Proceedings of the 10th International Conference on Heat Transfer and Fluid Flow (HTFF 2023)
Brunel University, London, United Kingdom –August 06-08, 2023
Paper No. HTFF 150
DOI: 10.11159/htff23.150

A Flexible Pulsating Heat Pipe with Multiple Heat Transfer Branches

Zhanxiao Kang[1,2], Jintu Fan[1,3]
[1]School of Fashion and Textile, Hong Kong Polytechnic University
Hung Hom, Kowloon, Hong Kong, China
z.x.kang@polyu.edu.hk; jin-tu.fan@polyu.edu.hk
[2]Future Intelligent Wear Centre, The Hong Kong Polytechnic University
Hung Hom, Kowloon, Hong Kong, China
[3]Research Institute of Sports Science and Technology, Hong Kong Polytechnic University
Hung Hom, Kowloon, Hong Kong, China

***Abstract* -** Flexible heat pipes are highly desired in many applications, such as human body thermal management, cooling of flexible electronic devices, and waste heat or renewable energy harvesting. In general, the thermal performance of flexible heat pipes is inversely proportional to flexibility. In this paper, a flexible heat pipe with multiple heat transfer branches was fabricated by Teflon tubes in the middle section and copper tubes in the heating and cooling sections based on the working principle of a pulsating heat pipe, which had both good thermal performance and flexibility. The experimental results showed that the thermal performance of the heat pipe decreased with increasing the bending angle or decreasing the inclination angle of the heat pipe. Furthermore, the apparent thermal conductivity of the proposed flexible heat pipe increased with the increasing heat power, which was up to 4333 W/(m·K) at the heat power of 24.6 W. In addition, as all the heat transfer branches had a large portion of the soft section (Teflon tube), they could deform independently with excellent flexibility. Therefore, the proposed flexible heat pipe can contribute to advanced thermal management and energy applications, which is beneficial to improve human thermal comfort as well as reduce fossil energy consumption and greenhouse gas emissions.

***Keywords*:** flexible heat pipe; pulsating heat pipe; multiple branches; heat and mass transfer; thermal management

1. Introduction

Heat pipes have high heat transfer capacity due to the high heat transfer coefficients of evaporation and condensation of the working fluid (e.g., water)[1-3], which are widely used in electronics cooling, waste heat recovery, industrial heat exchange, renewable energy harvesting, and even space/aircraft[4]. In general, the heat pipe is composed of a sealed pipe or tube partially filled with a working fluid. As non-condensable gas (e.g., air) can slash the heat pipe's thermal performance, a vacuum pump is generally used to remove the air from the empty heat pipe, and thus the classical heat pipes usually have a rigid structure to combat the vacuum. However, the rigid structure cannot meet the application demands in many cases when the heat transfer surfaces are complex (e.g., human body surface) or the positions of the heating and cooling sections are changeable or in different planes (e.g., flexible electronics).

To tackle this problem, flexible heat pipes have gained increasing attention[5]. One commonly used method to develop flexible heat pipes is to connect the rigid heating and cooling sections of the heat pipe using a flexible tube[6], whereas the flexibility of such heat pipes is limited due to the small fraction of the flexible sections. Hence, many studies are focused on making flexible heat pipes with flexible materials such as polymers. Hsieh and Yang[7] used silicone rubber to make a flexible heat pipe where a copper mesh was used as the wicking material, the thermal resistance of which varied from 5 to 7 K/W corresponding to the effective thermal conductivity from 98 to 137 W/(m·K). Oshman et al.[8] applied laminated composite sheets to develop a flexible heat pipe where a sintered copper woven mesh served as the wicking layer, leading to the lowest thermal resistance being up to 1.2 K/W [effective thermal conductivity: 824 W/(m·K)]. Furthermore, Liu et al.[9] adopted an aluminum compound packing film to fabricate a flexible heat pipe with functional copper meshes as the wick material, the thermal conductivity of which could be up to four times higher than that of copper. Nonetheless, the equivalent thermal conductivity of the abovementioned heat pipes fabricated by flexible materials were limited that cannot meet the demand for practical applications.

