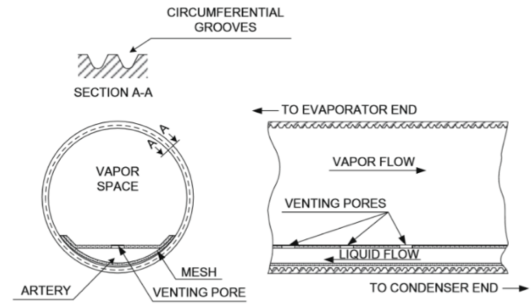


Fig. 2 Capillary wick with composite structure of micro groove and wire mesh (Kaya, 2009)

② Wire mesh and powder sintered composite capillary wicks

The combination of wire mesh and powder sintered capillary wicks can overcome the disadvantages of high thermal resistance and low capillary force in wire mesh capillary wicks, and the disadvantages of low permeability and high density in powder sintered capillary wicks in the meantime. Huang and Franchi (2007) sintered fine copper powder and nickel powder on the copper wire mesh to produce composite sintered wick. By observing the microstructure, it was found that the large pores of the wire mesh remained open after sintering. The effective thermal conductivity and maximum heat transfer of the heat pipe were optimized by changing the powder pore size distribution. As shown in Fig.3 is the microstructure of Cu (mesh)-Ni (powder) bi-modal structure in which the large pore size comes from the pores of the mesh itself. Franchi and Huang (2008) sintered the medium powder on the copper wire net, combining the large capillary pressure of the tiny pores of the powder with the advantages of the low flow resistance of the large pores in the copper wire mesh. The test results show that the composite wick heat pipe has better heat transfer performance. Increasing the number of wire mesh can improve the heat transfer limit of heat pipe.

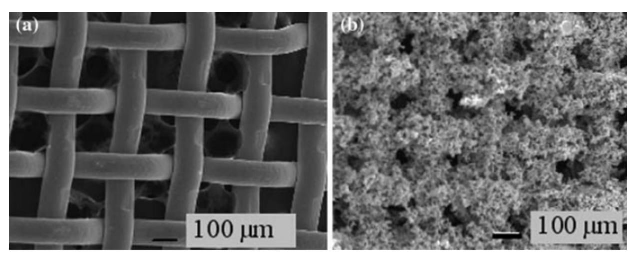


Fig. 3 Microstructure of Cu(mesh)-Ni (powder) bi-modal structure (Huang and Franchi, 2007)

③ Channel and powder sintered composite capillary wicks

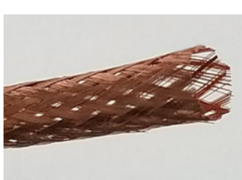
Channel and powder sintered composite capillary wicks combine the channel technology and sintering technology. Metal sintering provides the capillary force required for working fluid flow, and channel provides the reflux force required for liquid reflux. Lee and Byon (2018) made a plate heat pipe with a thickness of 1mm, in which a layer of copper channel with hydrophilic treatment was sintered, and three layers of coarse copper mesh were placed on it, which effectively increased the heat transfer efficiency. Zhu et al. (2019) designed and fabricated an ultra-thin flat heat pipe with a total thickness of 0.85mm. The capillary wick adopts sintered porous channel structure, realizing the combination of channel and porous structure. Compared with the single channel structure, the dual channel structure has lower thermal resistance, and the minimum difference between them is 21%. Tang et al. (2013) compared the heat transfer performance of sintered copper powder channel composite capillary structure and uniform porous capillary structure, analyzed the influence of channel width and depth on heat transfer performance of heat pipe, and found that when the groove depth was 0.85mm and width was 0.45mm, the composite wick could obtain the maximum capillary force.

④ Multi pore size composite capillary wick

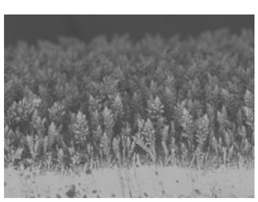
The structure of multi pore size composite capillary wick is characterized by holes with different pore sizes. Large pores can reduce the resistance of capillary wicks when working fluid flows, and small pores can increase the flow pressure of liquid reflux to help reflux. The general method is to combine the multi aperture wire mesh and add different proportion of pore forming agent during sintering powder. Lin et al. (2012) and Wu et al. (2013) put forward the concept of composite capillary wicks and carried out a series of studies on the pore size of capillary wicks. It is found that the pumping capacity of the composite capillary wick mainly depends on the pore characteristics of the capillary wick on the liquid side, and a specific scheme to improve the suction performance of the composite capillary wick by changing the pore size of each part of the capillary wick is proposed. Semenic and Catton (2009) prepared a double pore wick structure, which was composed of a large number of fine particles. There were some small pores between copper particles and large pores between clusters. Two kinds of pores with different sizes and independent each other provided the gas/ liquid phase exchange channel of composite pore capillary wick, and had high capillary pressure and low steam escape resistance. Liu et al. (2019b) carried out an experimental study on the evaporation characteristics of composite capillary wicks with gradually changing pore size, and studied the capillary wicks with increasing and decreasing pore size. Li et al. (2008a) and Su et al. (2008) respectively tested and studied the composite aperture capillary wick loop heat pipe, and found that compared with the single aperture loop heat pipe, the composite pipe diameter effectively reduces the system thermal resistance, improves the start-up speed, and has better performance. Lu et al. (2022) used fiber felt as the main material to prepare gradient pore capillary wick, and carried out capillary pumping performance experiments and evaporation-capillary pumping performance experiments, summarized the distribution characteristics of gradient pore composite capillary wick with the best pumping performance. Table 1 shows the preparation methods, pore size characteristics and experimental results of various porous composite capillary wicks.

2.3 New capillary wicks

The continuous improvement of the demand for the performance of the heat pipe promotes the development and optimization of the capillary wick. New types of capillary wicks that have emerged at present (As shown in Fig. 4), include: hybrid spiral woven mesh wick structure (Zhou et al., 2019b; Zhou et al., 2020): wire mesh is woven from copper wires of different diameters per share; bionic structure capillary wick: bionic tree structure (Wang et al., 2014c), bionic wood structure (Gan et al., 2020), biomimetic forest structure (Luo et al., 2021), biomimetic hydrophilic plant surface structure (Li et al., 2017a), etc., which can often be obtained through secondary sintering, ionization, etc.; 3D printing capillary wicks (Xie et al., 2018; Chen et al., 2019), etc. These new capillary wicks are often made of new materials or new preparation methods, which are continuously improved with the development of manufacturing processes and new materials, and often cross-development with materials and biology and many other fields.



(a) hybrid spiral woven mesh wick structure (Zhou et al., 2019b)



(b) biomimetic forest structure (Luo et al., 2021)

Fig. 4 Morphology of some new capillary wicks

3. PREPARATION METHOD OF CAPILLARY WICKS

Preparation technology is also one of the key factors restricting the comprehensive ability of capillary wicks. Different preparation methods usually have different characteristics and are suitable for different applications. According to the principle, different preparation methods of capillary wicks can be divided into the following categories:

3.1 Chemical etching

The electrochemical corrosion method uses the principle of intergranular and pitting corrosion in the electrolyte to etch the surface of stainless steel with multi void layers. The results show that the pore size of the porous layer obtained by this method is small and the pore distribution is not uniform, and the effect is not obvious in the medium with large surface tension. Moreover, due to intergranular corrosion, the micropores are blocked or covered, resulting in the decrease of the bulk strength of the material and the shortening of its service life. In addition, this method has the problem of complex processing technology, long processing cycle, high cost and energy consumption.

3.2 Spraying method

The spraying method uses a special flame spraying gun to spray metal powder with different particle size (such as aluminum powder, etc.) and organic polymer material powder or low melting point metal powder used as auxiliary pore forming agent onto the outer surface substrate of the treated and preheated metal pipe at high speed. Then, the surplus organic polymer material powder is burned off by flame to obtain the metal porous coating.

Metal powder capillary wicks is prepared by this method. The surface of carbon steel, copper, stainless steel, aluminum and its alloy tubes can be covered with porous metal layers such as aluminum, copper, stainless steel and so on. Compared with the powder sintering method, the cost of flame spraying process is lower, but this method can not produce metal porous layer on the inner surface of the pipe, and it is difficult to ensure the thickness and porosity of the powder sintered layer.Liu et al. (2019a) used two methods to modify the surface of carbon fiber, namely——electroless copper plating method (forming uniform copper coating on carbon fiber surface) and flame spraying metal powder method (forming metal coating on carbon fiber surface). Using high-speed camera, electronic scanning microscope and other characterization equipment, the surface morphology, hydrophilicity and capillary pumping force after treatment were compared. The results showed that the porous structure of the modified carbon fiber was not damaged, and the hydrophilic ability was improved obviously.

3.3 Machining method

Machining surface porous pipe is to use the method of mechanical processing to make holes of different shapes on the metal pipe wall.The general method of machining is to directly process fins, small holes and tunnels of various shapes on the outer surface of metal tubes (generally copper and other easily processed metals) with specially designed cutters on special machine tools, or draw V-shaped axial grooves on the inner surface of metal tubes. It can also be used to directly process various surface patterns such as low thread fin and low fin fin on the outer surface of metal tube by rolling. Although this method can produce a large number of porous tubes, it can not process very small pores, so the improvement of heat transfer performance is limited.

Tao et al. (2011) designed the structure of capillary wick at evaporation end and condensation end of hot column, and formed wick of hot column by plough extrusion processing method, analyzed the forming characteristics, conditions and forming mechanism of hot column wick by plough extrusion. The results show that the depth of plough extrusion plays a decisive role in the surface morphology of wick. The larger the plough extrusion depth is, the better the surface morphology is; only within a certain range of groove spacing can excellent surface morphology be formed. Tang et al. (2011) prepared a new type of aluminum grooved wick structure by ploughing extrusion and surface chemical processing. The capillary properties of the wick were characterized by capillary rise infrared spectroscopy. The effects

DOI: 10.5098/hmt.18.24

ISSN: 2151-8629

of different concentrations of $CuCl_2$ solution and soaking time on the capillary properties of wick structure were studied.

