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RESEARCH ARTICLE

Advanced wick structures for heat pipes and vapor chambers: a review on materials, design, and applications

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Abstract

High-heat-flux dissipation technology has become a key bottleneck restricting development in fields such as electronic information, new energy vehicles, aerospace, high-power semiconductor devices, and data centers. The heat transfer performance of heat pipes and vapor chambers mainly depends on the structural characteristics of their core part—the wick. Therefore, in-depth research on wick structures is of great practical significance for addressing the thermal management challenges in the fields. Focusing on metal-based wicks, this study combines a literature review with quantitative analysis and systematically classifies them into 4 major categories (with 13 subcategories). These four categories are homogeneous porous structures, biporous structures, composite structures, and other structures. The key influencing factors (such as particle size, pore size, thickness, and preparation process) and best parameter ranges of various wicks are systematically discussed, their heat transfer performance and application adaptability are compared, and a "scenario-parameter-performance" matching framework is set up. The results show that biporous metal powder wicks exhibit the best performance with respect to critical heat flux and superheat temperature; composite wicks possess both high capillary force and high permeability; homogeneous porous wicks are simple to prepare but have relatively limited performance. Notably, discrepancies between actual test results and theoretical predictions are mainly attributable to inconsistencies in test components (single-wick, assembled heat pipe or vapor chamber), dimensions, heating power, and cooling conditions. Based on the above findings, it can be inferred that the core of wick performance optimization lies in achieving a synergistic balance between capillary force and permeability, and in customizing parameters for specific application scenarios. This study proposes a refined classification system and conducts cross-type comparisons of their heat transfer performance, thereby providing a reliable reference for engineering applications. Future research should incorporate actual operating conditions, improve wick performance, perfect long-term reliability, standardize test methods, and promote the transformation of composite wicks from laboratory research to large-scale engineering applications.

Keywords: Wick structure, capillary force, permeability, heat transfer performance

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1. Introduction

Because high-heat-flux dissipation has become a bottleneck restricting technological development in many fields, thermal management is attracting increasing attention[1]. Electronic devices are evolving towards miniaturization, functionalization, integration, and high-frequency operation. The operating heat flux of these devices can reach 100 W/cm^2[2]. It has been reported that when the operating temperature of electronic devices exceeds the rated operating temperature by 10 °C,

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their reliability is reduced by 50% [3,4]. Common heat dissipation methods include air cooling, liquid cooling, and phase-change cooling, such as heat pipes (HPs) and vapor chambers (VCs). However, traditional cooling methods such as air and liquid cooling struggle to meet the cooling demands of high-power electronic devices due to their low heat dissipation efficiency[5]. As two-phase flow heat dissipation technologies, heat pipes and vapor chambers (HPs/VCs) are regarded as effective solutions for electronic thermal management owing to their high thermal conductivity, excellent temperature uniformity, and reversible heat flow direction [6,7]. They have been applied in numerous fields, such as the thermal control of electronic components in spacecraft[8,9], heat dissipation for nuclear power systems in aerospace vehicles [10,11],chip cooling in electronic products including mobile phones and laptops, heat dissipation for LED lighting [12,13] and industrial waste heat recovery [14]. Moreover, they are expected to be employed in the thermal management of electric vehicle batteries [12,13], as well as heat dissipation for data centers and 5G base stations [14,15].

The structure of an HP/VC forms a casing, whose inner wall features a capillary structure, and an evacuated chamber having a working fluid[2,16]. Their operation relies on the latent heat released and absorbed during the phase change of the working fluid, endowing these devices with a thermal conductivity ten of times higher than that of pure copper [16,17]. As shown in Figure 1, heat from the heat source is supplied to the evaporation zone of the HP/VC, causing the working fluid to evaporate. Under locally increased vapor pressure, the vapor flows from the evaporation section to the condensation section, releasing heat and condensing. The condensed liquid is transported back to the evaporation zone by the capillary force of the wick, enabling continuous heat transfer. In order to realize the gas-liquid circulation, the capillary force of the wick should be able to overcome the steam flow resistance, liquid reflux flow resistance, and gravitational force on the liquid, thereby ensuring the smooth return of the liquid to the evaporation section[17–19].

HPs/VCs perform two functions, heat transfer and temperature equalization, making heat-transfer efficiency their most critical performance indicator. The heat transfer efficiency of HP/VCs is influenced by both external and internal factors[20]. The external factors form the power of the heat source and gravity. The heat transfer coefficient varies with the temperature of the heat source [19,21–23]. Generally, when supplied by low-temperature (<100 °C) heat sources, HPs with relatively low heat fluxes can achieve efficient heat transfer. However, when higher-temperature heat sources are used, HPs may meet problems such as dry-out, which leads to their failure. Thus, VCs are required under high-heat-flux conditions to achieve the desired heat-transfer effect. Gravity can hinder the reverse flow of the working fluid in the liquid state, thereby affecting its circulation speed. Anti-gravity HPs/VCs have also been developed to reduce the effects of gravity[24,25]. Internal factors include the size of the HPs/VCs, physical properties of the working fluids, and wick structure[26–29]. The size of HPs/VCs affects the working fluid's transmission distance, and a long transmission distance impairs heat transfer. For example, with an increase in the length of the adiabatic section of HPs, the thermal resistance increases, and the heat transfer performance deteriorates[30]. By arranging porous support columns between the upper and lower plates of VCs, a shorter transmission path is formed, which can effectively reduce the thermal resistance [31]. Working fluids differ in heat-transfer efficiency because of differences in surface tension, boiling point, viscosity, and other physical properties.

According to heat transfer theory, improving the heat-transfer performance of HP/VCs essentially involves promoting the evaporation and condensation processes of the working fluid. The wick is a porous material that can provide the driving force for the circulation of the working fluid and serve as an interface for evaporation, thereby easing liquid supply. A high-performance wick guarantees improved evaporator performance and has three main functions: providing a channel for liquid reflux from the condensing end to the evaporating end; conducting heat between the inner wall and the liquid/vapor; and providing pores necessary for the liquid to generate capillary pressure. Therefore, the wick structure is the main factor affecting the performance of VCs [32]. The main parameters affecting the heat transfer performance of the wick are capillary force and permeability, both of which are decided by the pore size, porosity and wick thickness[2,33–36]. To achieve efficient heat transfer, the wick structure must have sufficient capillary pressure and permeability. However, these two factors are often mutually constrained: a small pore size can produce a large capillary pressure but low permeability, while a large pore size can achieve high permeability but insufficient capillary pressure[27,37]. High porosity can result in high permeability but lead to poor mechanical strength, while low porosity leads to poor permeability. The thickness of the wick also affects heat transfer performance: the thicker the wick, the faster the condensed fluid backflows, but the more difficult it is for the vapor to escape from the wick. This prevents the condensed fluid from entering the pores of the wick, ultimately leading to dry-out at the evaporator. The influence of the wick structure on heat transfer performance is the most important and complex factor, making it the focus of current research.

