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Original Research

Flexible heat pipes with integrated bioinspired design

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Abstract

In this work we report the facile fabrication and performance evaluation of flexible heat pipes that have integrated bioinspired wick structures and flexible polyurethane polymer connector design between the copper condenser and evaporator. Inside the heat pipe, a bioinspired superhydrophilic strong-base-oxidized copper mesh with multi-scale micro/nano-structures was used as the wicking material and deionized water was selected as working fluid. Thermal resistances of the fabricated flexible heat pipes charged with different filling ratios were measured under thermal power inputs ranging from 2 W to 12 W while the device was bent at different angles. The fabricated heat pipes with a 30% filling ratio demonstrated a low thermal resistance less than 0.01 K/W. Compared with the vertically oriented straight heat pipes, bending from 30° up to 120° has negligible influence on the heat-transfer performance. Furthermore, repeated heating tests indicated that the fabricated flexible heat pipes have consistent and reliable heat-transfer performance, thus would have important applications for advanced thermal management in three dimensional and flexible electronic devices.

Keywords: Flexible heat pipe; Superhydrophilic; Polymer; Thermal resistance

1. Introduction

Human as a natural three dimensional flexible system has integrated many natural flexible accessories. One of such flexible accessories is the blood vessel, which serves not only as a transportation highway for nutrition delivery, but also as a flexible thermal conductor for thermal management of human bodies. This paper intends to build an artificial flexible heat conductor using the principle of heat pipes. As a passive heat-transfer device with high effective thermal conductivities and requiring no maintenance, heat pipes have become an important tool for thermal management of electronic systems [1]. A heat pipe normally consists of a hermetic container, working fluid that can absorb heat from the heat source upon vaporization and release heat at the condenser section, and a wick structure that supplies capillary forces to pump the condensed liquid back to the hot evaporator section forming a heat-transfer cycle loop. The container materials were mostly made of rigid metals such as copper, aluminum and stainless steel, due to their high thermal conductivity, mechanical robustness and excellent barrier properties. Thus, the fabricated heat pipes are usually used in a straight configuration, lacking the flexibility and bendability to fulfill their wider applications required in contorted configurations where heat sources and heat sinks are not in the same plane or the heat source is not stationary [2,3]. A flexible heat pipe similar to the flexible human blood vessel is in urgent need in order to meet the thermal management requirement of three dimensional and flexible electronic systems.

The earliest effort in flexible heat pipes can be dated back to 1970. Bliss et al. [4] connected the rigid copper evaporator and condenser with a brass bellowed tube in the adiabatic section and realized bending of the heat pipes at 45° and 90° during horizontal operation. While bellows improved the bendability, in most cases the heat pipes were still rigid and were integrated into systems with bends fabricated a priori [5,6]. Heat pipes that can be easily bent for many times and easily bent into designed geometries are highly desired. In recent years, polymer based heat pipes have attracted increasing attention owing to the

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advantageous features from polymers including flexibility, lightweight, good processability and low cost. Various polymers such as polypropylene [7], polyimide [8], liquid-crystal polymers [9], polyethylene terephthalate [10–12] and silicone [13,14] have been utilized as the container material. These polymer based heat pipes were often flat, micro or pulsating heat pipes with small power capacities and large thermal resistances due to the low thermal conductivity of the polymer casing materials. To mitigate the issue of large thermal resistance for the pure polymer heat pipes, high thermal conductivity copper-filled thermal vias [9], copper mesh [11], or copper sheet [13] were fabricated in the evaporator and condenser sections. However, the fabrication usually involves complicated and time-consuming micro-fabrication processes such as multi-step molding, bonding and assembly.