Table 1 Preparation methods, pore size characteristics and experimental results of capillary wicks

Types of capillary wicks	Preparation method	Pore size characteristics	Conclusion	Reference
Make two-layer capillary wicks with different thickness ratio from copper powder with different particle size	The metal powder was sintered and the secondary capillary wick was prepared by twice sinter method.	The main capillary wick and secondary capillary wick of each sample have the same particle size and different thickness.	There is a better thickness ratio of double-layer capillary wick, large particle size: small particle size = 3:2; the double-layer capillary wick can effectively reduce the start-up power of heat pipe.	Hu et al., 2020
Mix copper powder with anhydrous $CaCl_2$ in different proportions	The powder is molded first and then fired.	The capillary wick sample presents a double pore structure, in which the macropore is the preformed pore formed after the removal of pore forming agent $CaCl_2$. The small hole is a gap pore formed by the gap space between copper particles.	The porosity and permeability decrease with the increase of sintering temperature and increase with the content of pore forming agent. The suction quality of capillary wick is positively correlated with the content of pore forming agent and negatively correlated with sintering temperature.	Sun et al., 2019
Spherical (made by water mist method) and tree (made by electrolysis method) powders were used to prepare composite capillary wicks	The mixed powder is pressed with low pressure first, then put into graphite barrel and sintered at high temperature.	Nine samples with different powder ratio (spherical, tree shaped), different material selection (copper powder, nickel powder, stainless steel powder), different proportion and size of pore forming agent were selected for comparison.	The order of influence on the porosity of capillary wicks and influence on the effective thermal conductivity of capillary wicks is: material selection > proportion of pore forming agent > size of pore forming agent > proportion of powder.	Wang, 2019
Two kinds of nickel powders, T255 and T123, were selected to prepare capillary wicks with pore size varying from large to small and from small to large.	Integrated sintering technology of capillary wicks and substrate	Two kinds of composite capillary wicks were prepared along the working fluid flow direction, which were gradually changed from large diameter to small diameter and from small diameter to large diameter. The porosity was controlled at about 47%, and other factors were the same.	Compared with the capillary wick with increasing pore size along the flow direction, the capillary wick with decreasing pore size has smaller heat leakage to the compensator, and the capillary wick with decreasing pore size has higher liquid suction and supply capacity, showing relatively higher heat transfer coefficient and lower substrate temperature.	Liu et al., 2019b
The nickel powder with different particle size was put into the mould in turn to form gradient, and then sintered .	Pressure sintering of metal powder	From large aperture to small aperture, from small aperture to large aperture, from mixed aperture to large aperture and from mixed aperture to small aperture	The capillary wick with decreasing pore diameter along the moving direction of working fluid is more conducive to improving the performance of loop heat pipe under high load; the capillary wick with increasing pore size along the working fluid flow direction has no optimization effect.	Zhang, 2018
Three layer capillary wick. The main capillary wick is grooved, the secondary capillary wick and the third capillary wick are flat. The thickness is 2 mm.	The main capillary wick is sintered on the wall of evaporation, the secondary capillary wick is made of secondary sintering and the third layer is attached with them.	The porosity of the main capillary wick branched copper powder is 47%, and that of the secondary capillary wick spherical copper powder is 53%. The third layer is attached with super absorbent heat insulation cotton.	The primary capillary wick is used to provide phase transition region and enhance heat transfer; the secondary capillary wick is used to prevent the vapor from diffusing into the compensation chamber and provide additional capillary power; the third capillary wick is used for heat resistance. They are organically integrated.	Wang et al., 2015
Two-layer composite capillary wicks with controllable pore characteristics were prepared by pore forming agents with different particle sizes. T255 type high-purity nickel powder was used as raw material, NaCl as pore forming agent.	The mixed powder with the same quality and different layers is put into the metal mold for cold pressing. After that, it was sintered in a high temperature argon protection sintering furnace	To control the pore size difference of the inner and outer layers by controlling the mesh number and percentage of pore forming agent and the same raw material of nickel powder	The overall capillary suction performance of the composite capillary wicks mainly depends on the pore characteristics of the inner capillary wick, and the small pore size distribution in the inner layer can improve the overall capillary suction performance of the composite capillary wicks.	Xu et al., 2012
Preparation of double-layer capillary wick with two kinds of metal powder	Be made of pressed and sintered metal powder	The outer capillary wick is sintered with carbonyl nickel powder with high thermal conductivity and small particle size, with a thickness of 2mm; the inner layer is made of stainless steel powder with low thermal conductivity and large particle size, with a thickness of 3mm	The heat transfer power density of the heat pipe is increased and the thermal resistance is obviously reduced. When starting at low power, the temperature fluctuation of heat pipe is intensified.	Li et al., 2008
Using foam metal copper or nickel as skeleton, fill it with a tree shaped copper or nickel powder.	The tree shaped metal powder and spherical pore forming agent were first mixed in a certain proportion, then filled into foam metal and sintered.	The sample 1 and 2 are filled with same tree shaped nickel powder; sample 3 and 4 are mixed with different proportions of powder; sample 5 and 6 are filled with same tree shaped copper powder.	The composite of metal is beneficial to reduce heat leakage. Loose sintering is the best match with this metal powder combination. On the whole, when the ratio of tree shaped powder and pore forming agent is 1:1, the performance of the composite capillary wick is the best.	Wang et al., 2020

DOI: 10.5098/hmt.18.24 ISSN: 2151-8629

3.4 Powder metallurgy

There are three main types of powder metallurgy capillary wicks: (1) pressure forming, that is, powder particles move, rearrange and plastic deformation under certain pressure, such as cold pressing, isostatic pressing, rolling and extrusion; 2) no pressure forming method, that is, powder is formed by loosening or pouring (Samanta et al., 2011). When the binder is contained in the blank, the strength is higher. The main methods are powder sintering, slurry casting and sol-gel method; 3) Special forming methods, such as injection molding, centrifugal deposition molding and laser rapid prototyping, etc. The steps and classification of powder metallurgy are shown in Fig. 5.

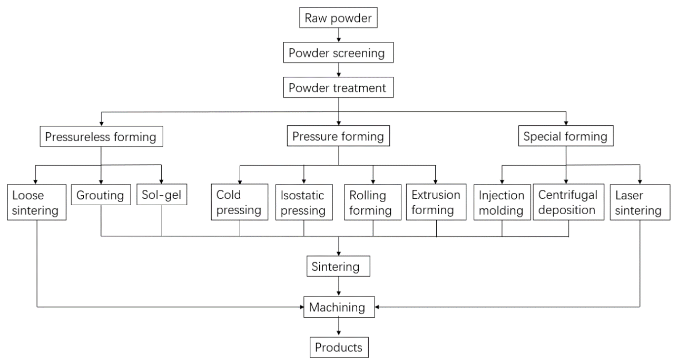


Fig. 5 Forming process of metal powder capillary wick

In the actual preparation process of powder sintered capillary wick, the common methods are surface sintering and pressing and sintering.

The surface sintering process is to put the metal tube in the ultrasonic instrument containing acid washing solution to remove oil and rust. After air drying, the surface of the metal tube is coated with appropriate amount of binder, and the liquid film is kept uniform under the action of centrifugal force.Then spray the powder on the glued surface. After the powder is firmly bonded, spray it again with the spray gun, so that the powder on the surface of the porous pipe can evenly cover the metal tube substrate, and then coat with metal powder of certain particle size. The metal powder is heated in the sintering furnace filled with protective gas, and the metal powder is sintered onto the pipe. In order to improve the microstructure and bonding properties of the thermal sprayed coating, Fan et al. (2002) sprayed the Ni-Al mixed powder on the surface of A3 steel substrate without reaction, and the coating samples with good bonding properties were prepared by reaction sintering at medium temperature. The changes of microstructure and phase structure of the coating before and after sintering were studied. The layer structure of the coating disappeared after sintering.

The process of sintering after pressing is to pack carbonyl nickel powder or ultra-fine stainless steel powder into a special shaped rubber sheath and perform static pressure forming under pressure. The formed compacts are sintered for 1-2h in protective atmosphere or vacuum after mechanical processing, and then the sintered porous capillary wick is cooled in liquid nitrogen. After heating the stainless steel tube shell with rectangular groove, the cooled porous capillary wick is quickly taken out from liquid nitrogen and quickly put into the heated expanded stainless steel tube shell to make the evaporator, the core component of loop heat pipe. Wang et al. (2014b) prepared Ni porous capillary wick for heat pipe by powder metallurgy method with carbonyl nickel powder as raw material, and studied the influence of charge density, sintering temperature and sintering time on porosity, average pore diameter, micro morphology, permeability and capillary pressure of capillary wick. Mahulkar and Sedani (2019) studied three kinds of nickel powder with different shapes and reported the best nickel powder suitable for electronic cooling application. The preparation process of capillary wick structure was analyzed, and the parameters of capillary wick structure such as porosity, permeability, capillary pressure and permeability coefficient were analyzed. The results show that 287 type nickel carbonyl powder with particle size of 2.6-3.3mm has a good application prospect.

The capillary wicks prepared by powder metallurgy can make full use of the characteristics of powder metallurgy process, and accurately control the pore size and permeability of capillary wicks by controlling the particle size of raw materials, forming pressure and sintering process parameters.

4. STUDY ON PROPERTIES OF CAPILLARY WICKS

The performance parameters of capillary wicks mainly include porosity, effective pore size, pore size distribution, pore morphology, permeability, capillary pressure, effective thermal conductivity, etc. These parameters affect the suction and heat transfer performance of the wick. Capillary pressure and permeability are two important properties of porous capillary wicks, which are directly related to pore size and porosity. The smaller the pore size is, the greater the capillary pressure is, but the lower the permeability of the working fluid is, the greater the flow resistance of the working fluid is. The capillary wick plays two main roles in the heat pipe. One is to pump the working medium from the compensation chamber into the heater, which is the part where the pumping characteristics have an impact on the capillary wick; The second is to provide heat transfer medium for the evaporation of working medium in the evaporator, and its thermal conductivity affects the heat transfer and flow of working medium. In the experimental study, the structure parameters of the capillary wicks are generally set, and the manufacturing and sintering parameters of the capillary wick are optimized according to the preliminary set data. After sintering, the structural parameters of the capillary wick are accurately characterized and analyzed by the experimental method.

1) Porosity

The overall structure of the capillary wick is porous. The porosity of the capillary wick generally refers to the percentage of the volume of the pore diameter in the whole volume of the capillary wick, which is expressed by ε. In the performance test of the capillary wick, the porosity mostly refers to the open porosity. At present, there are many methods to measure porosity, such as Archimedes method, vacuum oil immersion method, mercury indentation method, etc. The formula is as follows:

$$\varepsilon = \frac{V_{\mathrm{P}}}{V_{\mathrm{T}}} \times 100\% \tag{1}$$

where V_{P} is pore volume, V_{T} is total volume of capillary wick.