Wicks are basically divided into four categories: sintered porous wicks (porous metal powder [18,38], metal fiber, woven mesh [39], etc.), etched groove wicks [33,40–44], composite wicks, and wicks made of special materials, such as porous ceramics [45], metal foam [46,47], biomaterials [48], polymer materials [42], etc.

Moreover, wicks can be classified into homogeneous porous, biporous, and composite wicks based on their structures. This paper provides a comprehensive summary of research progress on various wick structures for HPs/VCs.

Earlier studies have extensively investigated wicks for heat pipes and vapor chambers, covering various wick structures (including homogeneous porous, biporous, and composite types), porous metals and carbon-based materials, and their manufacturing processes. The effects of key parameters, such as porosity, particle size, and structural matching, on the heat transfer performance have also been widely analyzed[49–51]. Although valuable progress has been made in various subfields, current research stays relatively fragmented, with insufficient quantitative characterization of critical parameters, inadequate consideration of practical application scenarios, and a lack of systematic cross-type comparisons.

To fill these gaps and meet the engineering requirements for refined wick designs, this study considers porous metal materials the primary research focus and classifies wicks into four major categories: homogeneous porous wicks, biporous wicks, composite wicks, and other structural wicks. Each category is further divided into 13 subcategories based on raw-material structures, such as metal powder, woven mesh, metal fiber, and grooves. This study systematically investigates the main influencing factors and best parameter ranges of various wicks, compares their thermal performance and suitability for applications, and sets up a "scenario–parameter–performance" matching framework based on a literature review and quantitative analysis. The novelty of this study lies in the development of a refined classification system that fills the research gaps in the precise design and cross-type comparison of wicks and provides a reliable reference for their engineering design and practical application.

The novelty of this study lies in the construction of a refined classification system that fills the research gaps in design refinements and cross-type comparisons of metal-based wicks and provides a valuable reference for engineering applications.

2. Homogeneous porous wicks

Homogeneous porous wicks are the most basic structural types developed for HP/VCs, as shown in Figure 2, and their performance parameters are listed in Table 1. Their preparation processes are relatively simple, but they are inherently limited in heat-transfer efficiency because they cannot effectively balance capillary pressure and permeability.

Table 1. Performance parameters of wicks with homogeneous pore structure

Authors	Wick structure	Equivalent pore size	Wick thickness	Porosity	Working fluid	Maximum heat flux	Remarks
Weibel J. A.[17]	45~75 μm copper powder	20~30μm	0.6 mm	0.65	Degassed distilled water	>500 W/cm^2	Evaporator wick was test at a stable temperature of 100 °C and at a stable saturation pressure.
	106~150 μm copper powder	45μm	0.9 mm	0.64		>500 W/cm^2	
	250~355 μm copper powder	150μm	1.2 mm	0.64		596.5 W/cm^2	
Hanlon M. A.[34]	150 mesh copper powder	635μm	5.7 mm	0.43	Water	80 W /cm^2	Evaporator wick was test at a thermal load of 100 W
Brautsch A.[52]	200 mesh 304L stainless steel woven mesh	/	Single Layer	0.47	Distilled water	16.85 W/cm^2	Evaporator wick was test at a working fluid temperature of 100 +10 °C, an atmospheric pressure, a heater power of 400 W.
	200 mesh 304L stainless steel woven mesh	/	5 layers	0.47	Distilled water	21.39 W/cm^2	
Li C.[53]	145 in^{-1} woven mesh with a diameter of 56 μm	/	0.74 mm	0.69-0.74	Degassed distilled water	367.9 W/cm^2	Wick was sintered on heating block and placed horizontally and tested at a atmospheric pressure, and a heater power of 300 W.
Khrustalev D.[54]	groove with width of 0.05 mm	/	0.3 mm	/	Ammonia/ ethane	25~40 W/cm^2	Wicks were combined into a heat pipe and tested at a heat source temperature of 90~120 °C, and with an aluminium alloy shell.
Kang S. W.[55]	grooves were etched on the silicon substrate with width of 350~700 μm at the evaporator and 150~500 μm at the condenser	/	0.163 mm	/	Degassed water	The temperature difference decreased by 33 % between the evaporator and condenser.	Grooved silicon was combined into a vapor chamber and depositing Cr and Au on the surface. Tested at an evaporator input thermal power of 27 W, and condenser with a constant temperature of 15 °C
Putra N.[48]	tabulate coral	52.95 μm	1.5 mm	/	Water	The chip temperature decreased by 38%.	Wicks were combined into a heat pipe and tested at a heat input temperature of 116 °C. Aluminum fined radiator nested outside the heat pipe.

2.1. Homogeneous metal powder wicks

Homogeneous wicks fabricated from metal powders are shown in Figure 2(a–e) [56,57][58][57][59][59]. These wicks are prepared from metal powders with a specific particle size range via high-temperature sintering or other methods and show uniform pore size and distribution. Interconnected pore channels form between the powder particles, providing a continuous capillary path for the reflux of the working fluid.

Such wicks show the highest capillary pressure but generally show low permeability, making them the most representative capillary structures in early heat pipes and vapor chambers. Their preparation is simple, and the pore size can be on the nanometer scale.

2.1.1. Effect of particle size on the performance of homogeneous metal powder wicks

The particle size of metal powder is an important factor affecting the performance of homogeneous metal powder wicks [35]. Jinjia Wei et al. [60] found that when the particle size of the metal powder was in the range of 2-20 μm, the pore size increased, and the capillary pressure performance was enhanced with the increase of the particle size. Although the wick composed of smaller particles has a smaller average pore radius and a resulting stronger capillary force, a large sintering neck between the particles leads to low porosity. Hence, their comprehensive performance is not as good as that of sintered wicks made from large particles [61]. Justin A. et al. [17] prepared wicks using copper powders with diameters of 45-75 μm, 106-150 μm, and 250-355 μm, respectively. Wicks prepared with copper powders 106-150 μm in diameter showed the smallest thermal resistance. Hanlon et al. [34] prepared wicks using copper powders of diameter 1.27 mm, 200 μm, and 20 μm, respectively. The evaporation heat-transfer coefficient increased as particle size decreased. Chien and Chang [62] prepared wicks using copper powder of diameters 50-500 μm and 180-360 μm, respectively. Wicks prepared with copper powders of diameter 180-360 μm exhibited lower evaporation thermal resistance. In summary, a best particle size range exists under specific working conditions, and the wicks prepared with a narrower particle size range exhibit better heat transfer performance.