In addition, the pulsating heat pipe is another promising approach to developing flexible heat pipes, since they can work without the wicking layers[10]. Lim and Kim[11] proposed a flexible pulsating heat pipe made of a multilayer laminated film and a low-density polyethylene sheet, the equivalent thermal conductivity of which was up to twice that of copper. Der et al.[12] used plastic materials to fabricate a flexible pulsating heat pipe with a sandwiched structure, where the plastic channels were sealed by two pieces of polypropylene sheets. The lowest thermal resistance was up to 2 K/W corresponding to the highest thermal conductivity of about 714 W/(m·K). Furthermore, by incorporating long fluororubber tubes and the short copper heating and cooling sections, Qu et al.[13, 14] constructed flexible pulsating heat pipes with the equivalent thermal conductivity being over 4000 W/(m·K). Inspired by the squid structure and the working principle of a pulsating heat pipe, Kang et al.[15, 16] developed a flexible heat pipe with multiple heat transfer branches, which has outstanding flexibility and excellent equivalent thermal conductivity up to 6750 W/(m·K).

Based on the squid-like heat pipe, we further fabricated a flexible heat pipe with Teflon tubes in the middle section and copper tubes in the heating and cooling sections and then tested its apparent thermal conductivity without insulating the middle section since the middle section of the heat pipe is generally not insulated in many applications (e.g., electronic cooling). To guarantee the universality of the proposed flexible heat pipe, the diameters of all the Teflon tubes are the same. This study could guide the design of the squid-like flexible heat pipe as well as its efficient working principles in practical applications, which is important for cooling flexible electronics, body thermal management, waste heat recovery, and renewable energy harvesting.

2. Experimental Method

The envisioned flexible heat pipe is shown in Fig. 1(a), which consisted of three heat transfer branches that were interconnected. Each branch was composed of the middle Teflon tube with inner and outer diameters of 1.8mm and 2.6mm, respectively, and the copper heating and cooling tubes with inner and outer diameters of 1mm and 2mm, respectively. The length of the Teflon tube was 107 mm, while the lengths of the heating and cooling sections were 66mm and 50mm, respectively. Hence, the equivalent heat transfer length of the heat pipe was 165 mm. Furthermore, the copper tubes in the heating and cooling sections were embedded in the aluminum blocks to increase the heat transfer area. Meanwhile, acetone was chosen as the working fluid and the filling ratio of 60% was tested in all the experimental cases[17]. The whole heat pipe was first vacuumed by a vacuum pump to about 4 mPa, and then acetone was injected into the heat pipe through the T-junction at the bottom. Moreover, three thermocouples (T_1, T_2, and T_3) were used to monitor the temperature development in the heating section, while the other three thermocouples of T_4, T_5, and T_6 were adopted to monitor the temperatures of the three cooling pads from the left to right, respectively, as shown in Fig. 1(a).