The capillary wick with larger porosity can provide larger working fluid capacity in the working process of heat pipe, but at the same time, it also makes the capillary wick more loose, the structure is not compact, the strength is reduced, it is easy to form fault, and can not provide continuous and powerful suction force. Therefore, the appropriate porosity has a crucial impact on the performance of the capillary wick. Ling et al. (2016) prepared porous copper fiber sintered sheet with single hole and composite pore by low temperature solid-state sintering technology. Then, a new type of annular heat pipe was constructed with porous copper fiber sintered sheet as the wick structure. The results showed that the capillary suction height increased with the decrease of porosity from 90% to 60%. Compared with single porosity, the loop heat pipe with composite porosity fiber sintered sheet has lower evaporator wall temperature and thermal resistance.

2) Aperture

Pore size is the pore size in the capillary wick structure. The pore size of capillary wicks is one of the most important parameters to measure the performance of capillary wicks. The pore size directly determines the capillary suction capacity of capillary wicks and the maximum heat transfer capacity of loop heat pipe. Scanning electron microscopy (SEM) is commonly used to observe multiple areas of the same sample, and the micrographs of 500 times, 2000 times, 3000 times and 5000 times are measured respectively. The scanning images of different parts of a sample were statistically analyzed by nano measure software, and the average pore size and pore size distribution were finally obtained. It is one of the most commonly used methods at present. Another common measurement method is bubble method. Its principle is: when the pressure of capillary wicks gradually increases to a certain value through full infiltration, the gas can push the liquid away from the gap and bubble will emerge. The maximum pore diameter of capillary wicks can be obtained by measuring the pressure difference of the first bubble.

3) Effective thermal conductivity

The effective thermal conductivity of the capillary wick is determined by the material properties and pore structure of the wick. The heat in the heat pipe is not only absorbed by the working fluid and taken away by the saturated steam, but also leaked through the heat conduction of the capillary wick. If the effective thermal conductivity of the capillary wick is too large, the capillary wick is easy to overheat. For example, the sintered copper powder capillary wick has the problem of large heat leakage caused by the excessive effective thermal conductivity.

A large number of models predict the effective thermal conductivity by solid thermal conductivity λ_s, fluid thermal conductivity λ_f and porosity ε. Several common models of effective thermal conductivity are listed in Table 2. In addition, Semenic et al. (2008) and Chernysheva & Maydanik model (2009) further deepened the calculation of thermal conductivity according to the structure of capillary wick and predicted the effective thermal conductivity model of copper powder sintered double-aperture capillary wicks.

Table 2 Several common models of effective thermal conductivity

Model name	Concrete model	Remarks
Parallel model (Progelhof et al., 1976)	$\lambda_{\mathrm{eff}} = \varepsilon\lambda_{\mathrm{f}} + (1-\varepsilon)\lambda$	The solid wick material and pores transfer heat synchronously. Upper limit of effective thermal conductivity
Series model (Progelhof et al., 1976)	$\lambda_{\mathrm{eff}} = \dfrac{\lambda_{\mathrm{f}}\lambda_{\mathrm{s}}}{\varepsilon\lambda_{\mathrm{s}} + (1-\varepsilon)\lambda_{\mathrm{f}}}$	The solid wick material and pores transfer heat alternately. Lower limit of effective thermal conductivity
Zehner-Schlunder model (Hsu et al., 1994)	$\begin{cases} \lambda_{\mathrm{eff}} = \lambda_{\mathrm{f}} \left\{ \begin{aligned} & 1-(1-\varepsilon)^{\frac{1}{2}} + \frac{2\cdot(1-\varepsilon)^{\frac{1}{2}}}{1\text{-}\kappa\cdot B} \\ & \left[\frac{(1\text{-}\kappa)}{(1-\kappa\cdot B)^2}\ln(\frac{1}{\kappa\cdot B}) - \frac{B+1}{2} - \frac{B-1}{1\text{-}\kappa\cdot B} \right] \end{aligned} \right. \\ \kappa = \lambda_{\mathrm{f}} / \lambda_{\mathrm{s}} \\ B = 1.25(\frac{1-\varepsilon}{\varepsilon})^{\frac{10}{9}} \end{cases}$	Saturated porous media with spherical particles
Assad model (Assad, 1955)	$\lambda_{\mathrm{eff}} = \lambda_{\mathrm{s}}(\lambda_{\mathrm{f}} / \lambda_{\mathrm{s}})^{c\varepsilon}$	For loose solids, the constant C = 1
Chaudhary&Bhandari model (Chaudhary and Bhandari, 1969)	$\begin{cases} \lambda_{\mathrm{eff}} = (\lambda_{\mathrm{max}})^n(\lambda_{\mathrm{min}})^{1-n}, 0.42 < n < 0.51 \\ \lambda_{\mathrm{max}} = \varepsilon\cdot\lambda_{\mathrm{f}} + (1-\varepsilon)\lambda_{\mathrm{s}} \\ \lambda_{\mathrm{min}} = \dfrac{\lambda_{\mathrm{f}}\lambda_{\mathrm{s}}}{\varepsilon\lambda_{\mathrm{s}} + (1-\varepsilon)\lambda_{\mathrm{s}}} \end{cases}$	For sintered metal powder capillary wicks, the recommended value of n is 0.42
Krupiczka model (Krupiczka, 1967)	$\lambda_{\mathrm{eff}} = \lambda_{\mathrm{f}}(\lambda_{\mathrm{s}} / \lambda_{\mathrm{f}})^{\eta}$ $\eta = 0.280 - 0.757\lg\varepsilon - 0.057\lg(\lambda_{\mathrm{s}} / \lambda_{\mathrm{f}})$	
Dunn&Reay model (Dunn and Reay, 1982)	$\lambda_{\mathrm{eff}} = \lambda_{\mathrm{s}}\left[\dfrac{2+\kappa-2\varepsilon(1-\kappa)}{2+\kappa+\varepsilon(1-\kappa)}\right]$	The relevant parameters are as above
Maxwell model (Maxwell, 1904)	$\lambda_{\mathrm{eff}} = \lambda_{\mathrm{s}}\dfrac{2\lambda_{\mathrm{s}} + \lambda_{\mathrm{f}} - 2(\lambda_{\mathrm{s}} - \lambda_{\mathrm{f}})\varepsilon}{2\lambda_{\mathrm{s}} + \lambda_{\mathrm{f}} + (\lambda_{\mathrm{s}} - \lambda_{\mathrm{f}})\varepsilon}$ $\lambda_{\mathrm{eff}} = \lambda_{\mathrm{f}}\dfrac{2\lambda_{\mathrm{f}} + \lambda_{\mathrm{s}} - 2(\lambda_{\mathrm{f}} - \lambda_{\mathrm{s}})(1-\varepsilon)}{2\lambda_{\mathrm{f}} + \lambda_{\mathrm{s}} + (\lambda_{\mathrm{f}} - \lambda_{\mathrm{s}})(1-\varepsilon)}$	Liquid saturated porous media

There are two main methods to measure effective thermal conductivity: steady-state method and transient method. The steady-state method calculates the thermal conductivity through the stable temperature gradient and heat flux density in the sample. Generally, it takes a long time to establish a stable test state; the transient method uses electrical signals to measure thermal properties, which can obtain the thermal conductivity measurement results in a short time. Hansen et al. (2016) analyzed the heat transfer characteristics of vertical flat heat pipe with unilateral heat source in laboratory and theory, focusing on the performance of capillary wicks. The compressed nickel covered the evaporator surface, and potassium was used as the working fluid. The influence of heat points at different parts of the capillary wick was analyzed by two-dimensional numerical simulation method. Zhou et al. (2019a) reconstructed the porous structure of nickel powder sintered capillary wick by computer, and accurately calculated the effective thermal conductivity of the capillary wick when flowing through liquid ammonia by lattice Boltzmann method. Through comparative analysis with different empirical formulas of effective thermal conductivity, it was concluded that the effective thermal conductivity of capillary wick structure was not affected by pore size, but only related to porosity. Chen et al. (2019) respectively tested the effective thermal conductivity of three kinds of capillary wicks under different conditions, and summarized their laws. Chen et al. (2012) carried out the thermal performance experiment of the loop heat pipe with double hole nickel powder sintered capillary wick, and measured the total thermal resistance of the system under different heat loads. Wang et al. (2020) measured the effective thermal conductivity of the composite capillary wick by using the standard sample reference method. As shown in Fig. 6, after the system temperature is stable, the effective thermal conductivity of the composite capillary wick is calculated by using Fourier's one-dimensional steady-state heat conduction basic law.

4) Permeability

The permeability has a great influence on the distribution characteristics and heat transfer performance of the fluid, which is an important basis for the design and manufacturing process. For porous structure, the higher the permeability, the smaller the resistance in the process of fluid flow; the smaller the permeability, the greater the resistance of working fluid flowing through the capillary wick, and the

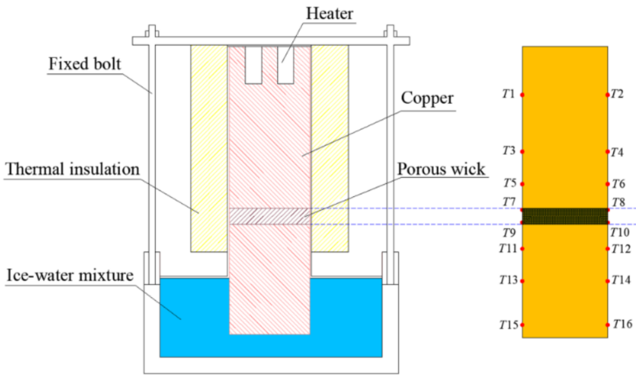


Fig. 6 Schematic diagram of effective thermal conductivity experiment (Wang et al., 2020)

greater the total pressure drop of the loop.

The common method is to calculate the permeability of capillary wick by Black-Kozeny empirical formula (Kaviany, 1995):

$$K = \frac{d_p^2 \varepsilon^3}{180(1-\varepsilon)^2} \tag{2}$$

Where K is the permeability, m^2; ε is the porosity, %; d_p is the average pore size of the sample, m.