Wick structure is another important component for designing and fabricating flexible heat pipes. Conventional sintered copper powders [1] or recently reported sintered copper felts [6,15] within copper tubes are not compatible with the low-temperature processing of polymer heat pipes. By contrast, copper meshes or copper fibers which were sintered at high temperatures under protective inert gas environment are used as the popular wicking materials for polymeric flexible heat pipes [16]. Besides the good bendability of the copper mesh, the wicking materials should have good wettability with working fluids to maximize their capillary pumping force. Previously, Oshman et al. [11] deposited an Al_2O_3/SiO_2 bi-layer coating on to the sintered copper mesh by atomic layer deposition technique to promote wettability of the mesh with water. Biological materials such as moss and *Rhacocarpus purpurescens* leaves have developed natural hierarchical micro/nano-structures rendering their surfaces superhydrophilic [17]. It is expected that by fabricating nature inspired hydrophilic materials and using them as the wicking material would be able to effectively improve the capillary pumping capabilities of heat pipes.

In this work, we report a facile approach to prepare flexible heat pipes that have integrated the bioinspired superhydrophilic wick structure and the flexible connector design in the adiabatic section. The cylindrical heat pipes were fabricated by connecting copper tubular evaporator and condenser with flexible polyurethane and using water as the working fluid. Superhydrophilic flexible strong-base-treated copper meshes were adopted as the wicking materials. Thermal performance tests were carried out with different thermal power inputs to the evaporator while the device was bent at 0°, 30°, 60°, 90° and 120°. Compared with the pure polymer heat pipes, our heat pipes demonstrated much smaller thermal resistances while maintaining excellent flexibility. It was found that bending has negligible impact on the thermal performance of the fabricated flexible heat pipes.

2. Experimental

2.1. Materials

Copper tubes, copper mesh (No. 300) and polyurethane tubes were purchased from Shanghai hydraulic pipe fittings Co., Ltd., Shanghai Hengxin wire & mesh Co., Ltd. and Shanghai Yihui Rubber & Plastics Co., Ltd., respectively. The bonding adhesive (TS1415) was purchased from Beijing Tianshan Kesaixin adhesive Co., Ltd. The HCl solution was obtained from Shanghai Lingfeng Chemical reagent Co., Ltd. KOH and $K_2S_2O_8$ were purchased from Sinopharm Chemical reagent Co., Ltd. and Aladdin reagent Co., Ltd., respectively.

2.2. Preparation of wick

The purchased copper meshes were subject to a chemical treatment by following the procedure described by Xie et al. [18]. The copper mesh was first immersed in a 4 mol/L HCl solution for 15 min followed by rinsing with deionized water. The acid-cleaned mesh was then transferred to the mixed solution of 0.065 mol/L $K_2S_2O_8$ and 2.5 mol/L KOH at 60 °C for 60 min. Finally, the treated mesh was cleaned and dried.

2.3. Fabrication of heat pipes

The cylindrical heat pipes were fabricated by utilizing copper tubes with an outer/inner diameter of 5/4 mm and a length of 150 mm at the evaporator and condenser section, and using a polyurethane tube with an outer/inner diameter of 8/5 mm and a length of 100 mm in the adiabatic section, respectively. The copper tubes were first cleaned by immersing them into 10 vol% sulfuric acid with the assistance of ultrasonic vibration. The copper tubes and the polyurethane tube were bonded together using an adhesive (TS1415) at room temperature for 24 h. The bonding was further mechanically strengthened by a tightening belt. Then, the aforementioned treated copper mesh was tightly inserted into the heat pipe to serve as the wicking material. Deionized water was selected as the working fluid. Three different filling ratios (20%, 30% and 40%) of deionized water were charged to identify the optimum filling ratio. The heat pipe was outgassed by heating the bottom section with a heater and a thermal couple was attached at the upper exit end to monitor the outgassing process. The charged heat pipe was clamped with a pinch-off tool and finally sealed with tungsten arc welding under the purge of Argon gas.

2.4. Characterization and property measurement

Microstructure of copper mesh wicking structures was examined by a scanning electron microscopy (FEI Sirion 2000). The wettability of the untreated and treated copper mesh wick was evaluated by measuring their contact angle with water.