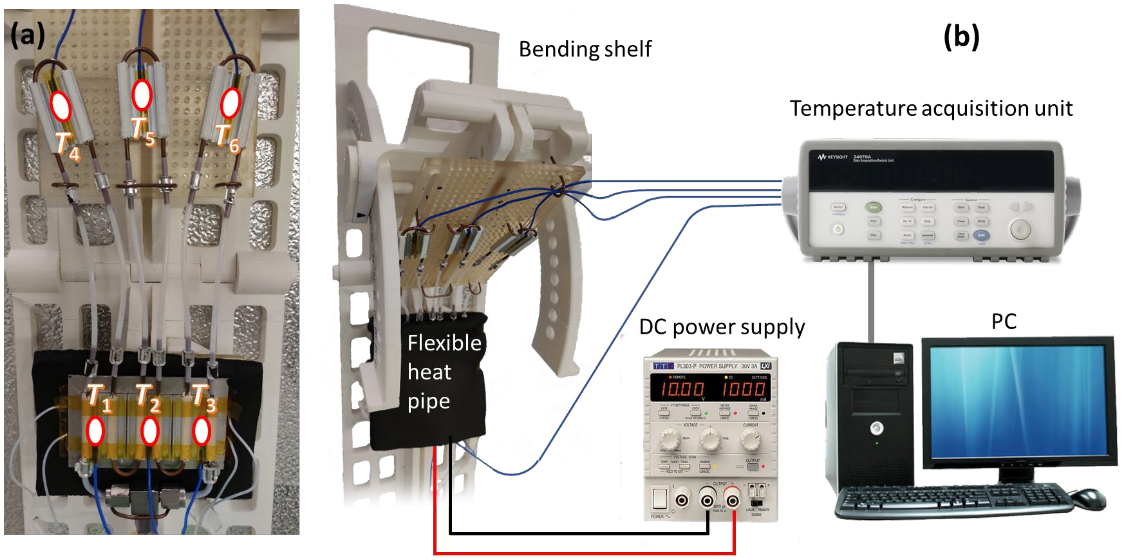


Fig. 1: (a) The envisioned flexible heat pipe with temperature monitoring points and (b) the schematic chart of the experimental setup.

In the experiment, a bending shelf was fabricated by 3D printing to adjust the bending angle of the heat pipe as indicated in Fig. 1(b). Additionally, a DC electric power supply was used to heat the ceramic heater in the heating section. It should be noted that an aluminum plate with width, length, and thickness of 5mm, 8mm, and 1.5mm, respectively, was attached between the heater and heating blocks to make the heat flux uniform. The electric voltage of 11 V was applied to study the effects of the bending angle (from 0 to 90°) and inclination angle (from 30° to 90°) on the thermal performance of the proposed heat pipe. Furthermore, the electric voltages from 11 to 15 V were used to investigate the effect of heat power on its thermal performance. The electric power was calculated through the electric voltage multiplied by the electric current. It should be noted that the heating section is insulated by insulation foam, so the heat power is assumed to be equal to the electric power. A temperature data acquisition unit (Agilent 34970a) was used to monitor the time course temperatures from T_1 to T_6 with the temperature acquisition time step of 10s. In this study, each case was tested for 15 min to make the heat pipe reach a quasi-steady state, and then the average temperatures in the following 5 min were used to characterize the heating and cooling temperatures.

The thermal performance of the flexible heat pipe was evaluated by the apparent thermal conductivity, which could be calculated by

$$k = \frac{Q \cdot L}{\mathrm{A} \cdot (T_h - T_c)} \tag{1}$$

where Q is heat power, L is the equivalent heat transfer length, A is the cross-section area of the Teflon tubes in the middle section, T_h is the average temperature in the heating section [i.e., $T_\mathrm{h} = (T_1 + T_2 + T_3)/3$], and T_c is the average temperature in cooling section [i.e., $T_\mathrm{c} = (T_4 + T_5 + T_6)/3$].

3. Results and Discussion

In this study, the bending angles and inclination angles were varied to investigate the thermal performance of the proposed flexible heat pipe under the bottom heating mode at the heating voltage of 11 V. As for the effect of heat power or heating temperature, the electric voltages of 11, 12, 13, 14, and 15V were applied the evaluate the heat transfer performance of the proposed heat pipe at the vertical orientation.