The pumping performance of capillary wick is the performance of both capillary pumping and permeability in the capillary wick. Li et al. (2010a) developed a new experimental method for studying the capillary pumping performance of capillary wicks. Li et al. (2011) proposed a method for measuring the permeability of porous structure with low requirements for the strength and shape of the sample, and carried out experimental verification. The results show that the capillary suction performance experiment can be used to measure the permeability of porous structure. The different influencing factors of capillary suction process were tested by this method. (Li et al., 2021) Sun et al. (2019) used the device shown in Fig. 7 to conduct capillary suction performance test, and calculated permeability through empirical formula. Li et al. (2020) combined micro X-ray computed tomography with pore scale computational fluid dynamics simulation and developed a unique tool to capture the pore scale geometry of porous media and accurately predict the non isotropic permeability of porous media.

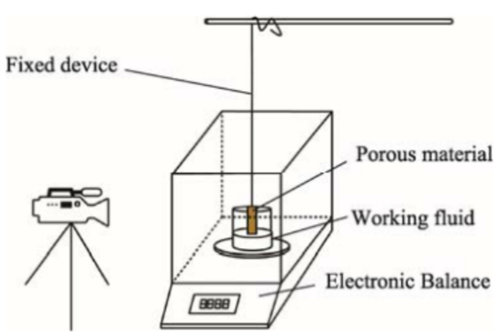


Fig. 7 Schematic diagram of capillary wick suction performance experimental device (Sun et al., 2019)

The performance of the capillary wick directly reflects the advantages and disadvantages of the capillary wick. At present, the research on the performance of the capillary wick mainly focuses on two directions. One is to study the influence of the preparation method, preparation parameters and preparation materials of the existing capillary wick on the performance of the capillary wick. For example, Song et al. (2017) studied the influence of different sintering parameters (sintering temperature, holding time etc.) on the properties of capillary wick with nickel as raw material. The results showed that with the extension of sintering temperature and sintering time, porosity, average pore diameter and permeability showed a downward trend. In addition, the most suitable sintering temperature and holding time were summarized. Wang et al. (2014) also studied the effect of sintering process on the properties of powder sintered capillary wicks using nickel as raw materials. Li et al. (2010b) studied the effects of molding pressure and different pore forming agents on the properties of capillary wicks by powder metallurgy. Li et al. (2013) studied the performance characteristics of fiber composite grooved capillary wick by comparing with copper powder composite grooved capillary wick. Li et al. (2021) carried out a comparative study of evaporation capillary suction experiments on capillary wicks with different working fluids. It was found that the suction rate of ethanol solution decreased with the increase of water content.

The second direction is to study whether the performance of the capillary wick is really optimized after improving structure and preparation of capillary wicks. For example, Xu et al. (2012) optimized the pore size of the capillary wick, prepared the double-layer composite structure capillary wick with different particle size pore forming agents, and studied its performance to obtain a reasonable pore size distribution. Using ethanol as working fluid, Tang et al. (2010) carried out meniscus rising experiments on a new type of powder sintered and micro groove composite capillary wick, and studied the capillary force of the capillary wick structure. The results show that the composite capillary wick greatly improves the capillary pumping force. In order to make capillary wicks in the heat pipe have the characteristics of high capillary pumping force, low flow resistance and enhanced heat transfer, Bai et al. (2011) developed a combined heat pipe capillary wick with triangular groove and metal fiber felt. Theoretical analysis, numerical simulation and experimental research were carried out on the capillary wick with this structure from the aspects of capillary pumping force, flow resistance and heat transfer characteristics Compared with the capillary wick with triangular groove, the capillary suction force is greatly improved. Wang and Ding (2020) coated the wire mesh core and the inner wall of the heat pipe container with a nano silicon dioxide layer to improve the heat transfer performance of the heat pipe. After coating the screen, the thermal resistance decreases by 47% on average. The nanoparticle layer on the wall acts as a very thin core. The coating of nanoparticles on the surface of the screen can improve the heat transfer performance of the heat pipe, and the coating on the inner surface of the container can reduce the size of the heat pipe.

5. NUMERICAL CALCULATION OF CAPILLARY WICKS

For the study of capillary wicks, the commonly used method is experimental analysis. But with the further promotion of the scope of use of heat pipe and the gradual development of software technology, people began to use numerical simulation for the operation analysis of heat pipe and its internal structure. This method is often used to study the mechanism of high temperature heat pipe. It is because the mechanism of fluid flow and heat transfer in high temperature liquid metal heat pipe is very complex, including heat conduction of tube wall, flow of liquid working fluid in capillary wicks, phase change of working fluid at gas-liquid interface and steam flow in cavity. Numerical simulation plays an important role in the study of flow and heat transfer mechanism in capillary wicks. In order to ensure the efficient and reliable operation of heat pipes, many scholars have made detailed theoretical analysis on the flow and heat transfer characteristics of capillary wicks in recent years. At present, the research methods of flow and phase change heat transfer in porous media are mainly the traditional CFD methods, such as finite element method, finite difference method, finite volume method and boundary element method. These methods treat the fluid medium as continuous medium from the macroscopic point of view. Some scholars use commercial software such as FloEFD based on traditional CFD method to study the numerical simulation of capillary wicks.For the first time, Yang and Przekwas (1998) used CFD software to simulate the capillary flow in microchannels. The CSF model (continuous surface tension model) was used to calculate the capillary force, and the VOF model (volume function of fluid) was used to track the gas-liquid interface, the calculated results are in good agreement with the theory.

In recent years, the research on numerical simulation of porous structure has been further advanced. Huang et al. (2004) put forward a new development direction for numerical simulation of flow and heat transfer in porous wick of CPL evaporator. Adding numerical calculation of unsaturated model in calculation is of great significance for real simulation of flow and heat transfer in porous core of evaporator. Zhang et al. (2019b) established a complete three-dimensional mathematical model of evaporator, focusing on the influence of structural parameters of capillary wick channel on heat transfer and flow under low load, and discussed the flow field and temperature field of capillary wick and the structure optimization of evaporator. Yu et al. (2018) simulated and studied the phase transformation process of metal sodium liquid in porous media with capillary wick of high temperature heat pipe. The porous medium model, fluid volume fraction model, continuous surface force model, mass transfer model and local heat balance theory were used to conduct numerical analysis on this process. The results showed that the higher the porosity and permeability, the higher the heat transfer efficiency, but the higher the probability of boiling heat transfer limit. Ge et al. (2017) introduced the model and calculation method of transient analysis program for high temperature liquid metal heat pipe, and carried out numerical simulation, obtained various parameters of tube wall and wick, and revealed the mass and heat transfer mechanism during the start-up process of high-temperature liquid metal heat pipe. Chen et al. (2019) took 3D printing titanium alloy capillary wick as an example, established a two-dimensional numerical model of the capillary wick, and used FLUENT software to simulate the heat transfer process of the capillary wick under wet conditions, and the simulation results were in good agreement with the experimental results. Koito (2021) conducted numerical analyses for an ultra-thin heat pipe in which a thin wick layer was placed on the bottom and found that the vapor temperature drop was reduced effectively by increasing the width of the heat pipe.

The numerical analysis method plays an indispensable role in better understanding the internal structure of the capillary wick and the operation status of the heat pipe. CFD simulation technology can well reflect the specific process and phenomenon of evaporation and condensation of liquid working fluid in heat pipe. VOF, LEE and other models are often used to study the flow of liquid working fluid in capillary wicks. For the numerical analysis of heat pipe, the capillary wick and working fluid are often considered together. For example, the flow pattern analysis of working fluid in the capillary wick and the influence of filling liquid ratio on evaporation and condensation end are also important research directions of capillary wicks.

6. STUDY ON THE COMBINATION OF CAPILLARY WICK AND HEAT PIPE

As the core structure of heat pipe, capillary wick is closely related to the performance of heat pipe. The current research mainly focuses on two aspects, namely, the influence of different capillary wicks on heat transfer performance of heat pipe and how to improve the capillary wick to make the heat pipe have better heat transfer performance.

In the aspect of experimental research, Wang et al. (2014a) studied in detail the influence of capillary structure on the performance of flat plate heat pipe, carried out experimental tests on three kinds of capillary structure heat pipes with the same overall size, and found out the best capillary structure suitable for flat plate heat pipe, namely double micro channel structure. Li (2015) according to the bionics principle, taking the micro convex structure of velvet bamboo taro surface as the design basis, sintered the conical capillary wick with nano scale copper powder as the material, constructed a new flat plate heat pipe, and studied its thermal performance with deionized water as the working fluid, which proved that the conical capillary wick greatly improved the heat transfer performance of the flat plate heat pipe. Li et al. (2017b), using ultra light porous foam copper metal as capillary wick and acetone as working substance, designed a new type of heat pipe and studied the influence of heat flux and inclination angle on the thermal performance of the new heat pipe, and compared with the thermal performance of the traditional heat pipe. The results show that the new heat pipe is not only the best thermal performance, but also has excellent uniform temperature characteristics. Cheng et al. (2020) investigated the thermal performance of ultra-thin heat pipes. The novel wick structure was copper braids modified to be superhydrophilic with higher capillary ability. It has a significant effect on the improvement of the thermal performance of the heat pipe.

In the aspect of theoretical research, the operation and heat transfer process after the combination of capillary wick and heat pipe are studied by building mathematical model and mathematical modeling. Liu et al. (2009) objectively reflected the operation mechanism of capillary wick heat pipe by establishing mathematical model. Wang et al. (2011) studied the relationship between the temperature fluctuation of heat pipe starting at low power and the thickness of capillary wick, and found that increasing the thickness of capillary wick can effectively inhibit the temperature fluctuation during the start-up of loop heat pipe.

In addition, there are studies on the combination of working fluids with heat pipes. As a part of circulation in heat pipes, working fluids are closely related to capillary wicks. Table 3 lists the research status of the combination of capillary wicks with heat pipe working fluids. At present, the research on the combination of capillary wicks and heat pipe working fluid mainly focuses on the performance of heat pipe under different capillary structures and working fluids, but there is little in-depth research on them. The future research can focus on the following aspects: the influence of factors such as the compatibility and contact angle of different capillary structure and different working medium on the overall performance; for the new capillary wick structure and various new working fluids, explore the combination effect; found the best coupling effect between working fluid and capillary wicks.