Fig. 1 presents the test setup for heat-transfer performance measurement. The evaporator section was encased by a silicone rubber heater. The heater was connected to an adjustable DC power supplier (TPR 3005T, Shenzhen Atten Technology, Co. Ltd.). The condenser section was in close contact with a cooling plate (Shanghai Bilon Equipment) running with circulated chilling water at 15 °C. A porous plastic thermal insulation material was used to wrap the evaporator and adiabatic sections to prevent heat loss. Two K-type thermocouples (DM6801A, Nanjing Victor Equipment, Co. Ltd.) were mounted on the heat pipe to record the temperature. The temperature readings

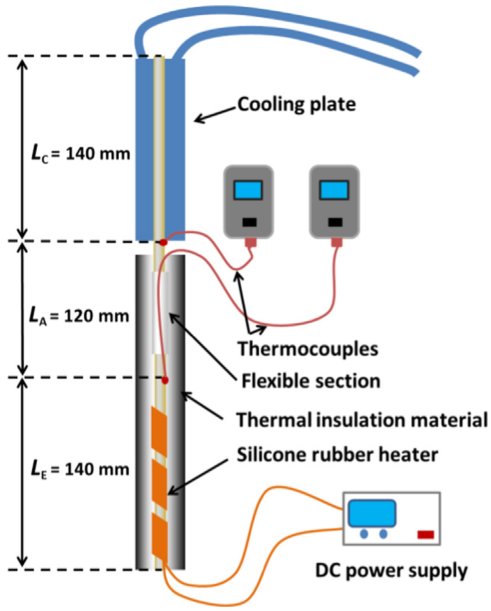

Fig. 1. A schematic of test setup for measurement of the thermal resistance of flexible heat pipes.

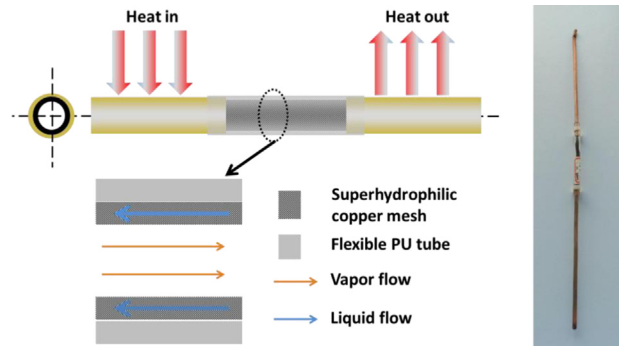

Fig. 2. A schematic cross-section of the flexible heat pipe and a photograph of the fabricated heat pipe.

were taken when they reached a steady state under a certain power input. The temperature difference between the evaporator (T_e) and the condenser (T_c) was used to calculate the thermal resistance (R) of the heat pipe as shown by the following equation:

$$R = \frac{T_e - T_c}{P}$$

where P is the heating power (from 2 W to 12 W). The heat pipes were tested in a straight configuration and bent with different angles (30°, 60°, 90° and 120°). An empty copper tube was used as the benchmark sample.

3. Results and discussion

Fig. 2 presents the schematic and a photograph of the prepared flexible heat pipe. Considering that the total thermal resistance (R_t) can be roughly estimated as a sum of the thermal resistance of evaporator wall (R_e), vapor channel (R_v) and condenser wall (R_c), whole pure polymeric heat pipes would have a large R_t as polymers generally have a low thermal conductivity. Here we used polyurethane which is flexible but with a high thermal resistance only at the adiabatic section to decrease R_e and R_c. Compared with other polymer materials such as silicones, polyurethane has a good combination of flexibility, mechanical robustness and gas barrier properties. The metallic copper evaporator and condenser ensure the good heat-transfer capability of the prepared heat pipes.