3.1. Effect of the bending angle

Fig. 2(a) shows the photos of the flexible heat pipe bending at the angles of 30°, 50°, 70°, and 90° from left to right, respectively, where three short copper wires were used to confine the movement of the bending sections leading to harsh bending of the three branches. It should be noted that the bending angle of 0 corresponded to the vertical orientation. Fig. 2(b) illustrates the temperatures in the heating section and the three cooling pads. The heating temperatures of T_1, T_2, and T_3 are close to each other, which means the heating surface had a uniform temperature distribution. Besides, the heating temperatures increase with the increasing bending angle because the larger bending angle of the harsh bending section results in higher flow resistance leading to lower heat transfer performance. Furthermore, the cooling pad temperature in the right branch (T_6) is the lowest, which is because the liquid plugs and vapour bubbles flowed from the right branch to the middle and left branches successively. In other words, the fluid flowing up in the right branch came from the left branch through the bottom tube connecting the T-junction. As the bottom tube was not connected to the heating surface and its backside was not well insulated as shown in Fig. 1(a), some heat will be dissipated from the bottom tube, leading to the lower temperature of the right cooling pad. In contrast, the temperatures of the middle and left cooling pads (T_4 and T_5) are close to each other and much higher than that of the right cooling pad since the backflow of the cooling fluid in these tubes was fully attached to the heating surface with good insulation in the heating section.

Fig. 2(c) presents the apparent thermal conductivity of the proposed flexible heat pipe as well as the corresponding heat flux from the aluminum heat-spreading surface. The heat flux was calculated by Q/S, where Q was the heat power and S was the surface area of the heat-spreading pad. Fig. 2(c) indicates that the apparent thermal conductivity of the heat pipe reduced by about 43% from 3100 W/(m·K) to 1767 W/(m·K) when the bending angle increased from 0 to 90°. This is because the harsh bending angle induced by the confined bending section led to large flow resistance for the fluid movement to transport heat. Consequently, the heating temperature increases with the bending angle as shown in Fig. 2(b). As the electric resistance of the heater is generally inversely proportional to its temperature, the heat flux decreases slightly by about 3.7% from 3753

W/m^2 to 3613 W/m^2 with the increasing bending angle as shown in Fig. 2(c) although the electric voltage is kept constant at 11 V. However, Kang et al.[15] had reported that if the branches bent naturally and smoothly without strict confinement, the bending angle could have a small effect on the flow resistance so the decrease in the heat transfer performance caused by the bending angle was very limited. Nonetheless, the apparent thermal conductivity of the proposed flexible heat pipe under bending was still 4~8 times higher than that of copper in this study.