2.1.2. Effect of wick thickness on the performance of homogeneous metal powder wicks

The thickness of the wicks also influences the heat transfer performance. Nathan Albu et al. [63] prepared wicks using copper powders with a diameter of 100-200 μm and found that the heat transfer performance was best when the thickness of the wick was equal to the particle diameter. Chien and Chang [62] also studied the relationship between the thickness and the particle size of the wick in HPs and found that thermal resistance decreased with the increase of thickness within the experimental range. The heat transfer performance reached a maximum when the ratio of thickness to particle size was 3.85 (0.95 mm/247 μm). Justin A. et al. [17] used metal powder with a particle size of 45-75 μm to prepare wicks with thicknesses of 600 μm, 900 μm, and 1200 μm. The study found that the impact of wick thickness on the heat transfer performance was modest. In short, the influence of wick thickness on the heat-transfer performance of HPs/VCs depends on multiple factors, and the best thickness must be decided for specific operating conditions.

2.1.3. Preparation methods of homogeneous metal powder wicks

Powder metallurgy is the most common method for preparing homogeneous metal powder wicks, owing to its low cost and well-established processing. Wicks prepared by this method can have smaller pore sizes but show low porosity and poor permeability. Although the addition of a pore-forming agent can increase porosity, it may reduce the bonding strength between metal particles and lead to particle detachment. Several new preparation processes have also been developed to fabricate wicks with improved performance. Metal porous wicks prepared by the 3D Selective Laser Melting (SLM) technique have more designable, regular internal channels that can avoid closed pores and cut the randomness of the internal structure. These wicks can obtain high porosity and strong capillary pressure at the same time, and their heat transfer performance is better; however, their cost is also higher [64–66].

2.2. Homogeneous woven mesh wicks

Woven mesh is often used to prepare wicks [39,52,67–72],as shown in Figure2(f) and (g). The woven mesh wicks are more permeable than the metal powder wicks, with a pore size greater than 40 μm, and porosity ranging from 40% to 70%[73].

2.2.1. Effect of mesh size on the performance of homogeneous woven mesh wicks

Andreas Brautsch et al.[52] prepared 304L stainless steel woven mesh wicks (mesh 50, mesh 100, mesh 150, and mesh 200). The results showed that, at a given heat flux, the heat transfer coefficient increased with increasing mesh number. This is because larger mesh numbers correspond to smaller mesh apertures and greater capillary pressure, thereby improving heat transfer performance. Yongle Tang et al. [74] investigated the thermal performance of ultra-thin flattened heat pipes (UTHPs, thickness of 1 mm) with mesh wicks in various mesh structures. The results prove that a higher mesh number of the wicks can not only accelerate the start-up response but also reduce thermal resistance during steady-state operation, which is consistent with the findings of Andreas Brautsch. However, excessively high mesh numbers entail disadvantages. The corresponding permeability decreases as the mesh number increases, resulting in greater resistance to working-fluid flow.

2.2.2. Effect of the number of mesh layers and stacking modes on the performance of homogeneous woven mesh

Andreas Brautsch et al. [52] found that at a certain heat flux, the heat transfer coefficient decreased with the increase of the number of layers. Stacking multi-layer meshes will increase the thermal resistance of the porous structure, thereby decreasing the heat transfer coefficient. However, multilayer stacking can increase the flow-channel area available to the working fluid and increase the maximum heat flux, making it more suitable for high-power heat sources. For the multi-layer woven mesh wick, the mesh stacking mode also influences the heat transfer performance. Chen Li et al. [53] studied two stacking structures (staggered and embedded) for multi-layer mesh wicks show the staggered structure on the left and the embedded structure on the right). The results showed that the staggered structure showed superior heat-transfer performance owing to its larger specific surface area, smaller effective pore size, and greater capillary pressure.

2.2.2. Effect of combination method on the performance of homogeneous woven mesh

The methods used to combine mesh wicks and HP/VC shells also affect heat transfer performance. When the mesh wick and the shell are not fully bonded—for example, when assembled by interference fit or spot welding — the working fluid can readily form a transverse vapor film at the interface between the shell and the wick, blocking the liquid transmission path and thus reducing heat transfer efficiency. The formation of transverse vapor film can be avoided by sintering, brazing or electroplating the mesh onto the inner wall of the shell, thereby increasing the critical heat flux[75].

2.3. Homogeneous metal fiber wicks

Metal fibers have high porosity and are also an effective wick material [73,76–78], as shown in Figure2(h), and (i). The wicks prepared from metal fiber mats have a minimum pore size of 10 μm and a maximum porosity of 95% [79,80]. Compared to metal powders and woven meshes, fiber mats can provide higher permeability in the longitudinal direction as well as smaller pore size in the transverse direction[73].

2.3.1. Effect of fiber diameter on the performance of homogeneous metal fiber wicks

Wicks prepared from uniform metal fibers cannot simultaneously achieve proper pore size and durability. V. Baturkin et al. [81] found that the fiber mats made of finer fibers will creep under long-term high temperatures, leading to the collapse of the wick and a later decrease in heat transfer performance. In contrast, mats made of coarser fibers have excellent steam exhaust characteristics, which address durability issues but increase the pore size of the mats, ultimately resulting in reduced heat transfer performance.

2.3.2. Effect of fiber order on the performance of homogeneous metal fiber wicks

Junxiang Wang et al.[82] prepared an ultra-thin copper fiber wick via limited fiber sintering and hydraulic pressure methods. They found that the largest capillary height of the ordered ultra-thin copper fiber wicks increased by more than 18% compared with other wicks, and their permeability was more than 1.32 times higher. These improvements are attributed to their higher porosity and more ordered structure.

2.4. Homogeneous groove wicks

Machining microgrooves on the inner wall of the VC/HP shell also produces a common wick structure[83,84], as shown in Figure 2(j), and (k). Typical groove cross-sectional shapes include rectangular [81,82], triangular, trapezoidal [54], dovetail [55], Ω-shaped [85], re-entrant cavity array [86], and others. Grooves with different cross-sections show different capillary forces, permeabilities, and working-fluid retention capabilities. Among them, rectangular and trapezoidal grooves are the most widely used in practical production due to their ease of fabrication. Traditional machining methods feature low cost, high processing efficiency, and easy scalability for mass production, thereby meeting the requirements of large-scale industrial manufacturing. However, it is difficult for traditional processes to produce microgrooves with high dimensional accuracy, resulting in relatively poor capillary performance of grooved wicks[87].