Fig. 3a shows a photograph of a curled copper mesh with a dimension of 30 mm × 400 mm. The SEM image at low magnifications in Fig. 3b presents that the copper mesh has a wire diameter of ~36 μm and a spacing of ~45 μm. The porous copper meshes have been used as the wicking materials for flexible heat pipes as they are industrial available and robust enough to allow for repeated bending while providing a strong capillary pumping force. However, the purchased copper mesh is highly hydrophobic showing a contact angle of 135° even after cleaning with dilute sulfuric acid. To improve the wettability of copper meshes with the deionized water working fluid, Li and Peterson [16] sintered them at a high temperature of 1030 °C for 150 min under the purge of Argon gas. In addition, multi-layered copper meshes or copper mesh micro-groove hybrid wick structures [9] were designed and fabricated to improve wettability of the wick materials and thus to enhance their capillary pumping capability.

As demonstrated by the photograph of a black curled mesh in Fig. 3c, after oxidation within a strong base solution the copper mesh turned into black colored but retained its flexibility feature. The treated mesh showed excellent wettability and water can easily spread on it. Comparison of the SEM images in Fig. 3c and d shows that unlike the smooth surface of the as-purchased copper meshes, dense acicular micro/nano-structures were observed on the surface of the treated copper mesh. According to description from Xie et al. [18], the involved chemical process is as following:

$$Cu + 2KOH + K_2S_2O_8 \rightarrow Cu(OH)_2 + 2K_2SO_4.$$

After treatment, Cu was converted into hydrophilic $Cu(OH)_2$ and the hierarchical mico/nano-structured rough surface further amplified the wettability rendering a superhydrophilic wick structure. It should be mentioned that conventional sintering approaches often only generate hydrophilic wicks and require high-temperature processing. By contrast, the strong base oxidation method is much simpler and yielding superhydrophilic structures.

To identify the influence of working fluid filling ratio on the heat-transfer performance of the heat pipes, three different volumetric loadings (20%, 30% and 40%) of deionized water were charged. Two thermocouples were mounted onto the evaporator and condenser to monitor the temperature change of the heat pipes in a vertical gravity-assisted configuration. Fig. 4a presents that the evaporator temperature (T_e) and the condenser temperature (T_c) increased linearly with increasing power input to the evaporator section as the heat transfer dominantly relies on heat conduction mechanism. Accordingly, the thermal resistance (R) of the copper tube showed a nearly