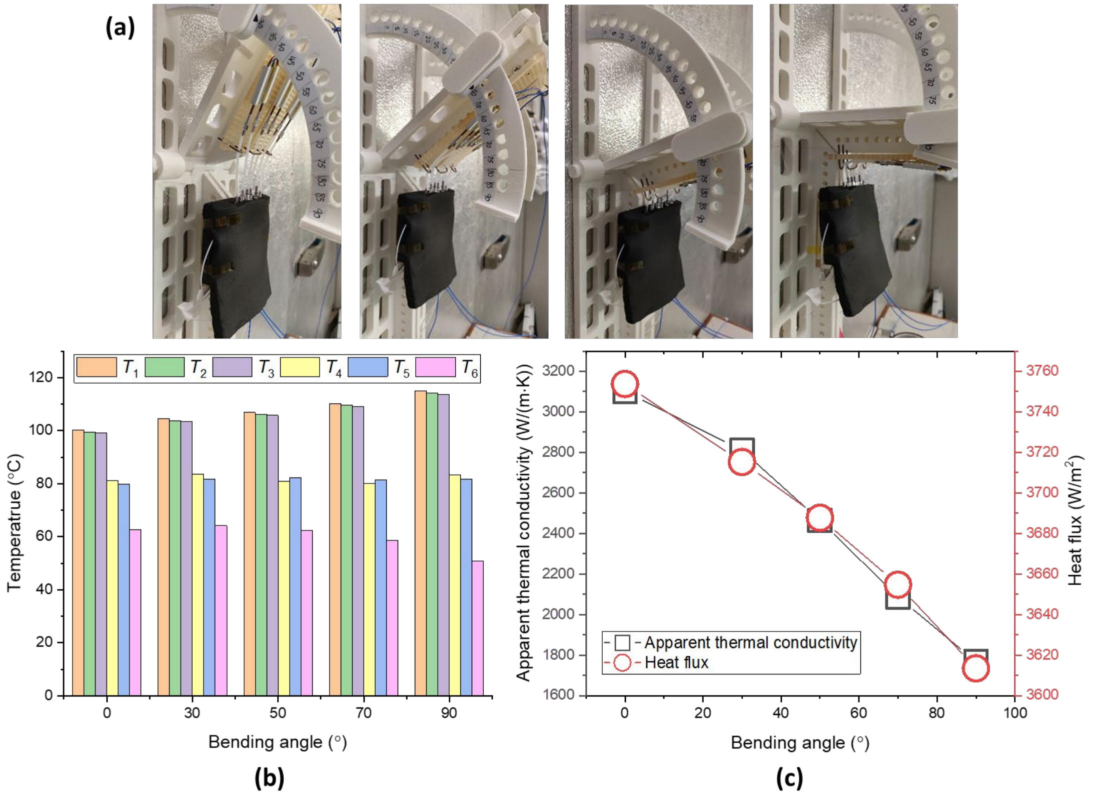


Fig. 2: The effect of bending angle at the heating voltage of 11V. (a) Photos of the flexible heat pipe at bending angles of 30° , 50° , 70° , and 90° from left to right; (b) the temperatures in the heating and cooling sections; (c) apparent thermal conductivity and the corresponding heat flux at different bending angles.

3.2. Effect of the inclination angle

Fig. 3(a) shows the photos of the flexible heat pipe under the inclination angles of 70° , 50° , and 30° from left to right, respectively. It should be noted that the inclination angle of 90° corresponded to the vertical orientation of the heat pipe. Fig. 3(b) depicts the temperatures of the heating section and the cooling pads with respect to the inclination angle, which shows that the right branch still has the lowest cooling pad temperature indicating the flow direction from the right branch to the middle and left branches successively. In addition, with the increasing inclination angle, the heating temperatures decrease, while the cooling temperatures increase. This is because gravitational force plays an important role in the fluid movement process. The larger inclination angle results in a stronger gravitational force component, which is beneficial to the backflow of the condensed liquid leading to a lower heating temperature at a higher inclination angle. Furthermore, due to the mass conservation of the fluid movement in the tubes, the fluid velocity from bottom to top in the hot tube will also increase owing to a large amount of liquid vaporization at a higher inclination angle, resulting in higher cooling side temperatures.

Fig. 3(c) demonstrates the development of the apparent thermal conductivity and the corresponding heat flux with respect to the inclination angle. As the inclination angle increases from 30° to 90° , the apparent thermal conductivity of the heat pipe is doubled from 1537 W/(m·K) to 3100 W/(m·K) since the larger gravitational force component facilitates the fluid flow within the tubes. Meanwhile, the heat flux increases slightly from 3657 W/m^2 to 3753 W/m^2 with an increasing rate of about 2.6% due to the lower heating temperature at a larger inclination angle as shown in Fig. 3(b). It should be noted that the proposed heat pipe did not work when the heat pipe was located at the horizontal orientation, which further denotes that gravity is significant for the thermal performance of the proposed heat pipe. Nevertheless, the proposed heat pipe still could work in a wide range of inclination angles, which is very useful in many application scenarios such as human body thermal management.