2.4.1. Effect of layout of the grooves on the performance of homogeneous groove wicks

Different groove structures produce distinct working-medium circulation paths. Therefore, the temperature uniformity of VCs can be regulated by controlling the layout of the grooves [88]. For example, inspired by plant transport of water and nutrients, arborescent and leaf-vein microgrooves have been developed as wick structures in VCs. In these structures, the grooves originate from the center of the disk and are arranged in multilevel branches around it. The branching angle, width, length and other parameters of the branches can be adjusted to improve the temperature uniformity of VCs and enhance their heat dissipation performance[87,89].

2.4.2. Preparation methods of homogeneous groove wicks

Manufacturing methods are the key to improving the capillary performance of wick structures. The milling process produces grooved wick structures with high efficiency, high accuracy, and low cost. Alijani et al.[63] employed micro-milling to manufacture rectangular grooved wick structures with widths of 0.2, 0.4, 0.8, and 1.6 mm on aluminum plates. It was found that, provided the heat pipe runs without dryout, its effectiveness increases with groove density, making pipes with narrower grooves preferable. However, once the dryout operating regime appears, it decreases as the heat flux increases.

Etching is an important method for processing HPs with grooved-wick structures. Yang et al. [90] used plasma etching to process a two-layer structure of pin fins and pin fin arrays on the surface of silicon. Test results show that both the pin fin and pin fin array VCs exhibit an appreciably lower thermal resistance than the solid silicon counterpart: the thermal resistance of the pin fin VCs is about 52 ~ 60% of that of solid silicon, whereas the corresponding thermal resistance of pin fin array VCs is only 17 ~ 20% of that of solid silicon. Hamidnia et al. [91] used dry etching to process three different shapes of silicon micro pillars on micro grooves. In addition, several specialized machining methods, such as ploughing-extrusion, flame spraying, and 3D printing [66,70,92,93] offer distinct advantages for fabricating grooved wick structures, which often have complex geometries, as they provide high material compatibility and flexibility.

2.5. Other homogeneous wicks

Foam materials with ultra-high porosity can also be used for wicks. Donghui Zhang et al. [46] found that VCs with copper foam wicks are more suitable for high-power heat sources (>60 W), because copper foam has higher porosity, which can provide more channels and increase the flow circulation, thereby improving the thermal performance of the VCs. Putra and Septiadi [48] used tabulate coral as wicks. The pore size distribution of the coral wick is narrow and uniform; its pore morphology resembles that of metal foam, and its heat-transfer performance is superior to that of copper-powder wicks. This is because the tabulate coral has relatively small, uniform pores that can generate sufficient capillary pressure. However, its industrial application is restricted by its high cost, poor durability, and low yield.

3. Biporous wicks

A desirable wick requires high capillary pressure and permeability—properties that are difficult to achieve for a homogeneous wick [94]. However, biporous wicks that contain both large and small pores can not only achieve high capillary pressure through small pores and high permeability through large pores but also enable the separation of gas and liquid phases of the working fluid, thus exhibiting superior heat transfer performance [40,73,95–99]. Under high heat flux, vapor preferentially fills the large pores, while liquid returns to the evaporator through the small pores, and then evaporates and exits from the wick through the large pores [100]. Specific forms of the biporous wick structure include biporous metal powder wicks, multi-layer woven-mesh wicks, multi-layer fiber wicks, other wicks, as shown in Figure 3; the relevant performance parameters are shown in Table 2.

Table 2. Performance parameters of wicks with biporous structure

Authors	Wick structure	Equivalent pore size	Wick thickness	Porosity	Working fluid	Maximum heat flux	Remarks
Semenic T.[101]	copper powder with a diameter of 53~63 μm; secondary particle with a diameter of 500~710 μm.	/	4 mm	0.63	Degassed distilled water	494 W/cm^2	Evaporator wick was tested at a heat input of 20 W/cm^2, and a working fluid pressure of 0.08 atm, and a temperature difference between evaporator and condenser of 128 °C, and condenser with a constant temperature of 40±0.5 °C.
Semenic T.[94]	copper powder with a diameter of 63 μm; secondary particle with a diameter of 455 μm.	/	3 mm	0.51-0.68		990 W/cm^2	Wick was tested at a superheat of 147 °C.
Zhang H. T.[97]	copper powder with a diameter of 1 μm	300 μm macroporous, 5-20 μm microporous	2 mm	/	/	/	Wick was fabricated by Composite Electroplating. Heat transfer performance didn't test.
Huang G. W.[98]	A 200-mesh single layer woven mesh and a spiral woven mesh with wire diameter of 0.04 mm	75 μm porous; vapor channel width of 2 mm	0.34 mm	/	Degassed distilled water	4.67 W/cm^2	The condenser with a temperature of 50 °C. The vapor chamber was air-cooled again.
Wena R. F.[102]	Spacing between long nanowire array was 80 μm; Microcavities between short nanowire clusters were 1~10 μm	80 μm large pores; 1~10 μm small pores	0.08 mm	0.67	Degassed distilled water	250 W/cm^2	The wick was tested at an atmospheric environment, and an overheating of 28.5 °C.
Wong S. C.[28]	Composite woven mesh with one layer 100 mesh and one layer 200 mesh	75 μm	0.338 mm	/	Water	Maximum heat load was 241.6 W	The wick was tested with an air cooling in condenser.
					Methanol	Maximum thermal load was 145.6 W	
					Acetone	Maximum heat load was 91.2 W	

3.1. Biporous metal powder wicks

Biporous metal powder wicks are shown in Figure 3(a)–(d)[103–106]. These wicks form a hierarchical pore structure including large and small pores through a specialized fabrication process. Compared with conventional homogeneous metal powder wicks, they can achieve higher porosity and permeability simultaneously, significantly reduce the flow resistance of the working fluid, and provide stronger capillary pressure through a small-pore structure, achieving an improved synergy between capillary force and permeability. However, their preparation requires precise control of powder gradation and the sintering process, making the fabrication procedure more complex than for homogeneous wicks.

3.1.1. Effect of powder on the performance of biporous metal powder wicks

Trinh Minh Hoan et al. [107] investigated the effect of particle size and geometry of copper powder on the porosity and capillary performance of porous wicks. The results proved that the porosity and capillary performance of both dendritic and spherical copper powders increased with particle size, and the dendritic powder showed superior capillary efficiency and greater porosity compared to spherical powder.

spherical powder. Weibel et al. [17] studied the performance of a flat plate HP by adjusting the particle size of the metal powder. Spherical powders of 45~75 μm, 106~150 μm, and 250~355 μm were selected, and each powder size was prepared at three levels of structural thickness. The results showed that the sample with a powder size of 106~150 μm and a proper thickness had the lowest thermal resistance. These findings suggest that the porosity and capillary performance of porous wicks are strongly dependent on both powder geometry and particle size.