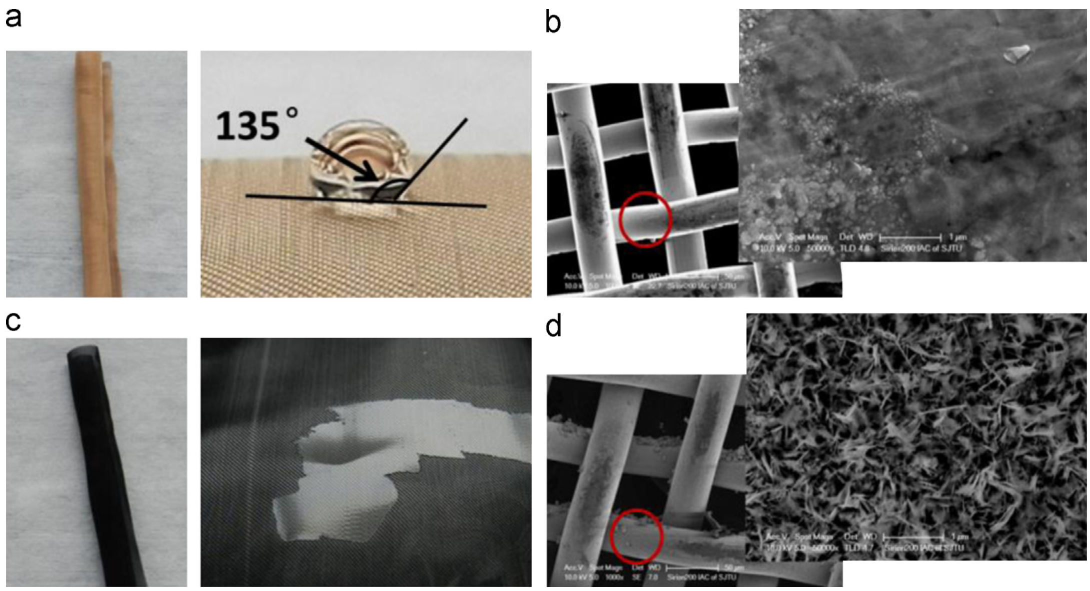

Fig. 3. (a) A photograph showing a curled flexible hydrophobic copper mesh; (b) SEM images of copper mesh at low and high magnifications; (c) a photograph showing a flexible hydrophilic copper mesh after treatment with strong bases; and (d) SEM images of treated copper mesh at low and high magnifications.

constant value (~8 K/W). Heat pipes with different filling ratios demonstrated different heat-transfer performances. At low power inputs, in general, there is no enough driving force to observe the heat pipe effect as evidenced by the large temperature difference between T_e and T_c at 2 W and 4 W. When the working fluid filling ratio was 20%, until the input power reached 10 W the temperature difference significantly reduced (Fig. 4b). With higher filling ratios, the near constant-temperature heat-transfer effect was observed when the heating power reached 6 W (Fig. 4c and d).

Fig. 5 presents that the thermal resistance of the heat pipes decreased with increasing power inputs. When the thermal input at the evaporator section was 2 W, the heat pipe filled with 40 vol% water even showed a lower thermal resistance than the benchmark copper tube sample. This probably could be related with the fact that with 40 vol% loading the upper liquid surface was very close to the thermocouple at condenser and water contributed as the additional heat conduction medium. By comparison, with 20% and 30% filling ratios the charged working fluid was not enough to fill the polyurethane tube. The low thermal conductivity polyurethane tube sacrifices the good thermal conducting properties of the fabricated heat pipe leading to a higher thermal resistance than the empty copper tube. Although 30% and 40% filling ratios yield similar thermal resistances, close examination indicates that the thermal resistance of the heat pipe charged with 30% filling ratio was even lower (less than 0.01 K/W). This value is much smaller than the data reported by others in pure polymeric heat pipes. It appears that 30% is an optimum filling ratio and this value is also close to the reported data in the literature [9–11]. At low filling ratios, there was no enough working fluid delivering heat from evaporator to condenser. The evaporator temperature kept increasing rapidly leading to a large temperature difference between T_e and T_c. While at high filling ratios, the heat at the evaporator initially can be delivered to the condenser, but too much working fluid would over-flood the evaporator section resulting in decreased wicking forces to pump the condensed fluid back to evaporator [19]. This finally leads to rising temperature at the evaporator and thus large temperature differences and thermal resistances.

In order to evaluate heat-transfer performances in the bending condition, the thermal resistance of heat pipes filled with 30% water was tested at different bending angles from 30° to 120° as schemed by Fig. 6a. The results were compared with heat pipes in the straight configuration. Fig. 6b depicts the thermal resistance of the bent heat pipes as a function of different heat power inputs. In general, the thermal resistance increment with increasing bending angles at lower heating powers (2 W, 4 W, 6 W) is distinguishable as the heat pipe effect was not effectively activated and thermal resistance of the pipe was high. As the heating power increases the thermal resistance difference gradually diminished. When the power was larger than 8 W, the thermal resistance curves were almost overlapped and the influence of bending was too subtle to be observed.

When the heat pipe bends, the cross-sectional area for the vapor channel would be reduced and the normal vapor flow in straight pipes would be interrupted. Specifically, in the curved pipes the secondary rotating flows, which were induced by the combined friction force at heat pipe walls and the centrifugal force, would add to the original main flow along the pipe axial. As summarized by Wongwises and Naphon [20], the correlation factor for vapor flow in curved tubes and straight tubes can be empirically described by:

$$\frac{f_c}{f_s} = 1 + f(R_e,\ D_e)$$

where f_c is the flow resistance factor of curved tubes, f_s is the flow resistance factor of straight tubes, the $f(R_e,\ D_e)$ term is a function of Reynolds number (R_e) and Dean number (D_e). This term is mainly related to the relative diameter of the cylindrical