At present, in order to improve the heat transfer performance of heat pipe, there are three aspects to optimize the capillary wick: one is to optimize the structure of the capillary wick, and to study more new composite structures for the existing single structure, so as to comprehensively realize the advantages of a single structure. The structure here not only refers to the macro structure of the capillary wick, such as the combination of wire mesh capillary wick and grooved capillary wick, but also refers to the microstructure of capillary wick, such as the pore size distribution inside the capillary wick. Through numerical analysis, Xuan et al. (2003) proved that the influence of pore radius in capillary wick on the flow resistance of working medium in capillary wick is very important, and composite wick is worth exploring. The application of new working fluid can improve capillary pumping force, improve heat transfer capacity and operation stability of capillary pump circuit. Qu and Zhang (2014) studied the properties of capillary wicks with double pore diameter distribution. Wang et al. (2015) designed a kind of multi-scale composite capillary wick loop heat pipe, prepared double-layer capillary wick by secondary sintering method, and then laid insulation cotton to form three-layer capillary wick, and tested its heat transfer performance under different heating power, placing angle and cooling mode. For the structure optimization of capillary wicks, more combination forms can be tried to pursue better capillary wick performance. For example, there are cross studies combining biological simulation with capillary wick structure. Or we can optimize the internal structure of the capillary wick more deeply. According to the evaporation flow characteristics of the capillary wick, we can determine the more suitable pore size distribution. According to the requirements of different working conditions, we can use the new capillary wick with different structure and pore size distribution.

The second is to optimize the preparation method and material of capillary wicks, and to prepare the capillary wick with more accurate control and better performance by using a new method different from the traditional method. Wang et al. (2018) adopted a new powder sintering dissolution method. Firstly, the metal nickel powder was uniformly mixed with the pore forming agent, and then the compact was sintered. Finally, the sintered sample was washed in water to dissolve and remove the residual pore forming agent, so as to obtain porous materials with controllable porosity, pore shape and pore diameter, and to study its performance. With the development of science and technology, more and more manufacturing methods are

Table 3 Research status of capillary wicks combined with heat pipe working fluids

Types of working fluids	Experimental design	Conclusion	Reference
A non azeotropic immiscible mixture for phase change heat transfer of pulsating heat pipe	Experiments on non azeotropic mixtures of water as high boiling point working fluid, HFE-7100 as low boiling point working fluid and their mixtures under different heating power and filling rate.	The mixed working fluid pulsating heat pipe can be started at low heating power (20W), and the start-up performance is better at all heating powers; when the filling rate is 30%, the start-up time of the system is the shortest.	Zhang et al., 2019a
Start up and heat transfer characteristics of flat plate heat pipe with methanol as working fluid at different liquid filling rates	The influence of different liquid filling rate on the performance of heat pipe is studied. Taking the best filling rate as an example, study the influence of heating power in evaporation section on the performance of heat pipe .	Compared with the heat pipe with other liquid filling rate, the heat pipe with 20% liquid filling rate shows the best working performance. The best filling rate range is 10% - 30%.	Wang et al., 2019
The mass flow rate of loop heat pipe with acetone, ethanol and propylene as working fluids was measured under different load powers	With acetone, ethanol and propylene as working fluids, the latent heat of vaporization, saturation pressure and density are greatly different. The loop heat pipe experiments with different heat loads are carried out to study the change of mass flow characteristics.	The fluctuation amplitude of mass flow of the three refrigerants decreased at first and then increased. In the capillary wick, compared with the gas mass flow rate, the liquid mass flow rate is more affected by the fluctuation of the two-phase region of the condenser.	Liu et al., 2020
Copper oxide / water nanofluids with stable suspension and good dispersion with different mass fractions	High performance nanofluids were prepared, and the heat pipe with copper oxide / water nanofluid as working fluid was encapsulated. The effects of the amount of CuO nanoparticles, the tilt angle of heat pipe and the heating temperature on the heat transfer performance of the heat pipe were investigated.	The amount and properties of CuO nanoparticles, the tilt angle of the heat pipe and the heating temperature of the heat pipe will affect the heat transfer performance of the heat pipe. The more the amount of CuO nanoparticles is, the better the heat transfer performance of the heat pipe is.	Ji, 2016
Binary mixture of nitrogen and argon	Using gravity thermosyphon, the heat transfer performance of cryogenic heat pipe with pure nitrogen and pure argon and nitrogen / argon binary mixture as working fluid was tested, and the experimental results of the three were analyzed and compared.	However, when the temperature of the condensing section is lower than the three-phase point of the working medium, the low-temperature heat pipe can not work normally.	Long and Zhang, 2012
Deionized water, methanol and ethanol	The effects of different working fluids, liquid filling rate and heating rate on the pulsating heat pipe were studied, and the heat transfer effects of different working fluids under different liquid filling rates were measured.	The thermal resistance of the heat pipe is the minimum when the filling rate of deionized water is 50%. Compared with methanol, the heat transfer effect of deionized water and ethanol is better and the thermal resistance is smaller.	Durga, 2017
Water, acetone and binary mixtures	The heat transfer performance of the oscillating heat pipe was studied by selecting 35% - 70% liquid filling rate, 10-100W heating power and water /acetone ratio of 13:1, 4:1, 1:1, 1:4, 1:13.	The starting speed of the mixed working fluid is better than that of the pure working fluid, and the thermal resistance of the mixed working medium wick is lower than that of the pure working medium at low liquid filling rate, and the opposite is true for high liquid filling rate.	Zhu et al. 2014
Distilled water, nanofluid, and a mixture of nanofluid and surfactant	The effects of input power and tilt angle on the performance of THP are investigated.	With the increase of the concentration of nanofluids, the thermal efficiency of thermosyphon increases and the thermal resistance decreases. Mixing the nanofluid with the surfactant will reduce the wall temperature and thermal resistance of the evaporator while increasing the thermal efficiency of the THP.	Ghorabaee et al. 2020

used to manufacture heat pipe and its accessories. For example, 3D printing technology, which is popular in recent years, has also been applied to the production of capillary wicks. Esarte et al. (2017) designed and manufactured a loop heat pipe with 3D printing selective laser melting capillary wick and proved the optimization effect of the technology on the performance of the heat pipe. Some new materials can be applied to the manufacture of capillary wick, for example, the latest foam metal material. As a capillary wick material, it can effectively improve the uniform temperature and thermal properties of the heat pipe. Developing new manufacturing methods and materials is one of the effective ways to improve the overall performance of capillary wick.

Another is to improve the combination of capillary wick and heat pipe. Qing et al. (2019) used fluent and VOF model to simulate the evaporation and condensation process of liquid working medium in heat pipe, and analyzed the influence of heating power and liquid filling rate on heat transfer performance of heat pipe. Zhang et al. (2019b) took the carbon fiber capillary wick loop heat pipe as the research object, and through the comparison of experimental and simulation results, it was determined that in the feasibility experiment, the thermal leakage facing the compensation cavity was the main cause of failure. It is proposed that the heat leakage of the metal shell can be effectively reduced by adding a layer of heat insulation layer on the contact surface between the evaporator shell and the compensator. These are the problems when the capillary wick is actually installed in the heat pipe. Reducing the heat leakage, selecting the appropriate input power and liquid filling ratio are also significant to improve the overall performance of the heat pipe.

7. SUMMARY AND PROSPECT

As an efficient heat transfer element, heat pipe has a broad application prospect in chemical industry, aerospace and electronic engineering. Capillary wick is the core component of heat pipe, which has a vital impact on the heat transfer performance of heat pipe. Improving the performance of capillary wick is a vital way to develop more efficient heat pipe. At present, the research on capillary wicks mainly focuses on the structure, preparation method, suction and permeability of capillary wicks. In order to improve the performance of capillary wicks, the future research directions can include the following aspects:

① The selection of materials and working medium of capillary wick and heat pipe is closely related to the working conditions of heat pipe. It is of great significance to select the working fluid, capillary wick and heat pipe material that match the environment for improving the performance of heat pipe.

② Combine new methods and materials with the updating technology and the traditional preparation method of capillary wicks, and prepare the products with higher accuracy data such as porosity and pore size, so as to improve the controllability of structural parameters. The controllability of capillary wick parameters is the key step of performance optimization.

③ According to the characteristics and requirements of heat pipe, set more reasonable structure distribution of heat pipe, and carry out further study on composite wicks. The combination mode of pore size distribution and capillary wick structure should be further adjusted to optimize the heat transfer performance of heat pipe.

④ Combine the capillary wick with heat pipe working fluid. At present, existing researches mainly focus on the simple performance research of working fluid or the improvement of capillary wick performance, and there is little comprehensive consideration of the combination of the two. It is also a future research direction to find the relationship between them and to couple their characteristics.

⑤ In addition to the performance improvement of the capillary wick itself, it is also an essential link to analyze the actual problems of installing the capillary wick into the heat pipe. Overall performance is the ultimate problem to be solved.

⑥ Make full use of numerical simulation to establish the model, and summarize more accurate relations for the suction and permeability performance of capillary wicks and the start-up and transmission characteristics in heat pipe. Using the results of numerical simulation to adjust the parameters of preparation.

ACKNOWLEDGEMENTS

The support of our research program by National Natural Science Foundation of China (No. 11802125) is greatly appreciated.

NOMENCLATURE

B	variable
C	constant
d_p	the average pore size of the sample (m)
K	permeability (m^2)
n	variable
V_p	pore volume (m^3)
V_T	total volume of capillary wick (m^3)

Greek Symbols

ε	porosity (%)
κ	variable
η	variable
λ_{eff}	effective thermal conductivity (W/m K)
λ_f	fluid thermal conductivity (W/m K)
λ_{max}	maximum thermal conductivity (W/m K)
λ_{min}	minimum thermal conductivity (W/m K)
λ_s	solid thermal conductivity (W/m K)

Subscripts

eff	effective
f	fluid
max	maximum
min	minimum
p	pore
s	solid

REFERENCES

Aoki, H., Ikeda, M., and Kimura, Y., 2012, "Ultra thin heat pipe and its application," *Frontiers in Heat Pipes*, **2**(4), 1-5. http://dx.doi.org/10.5098/fhp.v2.4.3003

Assad, A., 1955, "A study of thermal conductivity of fluid bearing porous rock," Berkeley, CA: University of California.

Bai, T., Zhang, H., Xu, H., and Ding, L., 2011, "Performance study on a novel combined wick of heat pipe," *Proceedings of the Chinese Society for Electrical Engineering*, **31**(23), 79-85. http://dx.doi.org/10.13334/j.0258-8013.pcsee.2011.23.012

Basha, M.S., Bansal, L., Sarma, D., Basu, S., Kumar, P., and Ambirajan, A., 2014, "Solar Thermal Power System Augmented with LHP," *Energy Procedia*, **49**, 295-304. http://dx.doi.org/10.1016/j.egypro.2014.03.032

Chaudhry, H. N., Hughes, B.R., and Gharri, S.A., 2012, "A review of heat pipe systems for heat recovery and renewable energy applications," *Renewable & Sustainable Energy Reviews*, **16**(4), 2249-2259. http://dx.doi.org/10.1016/j.rser.2012.01.038

Chaudhary, R., and Bhandari, R.C., 1969, "Thermal conductivity of two phase porous materials, " *British Journal of Applied Physics*, **2**(4), 609-610.