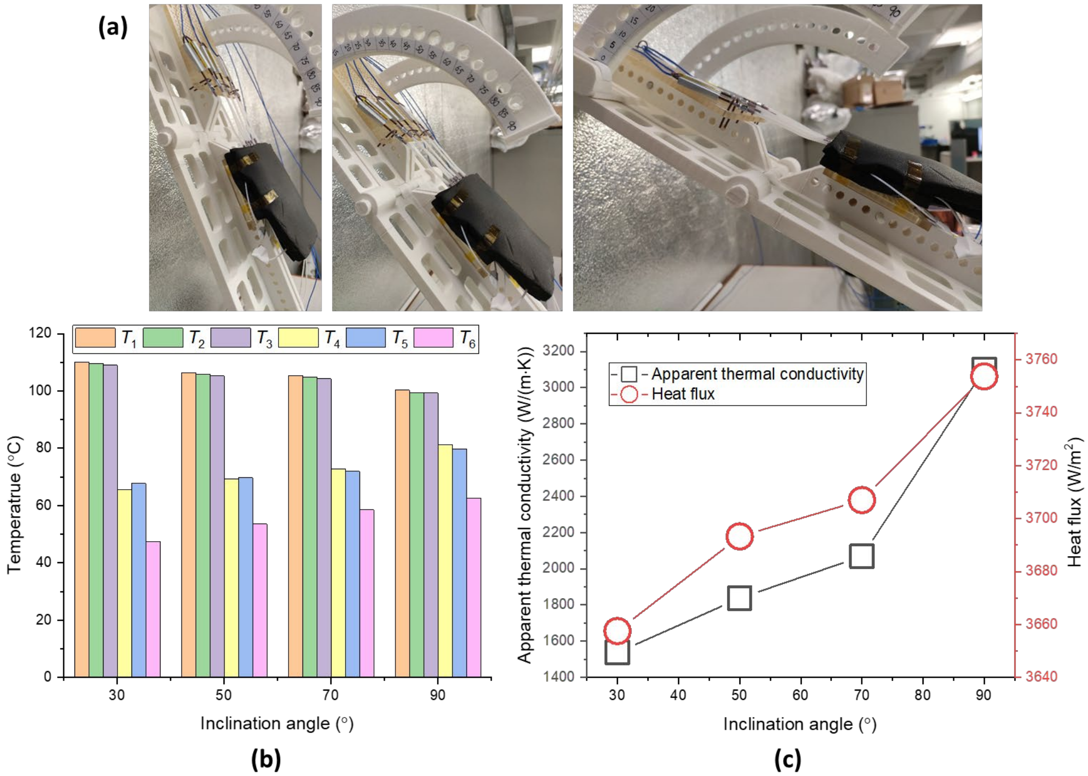


Fig. 3: Effect of the inclination angle at the heating voltage of 11V. (a) Photos of the flexible heat pipe at the inclination angles of 70º, 50º, and 30º from left to right; (b) the temperatures in the heating and cooling sections; (c) apparent thermal conductivity and the corresponding heat flux at different inclination angles.