3.1.2. Preparation methods of biporous metal powder wicks

Different pore sizes are generally achieved by metal powder choice, metal powder pretreatment, specialized processing methods, and other techniques. Wicks were prepared by Nathan Albu et al. using two types of copper powders with particle sizes of 200 μm and 100 μm[96]. Larger copper particles formed large pores that served as the main flow channels and improved permeability, while smaller copper particles formed small pores that increased capillary pressure. Munonyedi Egbo et al. [108] prepared sintered-particle wicks of biparticle size. The biparticle-size wicks are sintered structures composed of two particle sizes (200/60, 200/100, 350/60, 550/60 μm) and two particle weight ratios (75:25 and 50:50 wt%). It was found that the single-layer, 200/100 μm (50:50 wt%) biparticle-size wicks enhanced wickability by 27% compared to 200 μm monodisperse particle wicks and by 35% compared to 60 μm monodisperse particle wicks. Vityaz et al. [109] oxidized sintered copper wick to form a two-level structure (a bidispersed wick), which removed five times as much heat as the non-oxidized wick. The surface oxide of copper powder formed micropores with strong capillary suction, while the macropores between the powder particles eased vapor escape. Tadej Semenic et al. [101] also formed five biporous wicks by sintering clusters made of oxygen-free copper powder in a reducing atmosphere at 900–1000 °C.

Hongtao Zhang et al. [97] developed a novel biporous copper foam via composite electroplating, degreasing, and deoxidation treatments. The prepared composite material has macropores of about 300 μm, and the macroporous structure has micropores of 5–20 μm. Qifan Li et al. [110] fabricated a novel wick with a multi-scale structure via powder sintering and a two-step chemical treatment process. The copper powder was first sintered in a micro-grooved graphite mold, thereby forming pore channels by material migration and diffusion. Then, the samples were etched in an alkaline solution to form a dense layer of oxide nanostructures. Finally, nanograss from the sintered powder wick was removed via a chemical cleaning process, leaving a porous structure covered by high-density microcavities. The results showed that composite wicks covered with microcavities exhibited higher capillary pumping rates and wicking velocities.

3.2. Multi-layer woven meshes / fiber mats wicks

As shown in Figure 3(e), and (f), multi-layer woven meshes and multi-layer fiber mats are also commonly used to fabricate composite wicks[72,111]. By assembling woven meshes or fiber mats with different pore sizes layer by layer, gradient-stepped porous wicks can be constructed. Such wicks show higher permeability than biporous metal powder counterparts and prove superior heat transfer performance under multi-directional operating conditions. With a continuously interconnected pore network, they achieve a favorable balance between capillary force and flow resistance and have better structural stability and operational adaptability, making them highly promising wick structures for high-performance thermal management devices.

3.2.1. Effect of ratio of large holes to small holes on the performance of multi-layer woven meshes / fiber mats wicks

Gong Chen et al. [112] proposed a multilayer composite micromesh wick (MCMW) formed of course and fine meshes with different layer combinations to enhance wicking capability. The results showed that the MCMW structure, consisting of 3 layers of 100-mesh and 3 layers of 300-mesh, yielded a significant enhancement in wicking capability compared with multilayer single-mesh-wick (MSMW) structures. However, Richard R. Williams [73] used two step-graded metal mats as wicks, with the bottom layer being a fiber mat with larger pore sizes and the top layer a fiber mat with smaller pore sizes, to maximize permeability and the pore size ratio, thereby reducing thermal resistance and improving heat transfer performance. They conducted simulations and experimental tests on heat-transfer performance, but the experimental results differed significantly from expectations. This may be because the pore size difference between the two metal fiber mats used in the experiment was too large. After steam escapes from the bottom fiber mat, the top fiber mat cannot accommodate passage of large amounts of steam because of its small steam channel, resulting in limited steam release. Therefore, to ensure smooth fluid circulation, a proper pore-size ratio should be considered when preparing multi-layer woven meshes or fiber-mat wicks.

3.2.2. Effect of the type of meshes on the performance of multi-layer woven meshes wicks

Huang et al. [98] developed a 0.5 mm thick ultra-thin vapor chamber (UTVC), whose wick was prepared with a 6-strand spiral woven mesh and a single-layer plain woven mesh. This wick can reduce the pressure drop of vapor and liquid flow through the synergistic effect of a spiral-woven structure and a multi-layer, spaced, woven-mesh structure. The temperature difference across positions on the evaporator did not exceed 2 °C, and the effective thermal conductivity at the gravity position was approximately 18,000 W/m·K. Qi Chen et al. [113] fabricated a new ultra-thin heat pipe with a thickness of 0.85 mm. Its internal capillary wick is composed of a 200-mesh plain copper mesh and a hydrophilically treated spiral-woven wire mesh, which play a supporting role in the heat pipe while functioning as a capillary structure for liquid uptake. The results proved that heat transfer performance initially increased and then declined as the number of spiral-woven wire-mesh channels increased. The heat pipe composed of 64.10% spiral-woven wire-mesh channels showed the best thermal performance. When the number of spiral-woven wire meshes is small, there are fewer internal liquid channels, resulting in inadequate capillary pressure; this, in turn, leads to accumulation of working fluid in the condensation section and low heat transfer efficiency. However, when there are too many spiral-woven wire-mesh channels, the number of liquid channels becomes excessive, while the number of steam channels is insufficient. This causes a blockage of steam flow to the condensation section after the working fluid undergoes a phase change, leaving the condensation section with insufficient working fluid and reduced phase-change heat transfer efficiency. Therefore, it is necessary to select a proper wire mesh to set up a suitable number of liquid and gas channels.

3.3. Other biporous wicks

In addition, wicks with two layers of copper nanowires of different lengths have been prepared by electroplating. These double-layer wicks can accelerate the rewetting of the working fluid and the departure of vapor, and the critical heat transfer rate and heat transfer coefficient are increased by 16% and 46%, respectively, compared with a copper plate [102].

Compared with homogeneous wicks, biporous wicks can simultaneously achieve higher capillary pressure and permeability. By matching the particle size of the metal powder to the pore size of the woven mesh or fiber mat and selecting the proper preparation process, the heat-transfer performance of biporous wicks can be effectively improved.

4. Composite wicks

Composite wicks show higher capillary pressure and greater permeability than biporous wicks. Common types of composite wicks include metal powder-groove, woven mesh-groove, and metal powder-woven mesh composite wicks, as shown in Figure 4, and their performances are shown in Table 3. This type of wick offers greater flexibility, enabling the combination of small-pore-size wick components and high-permeability wick components: the small-pore-size components provide high capillary force, while the high-permeability components ensure the smooth flow of the working fluid. Composite wicks are currently the mainstream wick type for high-performance HP/VCs; relevant research primarily focuses on perfecting the synergy between capillary pressure and permeability to achieve optimal heat transfer performance.