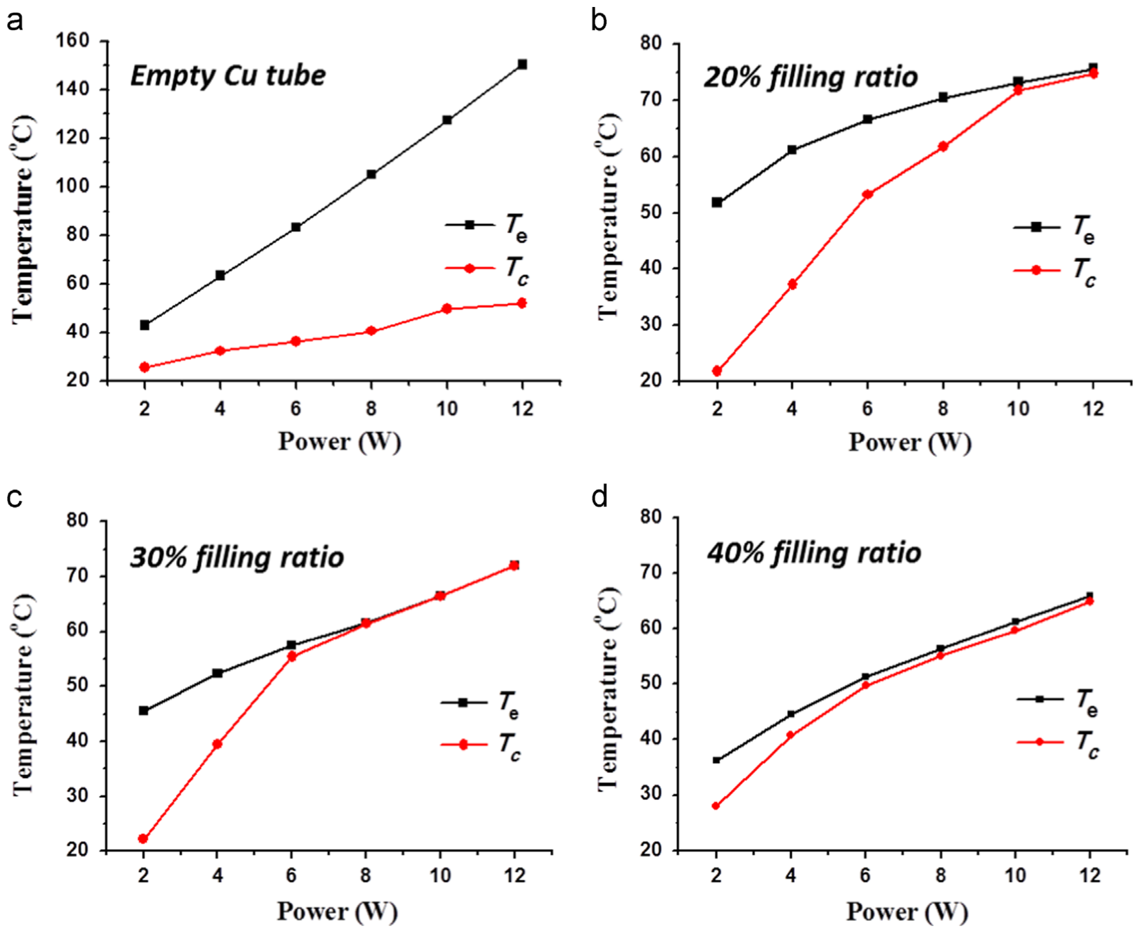

Fig. 4. Temperature of the fabricated flexible heat pipe at evaporator and condenser sections: (a) empty copper tube; (b) 20% filling ratio; (c) 30% filling ratio; and (d) 40% filing ratio.