Chen, B.B., Liu, W., Liu, Z.C., Li, H., and Yang, J.G., 2012, "Experimental investigation of loop heat pipe with flat evaporator using biporous wick," *Applied Thermal Engineering*, **42**, 34-40. http://dx.doi.org/10.1016/j.applthermaleng.2012.03.006

Cheng, H.C., Chen, T.H., Huang, H.S., and Chen, P.H., 2021, "An Experimental Investigation on Thermal Performance of Ultra-Thin Heat Pipes with Superhydrophilic Copper Braids," *Heat Transfer Engineering*, **42**(10), 824-838. http://dx.doi.org/10.1080/01457632.2020.1744245

Chen, L., Tian, Y.S., and Karayiannis, T.G., 2006, "The effect of tube diameter on vertical two-phase flow regimes in small tubes," *International Journal of Heat and Mass Transfer*, **49**(21-22), 4220-4230. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2006.03.025

Chen, X., Lin, Y., Sun, Q., and Xie, R.J., 2019, "Numerical simulation of flow and heat transfer of 3D-printed titanium alloy wick," *Vacuum & Cryogenics*, **25**(2), 94-98. http://dx.doi.org/10.3969/j.issn.1006-7086.2019.02.004

Chen, X., Lin, Y., Sun, Q., and Xie, R.J., 2019, "Experimental study on effective thermal conductivities of three kinds of capillary wicks." *Vacuum & Cryogenics*, **25**(2), 183-187. http://dx.doi.org/10.3969/j.issn.1006-7086.2019.03.006

Chen, X.P., Ye, H.Y., Fan, X.J., Ren, T.L., and Zhang, G.Q., 2016, "A review of small heat pipes for electronics," *Applied Thermal Engineering*, **96**, 1-17. http://dx.doi.org/10.1016/j.applthermaleng.2015.11.048

Chernysheva, M.A., and Maydanik, Y.F., 2009, "Heat and Mass Transfer in Evaporator of Loop Heat Pipe," *Journal of Thermophysics Heat Transfer*, **23**(4), 725-731. http://dx.doi.org/10.2514/1.43244

Chi, Y., Tang, Y., Chen, J.C., Deng, X.X., Liu, L., Liu, X.K., and Wan, Z.P., 2007, "Miniaturized capillary pumped loop heat controlling system and it's manufacturing technique," *Chinese Journal of Mechanical Engineering*, **43**(12), 166-170. http://dx.doi.org/10.3321/j.issn:0577-6686.2007.12.031

Deng, D.X., Liang, D.J., Tang, Y., Peng, J.M., Han, X.D., and Pan, M.Q., 2013, "Evaluation of capillary performance of sintered porous wicks for loop heat pipe," *Experimental Thermal and Fluid Science*, **50**, 1-9.

http://dx.doi.org/10.1016/j.expthermflusci.2013.04.014

Diallo, T., Yu, M., Zhou, J.Z., Zhao, X.D., Ji, J., and Hardy, D., 2018, "Analytical investigation of the heat-transfer limits of a novel solar loop heat pipe employing a mini-channel evaporator," *Energies*, **11**(1), 148. http://dx.doi.org/10.3390/en11010148

Dunn, P.D., and Reay, D.A., 1982, Heat Pipes. Beijing, China.

Durga, B., 2017, "Experimental study on thermal performance of pulsating heat pipe with different working fluids," *Journal of Engineering Thermophysics*, **38**(7), 1454-1458.

Esarte, J., Blanco, J.M., Bernardini, A., and San-José, J.T., 2017, "Optimizing the design of a two-phase cooling system loop heat pipe: Wick manufacturing with the 3D selective laser melting printing technique and prototype testing," *Applied Thermal Engineering*, **111**, 407-419.
http://dx.doi.org/10.1016/j.applthermaleng.2016.09.123

Fang, S.Q., Zhao, L., Shi, Q.H., and Lu, H.X., 2008, "Experiment research of enhanced heat transfer for spiral groove gravity heat pipe,"*Chemical Engineering (China)*, **36**(6), 19-21.
http://dx.doi.org/10.3969/j.issn.1005-9954.2008.06.006

Fan, X.F., Qiu, C.J., and Liu, R.L., 2002, "Microstructure evolution and bonding mechanism of thermal sprayed Ni-al coating during reactive sintering," *Materials Science & Tenchnology*, **10**(2), 183-185.
http://dx.doi.org/10.1007/s11769-002-0041-9

Filippeschi, S., 2011, "Comparison between miniature periodic two-phase thermosyphons and miniature LHP applied to electronic cooling equipment," *Applied Thermal Engineering*, **31**(5), 795-802.
http://dx.doi.org/10.1016/j.applthermaleng.2010.10.028

Franchi, G., and Huang, X., 2008, "Development of composite wicks for heat pipe performance enhancement," *Heat Transfer Engineering*, **29**(10), 873-884.
http://dx.doi.org/10.1080/01457630802125740

Gan, T., Lin, T., and Quan, X.J., 2020, "Structure and properties of bionic biporous-oriented pore capillary wicks prepared by ice-template method," *Materials for Mechanical Engineering*, **44**(4), 57-61.
http://dx.doi.org/10.11973/jxgccl202004011

Ge, P.H., Guo, J., Sun, X.B., Hu, G., and Ke, G.T., 2017, "Numerical simulation of high-temperature heat pipe startup characteristic based on SIMPLEC algorithm," *Atomic Energy Science and Technology*, **51**(11), 1974-1981.
http://dx.doi.org/10.7538/yzk.2017.youxian.0119

Ghorabaee, H., Emami, M.R.S., and Shafahi, M., 2020, "Effect of Nanofluid and Surfactant on Thermosyphon Heat Pipe Performance," *Heat Transfer Engineering*, **41**(21), 1829-1842.
http://dx.doi.org/10.1080/01457632.2019.1670470

Hansen, G., Næss, E., and Kristjansson, K., 2016, "Analysis of a vertical flat heat pipe using potassium working fluid and a wick of compressed nickel foam," *Energies*, **9**(3), 170.
http://dx.doi.org/10.3390/en9030170

He, D., Wang, L., Liu, R.T., Wang, Z.B., Xiong, X., and Zou, J.P., 2018, "Pore characteristic and performance of sintered copper-based porous wicks," *Materials Science and Engineering of Powder Metallurgy*, **23**(4), 389-397.
http://dx.doi.org/10.3969/j.issn.1003-9015.2016.03.009

He, W., Hong, X.Q., Zhao, X.D., Zhang, X.X., Shen, J.C., and Ji, J., 2014, "Theoretical investigation of the thermal performance of a novel solar loop-heat-pipe faade-based heat pump water heating system," *Energy & Buildings*, **77**, 180-191.
http://dx.doi.org/10.1016/j.enbuild.2014.03.053

Holley ,B., and Faghri, A., 2005, "Analysis of pulsating heat pipe with capillary wick and varying channel diameter," *International Journal of Heat and Mass Transfer*, **48**(13), 2635-2651.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2005.01.013

Hsu, C.T., Cheng, P., and Wong, K.W., 1994, "Modified Zehner-Schlunder models for stagnant thermal conductivity of porous media," *International Journal of Heat and Mass Transfer*, **37**(17), 2751-2759.
http://dx.doi.org/10.1016/0017-9310(94)90392-1

Huang, X., and Franchi, G., 2007, "Design and fabrication of hybrid bi-modal wick structure for heat pipe application," *Journal of Porous Materials*, **15**(6), 635-642.
http://dx.doi.org/10.1007/s10934-007-9143-1

Huang, X.M., Liu, W., and Han,Y.M., 2004, "A new model for the heat and mass transfer character of CPL evaporation," *Journal of Engineering Thermophysics*, **25**(4), 652-654.
http://dx.doi.org/10.3321/j.issn:0253-231X.2004.04.035

Hu,Y.M., and Wang,H.L., 1999,"Experiment research on boiling convection of metal grid padding surface in flat heat pipe," *Cryogenics*, 4, 163-167.
http://dx.doi.org/10.3969/j.issn.1000-6516.1999.04.034

Hu, Z.H., Wang, D.C., Xu, J.Y., and Zhou, Y.R., 2020, "Experimental analysis on heat transfer performance of loop heat pipes with double-layer wicks," *Journal of Thermal Science and Technology*, **19**(2), 130-138.
http://dx.doi.org/10.13738/j.issn.1671-8097.019113

Hwang, G.S., Kaviany, M., Anderson, W.G., and Zuo, J., 2007, "Modulated wick heat pipe," *International Journal of Heat and Mass Transfer*, **50**(7-8), 1420-1434.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2006.09.019

Ji, J.W., 2016, "Preparation of copper oxide Nanofluid and its application in heat pipe," M. D. thesis, Jinan University, Shandong, China.
http://dx.doi.org/10.7666/d.D01049373

Kaviany, M., 1995, "Principles of Heat Transfer in Porous Media," New York: Springer Verlag.
http://dx.doi.org/10.1007/978-1-4612-4254-3

Kaya, T., 2009, "Analysis of vapor–gas bubbles in a single artery heat pipe," *International Journal of Heat and Mass Transfer*, **52**(25-26), 5731-5739.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2009.08.015

Kaya ,T., and Garcia, M., 2007, "Comparative investigation of operational performance characteristics of axially grooved and arterial heat pipes," *Heat Mass Transfer*, **44**(6), 739-750.
http://dx.doi.org/10.1007/s00231-007-0304-1

Koito, Y., 2021, "Numerical Analyses on Vapor Temperature Drop In an Ultra-Thin Heat Pipe with a Thin Wick Sheet," *Frontiers in Heat and Mass Transfer*, **16**, 1-6.
http://dx.doi.org/10.5098/hmt.16.8

Krupiczka, R., 1967, "Analysis of thermal conductivity of porousty in granular materials," *International Chemical Engineering*, **7**, 122- 144.