Table 3. Performance parameters of composite wicks

Authors	Composite form	Wick structure	Wick thickness	Porosity	Working fluid	Maximum heat flux	Remarks
Zhao Y.[114]	Sintered copper powder and groove composite	50 μm sintered copper powder (equivalent pore size 13 μm); groove width 500 μm	2.5 mm (sintered powder: 0.5mm, groove: 2mm)	/	Degassed distilled water	~480 W/cm^2	Wick was tested with a chamber pressure of 100 kPa, and the wick placed vertically.
Weibel J. A. [115]	Sintered copper powder (carbon nanotube coated) and grooves	100 μm copper powder; grid-like grooves with a width of 508 μm	1 mm	0.5	Water	558 W/cm^2	Wick was tested with a chamber pressure of 101 kPa, and a superheat of 35 °C at evaporator.
Hua Z. H. [64]	Stainless steel powder and grid grooves	Stainless steel powder of unknown diameter grooves with a width of 200 μm	5 mm	0.509	Degassed distilled water	22.63 W/cm^2 Thermal load: 160 W	Wick was prepared by 3D printing process, which all pores are connected. It was tested with a liquid filling rate of 45 %, and air-cooling at the condenser.
Li Y. [116]	Copper powder and grooves	Copper powder with a particle size of 150~180 μm, groove with the depth of 120 μm and width of 60 μm	0.72 mm	/	Distilled water	Thermal load: 35 W; Thermal resistance: 0.027 K/W	Wick was assembled in condenser.

Hwang G. S.[117]	Sintered copper powder and copper woven mesh	Evaporator wick: copper powder with a diameter of 60 μm and 150 μm mixed; Condenser wick: two layers copper woven meshes of 145 mesh Porous column: copper powder with a diameter of 100 μm	0.06 mm (evaporator wick)	/	/	387 W/cm^2	Wicks were assembled into a vapor chamber, and tested with a heating power of 100 W, and the condenser was cooled by cooling plate.
Liu T. Y. [118]	Copper powder and copper grid	Copper powder with a diameter of 50 μm; Copper grid with 8*8 pores per cm^2	500 μm	0.66 (powder layer)	Water	800 W/cm^2	/
Srinivasan D. C. V.[119]	Etched microarrays and grooves on silicon wafers	Microcolumn with a diameter of 7.1 μm and pore size of 9.0 μm; grooves with a width of 30 μm	149 μm	0.79	Water	733.1 W/cm^2	Evaporator wick was tested with a chamber temperature of 100 °C, and a pressure of 1 bar.
Dai X. M. [120]	Woven mesh and grooves sintered composite	Copper woven mesh with a pore of 145 mesh and a wire diameter of 56 μm; Grooves with a width of 250 μm and depth of 250 μm.	320 μm	0.737 (woven mesh)	Degassed distilled water	152.2 W/cm^2	Evaporator wick was tested with a chamber temperature of 100 °C and a superheat of 16~18 °C

4.1. Metal powder - groove composite wicks

Figure 4(a) –(c) illustrates the representative structure and micro-morphology of the metal powder-groove composite wick, a typical composite structure[121–123]. The design intent of this composite structure is to address the performance limitations of traditional single-structure wicks, including single-metal-powder and single-grooved wicks. Traditional grooved wicks show high permeability, but their capillary force is limited by machining accuracy, making it difficult to improve further. In contrast, conventional metal powder wicks provide high capillary forces, but their permeability is limited by porosity and pore size, often leading to poor liquid reflux and dry out. By coupling sintered metal powder with a grooved substrate, the metal powder–groove composite wick achieves synergistic performance optimization: the small-pore metal powder layer provides high capillary force to drive the condensed liquid back from the condensation zone to the evaporation zone, while the large grooves act as efficient liquid transport channels to ensure smooth flow of the working fluid, thereby effectively balancing the trade-off between capillary pressure and permeability.

4.1.1. Effect of groove size on the metal powder - groove composite wicks

For sintered metal powder-groove composite wicks, groove size affects performance. Increasing the width of the groove can improve the permeability of liquid flow, while reducing the width can increase capillary pressure [93]. However, excessively narrow grooves generate overly strong capillary pressure, which can absorb the liquid into the wick at the evaporator and block the vapor escape channel, thereby causing performance degradation. Zhao et al. [114] found that the heat transfer performance of wicks with 500 μm wide grooves was much better than 150 μm-wide grooves. One explanation is that microchannels also generate capillary pressure: the 150 μm-wide microgrooves produce sufficient capillary force to pump “excess” liquid to the heating area, and this surplus liquid accumulates in the microgrooves, blocking vapor escape channels and leading to performance degradation. However, the width of the grooves should not be too large, as excessive width may cause powder to enter and fill the grooves during processing, thus affecting the permeability of the wicks. Li et al. [116] confirmed the effect of the groove width on metal powder-groove composite wicks. When the groove width was sufficiently small, powder particles did not enter the grooves; capillary pressure and permeability reached the best balance, and heat transfer efficiency was maximized. However, when the etching-groove width exceeded the metal powder particle size, the metal powder filled the etching groove, reducing permeability and, so, heat-transfer efficiency.

In addition, Tang et al. [92] concluded the depth of the grooves had a significant impact on the heat transfer performance of the VCs under high heat flux conditions. However, the grooves prepared by general processes were shallow and could not accommodate electronic devices with high heat flux (such as those used in spacecraft). Thus, they proposed a ploughing-extrusion method to prepare microgroove structures with high aspect ratios, secondary channels, and concave cavities. On this basis, Duan et al. [124] used a crosswise plough-extrusion method combined with chemical corrosion surface treatment to prepare VCs with copper powder-groove composite wicks, further improving their heat transfer performance.

4.1.2. Preparation methods of metal powder - groove composite wicks

Two main preparation processes exist for this type of wick. One approach is to directly create grooves in sintered metal powder to form a wick that combines the characteristics of sintered metal powder and grooves. The other is to process grooves on the inner wall of the

HP/VCs shell and then sinter metal powder onto the grooves to form a composite wick [116,125]. M. P. Mughal et al. [126] cut channels on the surface of sintered nickel powder to serve as the evaporator wick of the HP. These channels provided a low-resistance path for vapor escape, and the heat flux of this HP was experimentally found to be 200% greater than that of the HP with a sintered nickel powder wick. Moreover, adding channels extended the service life of the HP. Zhao et al. [114] machined grooves on the surface of sintered copper powder. These grooves further increased the specific surface area of the wick (thereby enhancing the evaporation rate) and provided a transport path for the working fluid (further increasing the fluid circulation rate). Compared with homogeneous wicks, powder-groove composite wicks have an undisturbed longitudinal fluid transport path, thereby increasing the boiling limit and improving heat transfer efficiency. Feng et al. [93] prepared a composite wick with copper powder coating and grooves via the flame spraying-chemical impregnation removal method. The porosity of the coating ranged from 2% to 44%, and the grooves had widths ranging from 160 μm to 530 μm; this composite wick showed higher capillary force than grooved wicks and higher permeability than powder-sintered wicks. Wang and Catton [127] found that the evaporative heat transfer coefficient of HP covered with a thin, porous layer on the groove surface was 3 to 6 times higher than that of a HP without the porous layer.