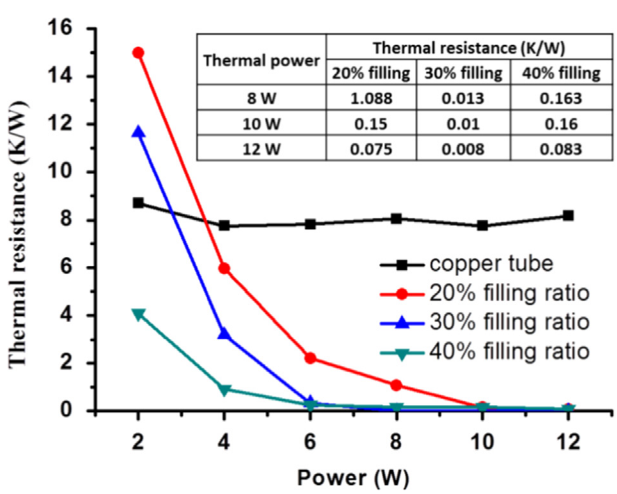

Fig. 5. Thermal resistance of fabricated flexible heat pipes charged with different filling ratios of working fluid.

heat pipe and radius of curvature of the bent polyurethane tubes. The higher f_c causes additional pressure drop resulting in extra thermal resistances. In our case, the small ratio of the channel diameter to radius of curvature would only produce a small pressure drop in the channel flow. Furthermore, the strong mechanical robustness of the cylindrical polyurethane tubes allows for conformal bending instead of being squeezed, thus ensuring smooth vapor flow. These two factors would minimize the bending influence on the thermal resistance of the fabricated flexible heat pipes.

It is worthy pointing out that in our gravity-assisted operation mode bending also affects the gravitational contribution. When bending angle increases to 90° the upper half section of the heat pipe is oriented to the horizontal configuration where the axial gravitational pressure drop was absent. When further increasing the bending angle to 120°, gravity became an opposing force to the capillary pumping force. Indeed, we did observe higher thermal resistances for heat pipes bent at large angles (90° and 120°). But the thermal resistance difference was almost negligible under high power inputs at the evaporator section. High heating power induces high vapor pressure and weakens the influence of flow resistance on heat-transfer. The good heat-transfer performance of the flexible heat pipes should be attributed to their strong capillary pumping capabilities that were associated with the bioinspired superhydrophilic wick structures.

A preliminary reliability test of the fabricated heat pipes was conducted by repeated measurement of their thermal resistances at a fixed bending angle of 90°. Every heating test by increasing the power input from 2 W to 12 W lasts for more than 2 h. Fig. 6c