Lataoui, Z., Romestant, C., Bertin, Y., Jemni A., and Petit, D., 2010, "Inverse thermal analysis of the drying zone of the evaporator of an axially grooved heat pipe," *Experimental Thermal and Fluid Science*, **34**(5), 562-574.
http://dx.doi.org/10.1016/j.expthermflusci.2009.11.009

Lee, D., and Byon, C., 2018, "Fabrication and characterization of pure-metal-based submillimeter-thick flexible flat heat pipe with innovative wick structures," *International Journal of Heat and Mass Transfer*, **122**, 306-314.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2018.01.135

Lee, J., Kim, D.M., Mun, J.M., and Kim, S., 2020, "Heat-transfer characteristics of a cryogenic loop heat pipe for space applications,"

Energies, **13**(7), 1616.
http://dx.doi.org/10.3390/en13071616

Li, H.C., 2015, "Study on heat transfer properties of flat heat pipe with conical capillary wicks," *Journal of Mechanical Engineering*, **51**(24), 132-138.
http://dx.doi.org/10.3901/JME.2015.24.132

Li, H.C., Ji, X.B., and Xu, J.L., 2017a, "Investigation on performance of bionic wick flat heat pipes," *Journal of Aerospaces Power*, **32**(10), 2403-2409.
http://dx.doi.org/10.13224/j.cnki.jasp.2017.10.013

Li, H.C., Ji, X.B., Zhou, D.D., and Xu, J.L., 2017b, "Experimental investigation on thermal performance of metal foam capillary wick heat pipe," *Journal of Central South University (Science and Technology)*, **48**(12), 3400-3405.
http://dx.doi.org/10.11817/j.issn.1672-7207.2017.12.034

Li, J.W., Lu, N.X., and Cong, T.S., 2021, "Experimental study on evaporation-capillary pumping flow in capillary wick and working fluid system," *Thermal Science*, **25**(1), 367-375.
http://dx.doi.org/10.2298/TSCI180918413L

Li, J.W., Zou, Y., and Cheng, L., 2010a, "Experimental study on capillary pumping performance of porous wicks for loop heat pipe," *Experimental Thermal and Fluid Science*, **34**, 1403-1408.
http://dx.doi.org/10.1016/j.expthermflusci.2010.06.016

Li, J.W., Zou, Y., Cheng, L., Singh R., and Akbarzadeh A., 2010b, "Effect of fabricating parameters on properties of sintered porous wicks for loop heat pipe," *Powder Technology*, **204**, 241-248.
http://dx.doi.org/10.1016/j.powtec.2010.08.008

Li, J.W., Zou, Y., and Cheng, L., 2011, "Development and experimental verification of capillary pumping model for porous structure," *Proceedings of the Chinese Society for Electrical Engineering*, **31**(11), 57-61.
http://dx.doi.org/10.13334/j.0258-8013.pcsee.2011.11.014

Li, Q., Zhou, H.Y., and Xuan, Y.M., 2008a, "Investigation of heat transfer characteristics of composite capillary evaporator," *Journal of Engineering Thermophysics*, **29**(1), 148-150.
http://dx.doi.org/10.3321/j.issn:0253-231X.2008.01.046

Li, X.B., Li, Y., Xu, Z.C., and Tang, Y., 2008b, "A mathematical modeling method and experimental investigation on micro heat pipe with a rectangle-grooved wick structure," *China Mechanical Engineering*, **19**(15), 1847-1852.

Li, X.L., Wang, F.Z., Riley, G.A., Egbo, M., Derby, M.M., and Hwang, G., 2020, "Integrated Micro X-Ray Tomography And Pore-Scale Simulations for Accurate Permeability Predictions Of Porous Media," *Frontiers in Heat and Mass Transfer*, **15**, 1-8.
http://dx.doi.org/10.5098/hmt.15.1

Li, Y., Chen, C.Y., and Zen, Z.X., 2013, "Experimental investigation into heat transfer performance of micro heat pipe with fiber-composite grooved wick," *Journal of South China University of Technology (Natural Science Edition)*, **41**(7), 45-49,55.
http://dx.doi.org/10.3969/j.issn.1000-565X.2013.07.008

Ling, W.S., Zhou,W., Liu, R.L., Qiu, Q.F., and Liu, J., 2016, "Thermal performance of loop heat pipe with porous copper fiber sintered sheet as wick structure," *Applied Thermal Engineering*, **108**, 251-260.
http://dx.doi.org/10.1016/j.applthermaleng.2016.07.121

Ling, W.S., Zhou, W., Yu, W., and Chu, X.Y., 2018, "Capillary pumping performance of porous copper fiber sintered wicks for loop heat pipes," *Applied Thermal Engineering*, **129**, 1582-1594,
http://dx.doi.org/10.1016/j.applthermaleng.2017.10.150

Liu, C., Xie, R.J., and Dong, D.P., 2020, "Investigation on characteristic of mass-flow in loop heat pipe with different working fluids under different load powers," *Chemical Industry and Engineering Progress*, **39**(8), 2980-2988.
http://dx.doi.org/10.16085/j.issn.1000-6613.2019-1776

Liu, J.Y., Luan, T., Liu, L.F., and Zou, Y., 2019a, "Comparative study of surface modified carbon fiber capillary wicks in loop heat pipe," *Surface Technology*, **48**(1), 175-181.
http://dx.doi.org/10.16490/j.cnki.issn.1001-3660.2019.01.023

Liu, W., Liu, Z.C., Yang, K., and Tu, Z.K., 2009, "Phase change driving mechanism and model of capillary core heat pipe," *Chinese Science Bulletin*, **54**(13), 1932-1936.
http://dx.doi.org/10.1007/s11434-009-0220-5

Liu,Y., Chen, Y., Yang, B.W., Zhang, P., Zhang, J.C., and Xin, G.M., 2019b, "Investigation on evaporation for composite wicks with changing pore size," *Journal of Engineering Thermophysics*, **40**(7), 1627-1631.

Liu, Z.C., Li, H., Chen, B.B., Yang, J.G., and Liu, W., 2012, "Operational characteristics of flat type loop heat pipe with biporous wick," *International Journal of Thermal Sciences*, **58**, 180-185.
http://dx.doi.org/10.1016/j.ijthermalsci.2012.02.027

Long, Z.Q., and Zhang, P., 2012, "Heat transfer performance of cryogenic heat pipe with binary mixture working fluid," *Chemical Industry and Engineering Progress*, **63**(S1), 69-74.
http://dx.doi.org/10.3969/j.issn.0438-1157.2012.z1.014

Lu, N.X., Li, J.W., and Liu, F.R., 2022, "Experimental Study on Gradient Pore Size Capillary Wicks," Heat Transfer Research, **53**(7), 57-75.
http://dx.doi.org/10.1615/HeatTransRes.2022040095

Luo, J.L., Mo, D.C., Wang, Y.Q., and Lyu, S.S., 2021, "Biomimetic copper forest wick enables high thermal conductivity ultrathin heat pipe," *ACS Nano*, **15**(4), 6614-6621.
http://dx.doi.org/10.1021/acsnano.0c09961

Ma, T.Z., Wang, Z.P., and Zhao, J.Q., 1980, "A study of capillary and permeability characteristics of heat pipe screen wicks," *Journal of Engineering Thermophysics*, **1**(2): 156-164.

Mahulkar, Y., and Sedani, C., 2019, "Development of nickel bi-porous wicks for miniature loop heat pipe applications," *World Journal of Engineering*, **16**(2), 331-339.
http://dx.doi.org/10.1108/WJE-03-2018-0096

Maxwell, J.C., 1904, A treatise on electricity and magnetism, 3rd ed. England: Clarendon Press.

Pastukhov, V.G., Maidanik, Y.F., Vershinin, C.V., and Korukov, M.A., 2003, "Miniature loop heat pipes for electronics cooling," *Applied Thermal Engineering*, **23**(9), 1125-1135.
http://dx.doi.org/10.1016/S1359-4311(03)00046-2

Pastukhov, V.G., and Maydanik, Y.F., 2013, "Combined LHP and PHP based heat-transfer system," *International Journal of Thermal Sciences*, **74**, 81-85.
http://dx.doi.org/10.1016/j.ijthermalsci.2013.07.012

Progelhof, R.C., Throne, J.L., and Ruetsch, R.R., 1976, "Methods for Predicting the Thermal Conductivity of Composite Systems: A Review," *Polymer Engineering Science*, **16**, 615-625.
http://dx.doi.org/10.1002/pen.760160905

Qin, Q., Zhang, D.C., Chen, D.W., and Li, K.Q., 2019, "Numerical simulation of the phase change heat transfer process in gravitational heat pipe," Mineral Engineering Research, **34**(4), 57-64.
http://dx.doi.org/CNKI:SUN:KTGC.0.2019-04-010

Qu, Y., and Zhang, K.F., 2014, "Review of bi-porous wick structure for loop heat pipe," Powder metallurgy industry, **24**(3), 48-55.
http://dx.doi.org/10.3969/j.issn.1006-6543.2014.03.009

Semenic, T., and Catton, I., 2009, "Experimental study of biporous wicks for high heat flux applications," *International Journal of Heat*

and Mass Transfer, **52**(21-22), 5113-5121.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2009.05.005

Samanta, S.K., Sharma, B.B., Das, P., and Lohar, A.K., 2012, "Development of tubular Ni wick used in LHP for space applications," *Frontiers in Heat Pipes*, **2**(4), 1-5.
http://dx.doi.org/10.5098/fhp.v2.4.3004

Semenic, T., Yu, L.Y., and Catton, I., 2008, "Thermo-physical properties of biporous heat pipe evaporators," *Journal of Heat Transfer*, **130**, 1-10.
http://dx.doi.org/10.1115/1.2790020

Singh, R., Velardo, J., Ahamed, M.S., Date, A., and Akbarzadeh, A., 2021, "Thin Thermal Management Modules Using Flattened Heat Pipes And Piezoelectric Fans for Electronic Devices," *Frontiers in Heat and Mass Transfer*, **17**, 1-11.
http://dx.doi.org/10.5098/hmt.17.1

Song, H., Dong, J.M., Han, Z.T., Chen, X.L., Li, C.L., and Pan, X.X., 2017, "Effects of sintering parameters on performance of Ni porous wick," *Journal of Chemical Industry and Engineering (China)*, **68**(S1), 178-183.
http://dx.doi.org/10.11949/j.issn.0438-1157.20170618

Su, D.S., Tang, Y., Tang, B., and Chi, Y., 2008, "Reseach on capillary pumped loop with screen mesh capillary wick," *Fluid Machinery*, **36**(7), 9-12,24.
http://dx.doi.org/10.3969/j.issn.1005-0329.2008.07.003