4.2. Woven mesh - groove composite wicks

Woven mesh-groove composite wicks have also been extensively studied[72,128,129], as shown in Figure 4(d)-(f). This type of composite structure was developed to address the insufficient capillary performance of traditional grooved wicks, which is caused by limitations in machining accuracy. By coupling woven meshes with grooved substrates, these wicks combine the high capillary force of the meshes and the high permeability of the grooves, thereby achieving a synergistic improvement in capillary performance. Studies have demonstrated that their maximum heat load is significantly higher than that of double-layer woven mesh wicks, single grooved wicks, and powder-groove composite wicks, with particularly outstanding performance in ultra-thin flat heat pipes, exhibiting great application potential in high heat flux and ultra-thin thermal management scenarios [83,130].

4.2.1. Effect of groove shape on the performance of woven mesh - groove composite wicks

The shape of the groove can further improve the stability of VCs. Yao et al. [25] prepared a composite wick using an 80/200-mesh and tree-shaped grooves for an anti-gravity VC. The hybrid mesh eased the countermovement of condensate reflux and vapor flow, while the tree-shaped grooves induced vapor distribution; both features greatly improved the heat transfer efficiency of the VC.

4.2.2. Effect of interface on the performance of woven mesh - groove composite wicks

Dai et al. [120] diffusion-bonded a monolayer copper mesh onto grooves, which effectively promoted capillary pressure, reduced flow resistance, and achieved a maximum heat flux of 152.2 W/cm2. However, woven mesh–groove composite wicks show certain problems. If the interface between the mesh and groove is not in tight contact, interfacial thermal resistance increases, seriously impairing heat transfer efficiency. For example, during the flattening process of flat HPs, the woven mesh and grooves are prone to separation, resulting in the formation of a vapor film between the mesh and the grooves during operation, thereby increasing thermal resistance and reducing heat transfer efficiency[83].

4.3. Metal powder - woven mesh composite wicks

Metal powder–woven mesh composite wicks have been less studied[121,123,131], as shown in Figure 4(g) - (i). With the growing demand for ultra-thin VCs, composite wicks with grooves cannot meet thickness requirements, thereby endowing metal powder-woven mesh composite wicks with a distinct application advantage. Xu et al. [130] prepared an ultra-thin VC by electroplating a single-layer stainless steel mesh onto copper micropillars to form a hybrid wick. Stainless steel mesh was chosen because it has a thinner profile than commercially available copper mesh. This VC can operate under a heat load of up to 7.9 W over a heating area of 8 mm × 8 mm, resulting in an effective thermal conductivity of 1398 W/m-K. Feng et al. [132] proposed a novel double-layer wick structure consisting of two layers: a layer of sintered copper powder with four different particle sizes and a layer of spiral woven mesh. The results showed that, compared to the single-wick structure, the proposed double-layer wick structure showed an 11.1% increase in ultimate power.

4.4. Other composite wicks

Composite wicks with alternative structural designs also exist. For example, Sudhakar et al.[133] prepared a composite wick using 5 nm-diameter carbon nanotubes (CNTs) - copper powder, which was applied to the central heating zone of the evaporator. Using this integrated nanostructured wick, the thermal resistance was reduced by a factor of 13 compared with a homogeneous metal powder wick. The small-pore structure formed by the CNT arrays increases the evaporative surface area, thereby increasing the evaporative heat transfer rate. Vinod Srinivasan[119] prepared needle shaped micropillar arrays with a diameter of 3-29 μm via etching technology. These micropillars formed pores of approximately 5–29 μm, while the pillar arrays formed channels 30–60 μm wide and 130–250 μm deep. The heat transfer performance of the composite wick structure formed by the channels between the needle-like micropillars and the arrays could reach 733.1(± 103.4) W/cm^2.

5. Other structure wicks

In addition, adding porous columns between the evaporator and the condenser can enhance heat transfer efficiency. G.S. Hwang et al.[117] integrated distributed porous copper columns into the wick within the 1×1 cm central heating region of the VC, which significantly accelerated the circulation of the working fluid between the evaporator and the condenser in the central heating zone, thereby improving the heat transfer efficiency. And in a separate study, they used multiple porous channels instead of porous columns; this modification further reduced the pressure drop of the working fluid, increased the evaporation surface area, and improved the heat transfer efficiency[134].

There is also a consensus on using wick with different properties for the evaporator and the condenser[135,136]—for instance, employing sintered copper powder as the evaporator wick and copper woven mesh as the condenser wick[117]. Overheating in a VC is usually caused by the formation of a vapor film at the evaporator. By adjusting the capillary pressure and permeability of the wick, the nucleation sites of bubbles can be constrained, which delays the vapor film formation and improves heat transfer performance[95].

6. Comparison of heat transfer performance of different types of wicks

The proper wick structure should be selected based on the specific heat flux and operating temperature conditions[137]. According to literature reports, the critical heat flux and superheat temperature for different types of typical wicks are summarized in Figure 5. The structures and heat-transfer performance of three types of wicks are summarized in Tables 1, 2, and 3. Specifically, Table 1 focuses on wicks with homogeneous pore structures, encompassing copper powder beds, woven meshes, and grooved configurations. These wicks show maximum heat flux values ranging from ~16 to 367.9 W/cm^2; their performance depends heavily on pore size and structural thickness. Table 2 highlights biporous metal powder wicks, which prove exceptional heat transfer capabilities—with a maximum heat flux of up to 990 W/cm^2—owing to their hierarchical large-pore/small-pore networks that balance capillary forces and permeability. Table 3 presents composite wicks (e.g., powder-groove, powder-woven mesh, and etched microcavity structures) running at heat fluxes spanning ~ 22.6 to 800 W/cm^2, reflecting their tailored design for advanced thermal management scenarios. As shown in Figure 5, biporous metal-powder wicks show the highest critical heat flux and superheat temperature among the categories. Metal powder-groove composite wicks and metal powder-woven-mesh composite wicks rank equally second in superheat temperature, with negligible differences between them, while their critical heat flux values rank second and third, respectively. The critical heat flux and superheat temperature of homogeneous, multi-layer woven mesh, and woven mesh-groove composite wicks are not significantly different.