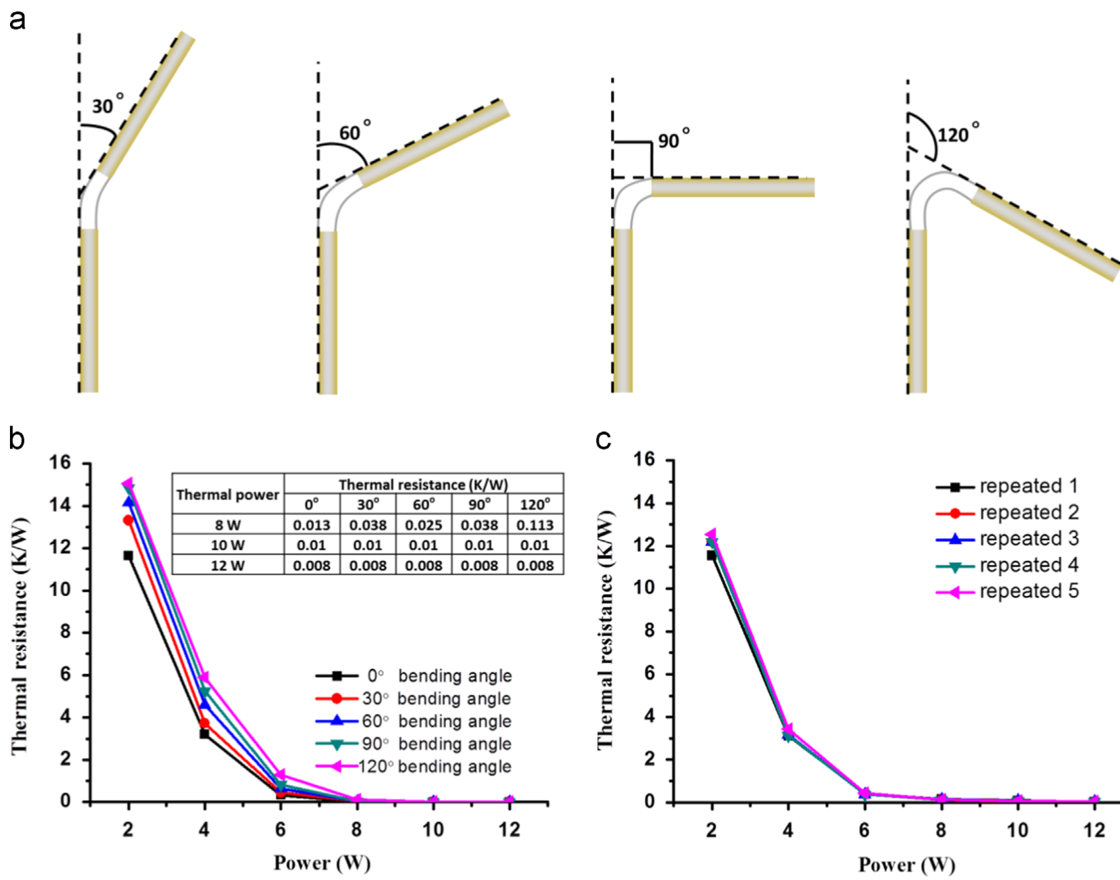

Fig. 6. (a) Schematic illustration of bending experiments; (b) thermal resistance of flexible heat pipes filled with 30% working fluid bent at different angles; and (c) thermal resistance after repeated bending tests.

shows that the fabricated heat pipes demonstrated consistent and stable thermal resistances and no obvious degradation of thermal performance was observed after more than 10 h operation. It should be mentioned that after the repeated cycling tests the original as-fabricated superhydrophilic $Cu(OH)_2$ wick layer was converted into thermodynamically more stable CuO at high temperatures. This transition was confirmed by XRD analysis of the wick meshes within the tested heat pipes. However, the converted hierarchical CuO wick meshes still preserve their excellent wettability with water. The unique wicking structure design and utilization of copper tubes in the evaporator and condenser achieved an overall low thermal resistance of the flexible heat pipe. This low thermal resistance enabled effective and timely heat transfer from evaporator to condenser, which in turn benefits the good reliability of fabricated flexible heat pipes. In the future work, metal laminated polymeric flexible connectors will be explored to realize higher thermal power delivery and thermal management of high-power electronic devices.

4. Conclusions

In this work, a bioinspired high-performance flexible heat pipe has been successfully developed by a simple and cost-effective low temperature process. Different from widely explored whole polymeric heat pipes, a flexible polyurethane tube was only used at the adiabatic section to connect copper tubes at the evaporator and condenser to minimize the overall thermal resistance and to mimic the flexibility of the heat conducting blood vessel in human body. Strong-base-oxidized superhydrophilic copper meshes bearing bioinspired hierarchical micro/nano-structures were utilized as the wicking material. Tested under a vertically gravity-assisted configuration, the results showed that bending had almost negligible influence on the thermal resistance of the fabricated heat pipes especially under high heating power inputs at the evaporator section. The combined flexibility and the consistent thermal performance could be attributed to the flexible polymeric connector design and the strong capillary pumping from the bioinspired superhydrophilic wicking structure. It is anticipated the higher power and reliable flexible heat pipes could be also developed by the similar approach, offering a powerful thermal management tool for flexible and wearable electronic devices.

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