Suman, B., 2008, "Effects of a surface-tension gradient on the performance of a micro-grooved heat pipe: an analytical study," *Microfluidics and Nanofluidics*, **5**(5), 655-667.
http://dx.doi.org/10.1007/s10404-008-0282-8

Sun, J., Mao, C.L., Wang, Y.X., Chang, X.P., and Quan, J.W., 2019, "Preparation and properties of bi-porous capillary wicks for loop heat pipe," *Journal of Ceramics*, **40**(6), 840-846.
http://dx.doi.org/10.13957/j.cnki.tcxb.2019.06.022

Tang, H., Tang, Y., Wan, Z.P., Lu, L.S., Wu, X.Y. and Lu, Y.J., 2019, "Fabrication and capillary performance of micro-grooved wicks for aluminium flat-plate heat pipes," *Journal of Mechanical Engineering*, **55**(6), 186-192.
http://dx.doi.org/10.3901/JME.2019.06.186

Tang, Y., Deng, D.X., Huang, G.H., Wan, Z.P., and Lu, L.H., 2013, "Effect of fabrication parameters on capillary performance of composite wicks for two-phase heat transfer devices," *Energy Conversion and Management*, **66**, 66-76.
http://dx.doi.org/10.1016/j.enconman.2012.09.027

Tang, Y., Deng, D.X., Lu, L.S., Pan, M.Q., and Wang, Q.H., 2010, "Experimental investigation on capillary force of composite wick structure by IR thermal imaging camera," *Experimental Thermal and Fluid Science*, **34**(2), 190-196.
http://dx.doi.org/10.1016/j.expthermflusci.2009.10.016

Tao, S.L., Tang, Y., Pan, M.Q., Wan, Z.P., and Lu, L.S., 2011, "Forming method of wick structure for heat column," *Transaction of Nonferrous Metals Society of China*, **21**(7), 1587-1594.
http://dx.doi.org/10.1016/S1003-6326(11)60901-1

Wang, C., Li, Y.X., Liu, Z.L., Zhang, G.M., and Zhang, M., 2014a, "Influences of capillary structures on flat plat heat pipe performance," *Journal of Chemical Industry and Engineering (China)*, **65**(S1), 359-363.
http://dx.doi.org/10.3969/j.issn.0438-1157.2014.z1.058

Wang, D.D., Liu, P.J., Chu, H.Q., Wang J.X., and Lu, H.Y., 2020. "Physical properties test of a composite porous wick based on foam metal," *Chinese Journal of Process Engineering*, **7**(20), 852-859.
http://dx.doi.org/10.12034/j.issn.1009-606X.219310

Wang, D.Z., Wang, X.Y., Zhou, P., Duan, B.H., and Wang C., 2014b, "Effect of sintering process on properties of Ni porous capillary wicks for loop heat pipe," *Materials Science and Engineering of Powder Metallurgy*, **19**(5), 687-694.
http://dx.doi.org/10.3969/j.issn.1673-0224.2014.05.004

Wang, G., Zhao, Y.H., Quan, Z.H., and Wang, H.Y., 2019, "Characteristics of flat plate heat pipe with different filling ratios," *Chemical Industry and Engineering Progress*, **38**(5), 2123-2131.
http://dx.doi.org/10.16085/j.issn.1000-6613.2018-1520

Wang, J.X., 2019, "Study on evaporation heat transfer characteristics of composite porous wick with spherical-dendritic powders," M. D. thesis, Anhui University of Technology, Anhui, China.
http://dx.doi.org/10.27790/d.cnki.gahgy.2019.000466

Wang, M., and Okawa, T., 2020, "Effect of Nanoparticle Layer Coating on Heat Transfer Performance of Heat Pipe," *Heat Transfer Engineering*, **42**(19-20), 1748-1754.
http://dx.doi.org/10.1080/01457632.2020.1818420

Wang, Q., Hong, J.J., and Yan, Y.Y., 2014c, "Biomimetic capillary inspired heat pipe wicks," *Journal of Bionic Engineering*, **11**(3), 469-480.
http://dx.doi.org/10.1016/S1672-6529(14)60059-7

Wang, S.F., Zhang, W.B., Zhang, X.F., and Chen, J.J., 2011, "Study on start-up characteristics of loop heat pipe under low-power," *International Journal of Heat and Mass Transfer*, **54**(4), 1002-1007.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2010.10.014

Wang, T.Y., Zhou, Y., and Sun, Y.D., 2018, "Preparation and structural characteristics of porous nickel by sintering-dissolution process," Chinese Journal of Rare Metals, **42**(12), 1301-1308.
http://dx.doi.org/10.13373/j.cnki.cjrm.XY17110017

Wang, X.Y., 2014, "Preparation and properties of porous wick for loop heat pipe," M. D. thesis, Central South University, Hunan, China.

Wang, Y., Ji, X.B., Zheng, X.H., and Xu, J.L., 2015, "Heat transfer characteristics of loop heat pipe with modulated composite porous wick," *Journal of Chemical Industry and Engineering (China)*, **66**(6), 2055-2061.
http://dx.doi.org/10.11949/j.issn.0438-1157.20141581

Wang, Y., Ji, X.B., Zheng, X.H., Yang, W.L., and Xu, J.L., 2016, "Capillary pumping characteristics of sintered porous wicks for loop heat pipes," *Journal of Chemical Engineering of Chinese Universities*, **30**(3), 560-565.
http://dx.doi.org/10.3969/j.issn.1003-9015.2016.03.009

Wu, S.C., Huang, C.J., Chen, S.H., and Chen, Y.M., 2013, "Manufacturing and testing of the double-layer wick structure in a loop heat pipe," *International Journal of Heat and Mass Transfer*, **56**(1-2), 709-714.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.09.054

Xie, S.Q., Wu, Y.N., Xie, R.J., Sun, Q., and Liu, C., 2018, "Study on 3D printing capillary wick suction capacity in the loop heat pipe," Cryogenics and Superconductivity, **46**(9), 15-20.
http://dx.doi.org/10.16711/j.1001-7100.2018.09.004

Xuan, Y.M., Qian, J.Y., and Li, Q., 2003, "Analysis on flow performances of composite wick and working fluid characteristics for CPL," *Journal of Engineering Thermophysics*, **24**(6), 1007-1009.
http://dx.doi.org/10.3321/j.issn:0253-231X.2003.06.031

Xu, J.Y., Zou, Y., and Cheng, L., 2012, "Pore structure Optimization and properties of composite wicks for loop heat pipes," *Proceedings of the Chinese Society for Electrical Engineering*, **32**(23), 70-74.
http://dx.doi.org/10.13334/j.0258-8013.pcsee.2012.23.002

Yang, H.Q., and Przekwas, A.J., 1998, "Computational modeling of microfluid devices with free surface liquid handling," International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators, Santa，Clara，California.

Yu, P., Huang, C.H., Zhang, H., Xu, H., and Shen, Y., 2018, "Simulation for liquid-vapor phase change of metal sodium in combined wick," *Journal of Engineering Thermophysics*, **39**(12), 2732-2737. http://dx.doi.org/CNKI:SUN:GCRB.0.2018-12-024

Zaghdoudi, M.C., Maalej, S., Mansouri, J., and Sassi, M.B.H, 2013, "Flat Miniature Heat Pipes for Electronics Cooling: State of the Art, Experimental and Theoretical Analysis," *International Journal of Engineering & Applied Sciences*, **38**(75): 166-189. http://dx.doi.org/10.1016/0301-0104(79)85036-3

Zhang, C.B., Shi, M.H., Chen, Y.P., and Wu, J.F., 2008, "Flow and heat transfer characteristics of heat pipe with axial "Ω"-shaped grooves," *International Journal of Heat and Mass Transfer*, **59**(3), 544-550. http://dx.doi.org/10.3321/j.issn:0438-1157.2008.03.002

Zhang, C., Xu, R.J., Chen, J.Y., and Wu, Q.P., 2019a, "Analysis of start-up characteristics of pulsating heat pipe with zeotropic immiscible mixtures," *Chemical Industry and Engineering Progress*, **38**(12), 5279-5286.
http://dx.doi.org/10.16085/j.issn.1000-6613.2019-0468

Zhang, J.C., 2018, "Investigation of functional gradient porous wicks for loop heat pipe," M. D. thesis, Shandong University, Shandong, China.

Zhang, Y.X., Liu, J.Y., Liu, L.F., Jiang, H.L., and Luan, T., 2019b, "Numerical simulation and analysis of heat leakage reduction in loop heat pipe with carbon fiber capillary wick," *International Journal of Thermal Sciences*, **146**, 106100. http://dx.doi.org/10.1016/j.ijthermalsci.2019.106100

Zhou, L., Liu, Y., and Wei, Z.H., 2019a, "Prediction of effective thermal conductivity of loop heat pipe capillary core," *Chemical Engineering Design Communication*, **45**(9), 170-172. http://dx.doi.org/10.3969/j.issn.1003-6490.2019.09.111

Zhou, W.J., Li, Y., Chen, Z.S., Deng, L.Q., and Gan, Y.H., 2019b, "A novel ultra-thin flattened heat pipe with biporous spiral woven mesh wick for cooling electronic devices," *Energy Conversion and Management*, **180**, 769-783. http://dx.doi.org/10.1016/j.enconman.2018.11.031

Zhou, W.J., Li, Y., Chen, Z.S., Deng, L.Q., and Li, B., 2020, "Experimental study on the heat transfer performance of ultra-thin flattened heat pipe with hybrid spiral woven mesh wick structure," *Applied Thermal Engineering*, **170**, 115009. http://dx.doi.org/10.1016/j.applthermaleng.2020.115009

Zhu, M.H., Bai, P.F., Hu, Y.X., and Huang, J., 2019, "Heat transfer performance of ultra-thin plate heat pipe with sintered porous channels structures wick," *Journal of Chemical Industry and Engineering (China)*, **70**(4), 1349-1357. http://dx.doi.org/10.11949/j.issn.0438-1157.20180720

Zhu, Y., Cui, X.Y., Han, H., Sun, S.D., and Li, Z.H., 2014, "Heat transfer performance of pulsating heat pipes with water-acetone mixtures," *Chemical Industry and Engineering Progress*, **65**(8), 2940-2947.
http://dx.doi.org/10.3969/j.issn.0438-1157.2014.08.013