However, as detailed in Tables 1, 2, and 3, testing conditions and methodologies vary markedly across studies, introducing substantial uncertainty in comparisons of performance across types. For example, in Table 1, homogeneous wicks were tested both in standalone configurations and in assembled heat pipes, with working fluids ranging from degassed water to ammonia and cooling conditions switching between air and water. Table 2 reports evaluations of biporous wicks under varying vapor chamber pressures and heating powers, while Table 3 presents data on 3D-printed, sintered, and etched composite structures in which fabrication methods directly influenced porosity and pore connectivity. These variations in testing components (single wick, assembled HP, or assembled VC), part dimensions, heating power, and cooling conditions can significantly skew reported critical heat flux and superheat values, underscoring the urgent need for standardized testing protocols to enable meaningful cross-study comparisons.

7. Applicability of wicks in different scenarios

As the core functional unit of heat pipes and vapor chambers, the structural design and material selection of wicks must be highly tailored to the thermal management challenges of different scenarios, which directly determines the performance upper limit of thermal management systems (Egbo et al., 2026). Table 4 summarizes common heat dissipation scenarios and the corresponding wicks for heat pipes and vapor chambers.

In mobile-phone thermal-dissipation scenarios, ultra-thinness, high integration, and compatibility with compact spaces are core requirements. Ultra-thin sintered copper mesh wicks and stainless steel etched grooved wicks have become the mainstream owing to their ultra-thin profile and excellent integrability and have been applied to flagship models such as Huawei Mate 60 Pro and Samsung Galaxy S25 Ultra to meet their dual needs of slim design and stable thermal dissipation [2]. For laptops, portability and adaptive performance under dynamic heat flux conditions are core goals. Sintered copper powder wicks have been adopted in models such as Razer Blade 16 and Lenovo Legion Y9000X owing to their high porosity and excellent capillary pumping capacity.

For thermal dissipation of high-power LEDs, the core challenges include high heat flux density (50~200 W·cm^{-2}), anti-dry out performance, and high-temperature resistance. Flat heat pipes integrated with sintered copper powder wicks have become the mainstream solution, whose superior capillary force and thermal stability can effectively resist the risk of working fluid dry-out under long-term high-temperature conditions[139]. For the thermal dissipation of electric vehicle batteries, liquid cold plates stay the mainstream at present, but studies on loop heat pipes have proved the potential to adapt to the large-volume and high-reliability thermal dissipation requirements of battery packs [140]. In server CPU thermal-dissipation scenarios, liquid cooling stays the mainstream approach; however, vapor chambers have shown promising prospects for CPU cooling in blade servers. Their matched wicks need to enhance vibration resistance by using high capillary forces to adapt to the harsh environment of data centers.

For extreme scenarios such as aerospace and space nuclear energy, wicks must meet requirements for extreme environmental tolerance, high reliability, lightweight design, and resistance to strong vibration and impact. The sintered stainless steel powder wick adopted in the Hispasat 30W-5 satellite copes with the space vacuum and drastic temperature changes by virtue of the high temperature and corrosion resistance of stainless steel; the Kilopower space nuclear energy system selects titanium grooved wicks or hybrid screen-groove composite wicks, and the radiation resistance and high thermal stability of titanium materials are adapted to the extreme working conditions of nuclear energy thermal conversion[141].

Overall, the thermal management requirements vary significantly across different scenarios. With continuously increasing thermal dissipation demands across various application fields, the application scope of heat pipes/vapor chambers will continue to expand from consumer electronics and data centers to new energy, aerospace, and other scenarios, thereby proving broader market prospects and technical potential. As a core part of heat pipes and vapor chambers, wicks will also undergo increasingly diversified and scenario-targeted development.

8. Development directions

Wick structures have gradually evolved from homogeneous and biporous designs to composite configurations, with corresponding significant improvements in thermal transport performance. However, in large-scale, stable practical applications, most fields still adopt homogeneous wick materials, such as metal powders and woven meshes, while the application of composite wicks stays rare. The main reasons for this phenomenon are that the thermal performance of homogeneous wicks is sufficient to meet the requirements of most current applications, eliminating the demand for more complex wick structures; that the fabrication processes of composite wicks are relatively complicated and require precise matching of multiple components as well as sophisticated forming control, which makes batch production with stable performance difficult to achieve; that such complex manufacturing inevitably raises production costs and results in weaker economic competitiveness compared with mature homogeneous wicks; and that long-term reliability validation for composite wicks is still insufficient, which restricts their direct large-scale engineering application. In summary, the large-scale and stable application of composite wicks still requires long-term research and exploration.

Therefore, further research is needed to improve the consistency between testing methods and actual operating conditions, to promote the transition of composite wicks from laboratory research to engineering applications. First, common problems in wicks must be addressed, such as particle detachment in metal powder wicks; the slow response of the working fluid during heat transfer; and the generation of non-condensable gases under long-term cyclic operation. These problems not only reduce the heat transfer efficiency and temperature uniformity of heat pipes/vapor chambers (HP/VCs), but also markedly shorten components' service life and limit their reliable application in key fields.

Second, performance priorities for wicks should be perfected according to the requirements of different practical application scenarios. For example, HP/VCs for aerospace applications need to consider a lightweight design, heat-transfer efficiency under extreme temperatures, and a long service life to adapt to harsh space conditions. Wicks for portable electronic devices should be customized for minimal thickness and omnidirectional heat-transfer performance (horizontal, vertical, and inclined orientations) to meet the trend toward lightweighting. For high-temperature and high-power scenarios such as charging stations and data centers, heat transfer efficiency should be considered the primary optimization aim to ensure effective heat dissipation. Thirdly, it is necessary to further improve heat transfer simulation models and testing platforms to compensate for existing platforms' shortcomings in reproducing complex, real operating conditions, in order to obtain test data that are highly consistent with real operating states and to provide more accurate and reliable technical support for the performance optimization, structural design, and practical engineering application of wicks.

Author contributions

LL, YW: Conceptualization, Methodology. JZ: Writing – original draft. KT: Investigation, Resources. HL: Formal analysis, Data Curation. JW, RL: Writing – review & editing, validation. All authors read and approved of the final manuscript.

Conflict of interest

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Abbreviations

HP	Heat pipe
VC	Vapor chamber
LED	Light Emitting Diode
SLM	Selective Laser Melting
UTHP	Ultra-thin heat pipe
MCMW	Multilayer composite micromesh wick

MSMW Multilayer single mesh wick
UTVC Ultra-thin vapor chamber
CNT Carbon nanotubes

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