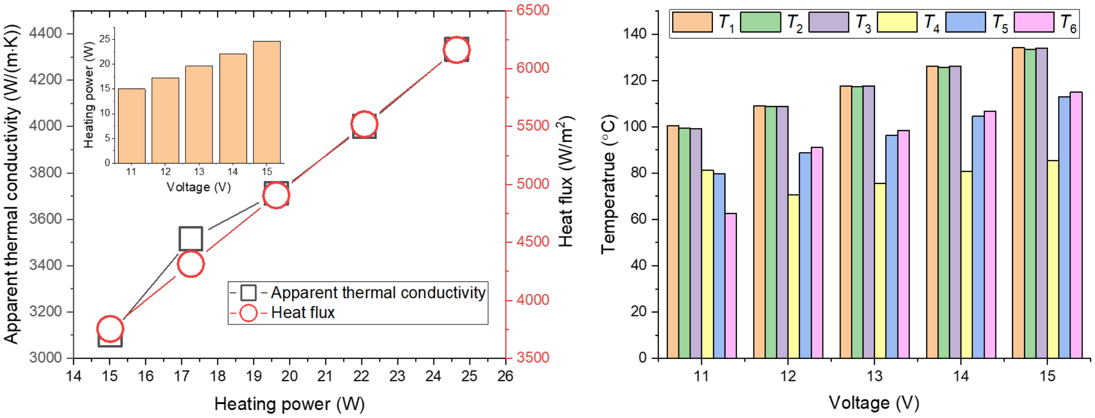
3.3. Effect of the heat power

Fig. 4 describes the effect of heat power on the thermal performance of the proposed heat pipe when heating at the vertical orientation. The inserted figure in Fig. 4(a) shows the heat power increases from 15W to 24.6W when the electric voltage increases from 11V to 15V. Consequently, the corresponding heat flux increases from 3754 W/m^2 to 6161 W/m^2 as shown in Fig. 4(a). In addition, Fig. 4(a) further denotes that the apparent thermal conductivity of the heat pipe increases from 3100 W/(m·K) to 4333 W/(m·K) with the increasing heat power or heating voltage. This is because large heat power can intensify the boiling process in the heating section and enlarge the driven force for the fluid movement, which increases the flow velocity of the liquid plugs and vapour bubbles within the heat pipe.

Fig. 4(b) shows all the temperatures in the heating and cooling sections increase with the electric voltage or heat power. It is interesting to note that the right cooling pad (T_6) has the lowest temperature at the heating voltage of 11V, whereas the temperature of the left cooling pad (T_4) is the lowest at the other heating voltages, which is induced by the reversed flow direction of the liquid plugs and vapour bubbles. As all the cooling branches had the same tube diameters in this study, the fluid pressures in the adjacent tubes were similar to each other at the starting point of the working fluid movement. Hence, the flow direction induced by the pressure perturbation became arbitrary at the starting point since the pressure imbalance is the driving force of the fluid flow. Nonetheless, the flow direction has little effect on the heat transfer performance of the proposed heat pipe.

All in all, the apparent thermal conductivity was larger at higher heat power or heating temperature, which is preferred in practical applications for efficient heat transport. Meanwhile, the highest apparent thermal conductivity was up to 4333

W/(m·K), over 10 times higher than that of copper, which has great potential in advanced thermal management and energy applications.



(a) (b)

Fig. 4: Effect of heat power at the vertical orientation. (a) Apparent thermal conductivity and the corresponding heat flux with respect to the heat power (inserted figure: heat power versus electric voltage); (b) the temperatures in the heating and cooling sections at different heating voltages.

4. Conclusion

Based on the working principle of a pulsating heat pipe, a high-performance flexible heat pipe with three heat transfer branches was fabricated by Teflon tubes with copper heating and cooling sections, which has excellent flexibility since the three branches can deform independently. The effects of bending angle, inclination angle, and heat power on the thermal performance of the proposed flexible heat pipe were investigated experimentally. The results showed that the apparent thermal conductivity decreased with the increasing bending angle, while the thermal performance was enhanced at a larger inclination angle. As the bending angle increased from 0 to 90°, the apparent thermal conductivity declined by about 43% due to the confined bending section. Besides, its thermal performance almost doubled when the inclination angle increased from 30° to 90°. Furthermore, the apparent thermal conductivity could be improved by increasing the heat power or heating temperature, and the highest apparent thermal conductivity was up to 4333 W/(m·K), which is over 10 times higher than that of copper. Overall, the proposed flexible heat pipe has both good flexibility and heat transfer performance, which is of great importance for human body thermal management, cooling flexible electronics, waste heat recovery, and renewable energy harvesting.

Acknowledgments

The financial support from the Research Grant Council of Hong Kong (GRF project number: 15216722) and the Hong Kong Polytechnic University (startup project number: BD3H, AoEC project number: ZE1H, and PolyU project number: CD6M) are acknowledged.

References

[1] Z. Kang and L. Wang, "Boiling heat transfer on surfaces with 3D-printing microstructures," *Experimental Thermal and Fluid Science,* vol. 93, pp. 165-170, 2018.
[2] Z. Kang, D. Shou, and J. Fan, "Numerical study of single-loop pulsating heat pipe with porous wicking layer," *International Journal of Thermal Sciences,* vol. 179, 2022.
[3] Z. Kang and J. Fan, "Heat-pipe-based tunable multimode horizontal thermal rectifier," *Energy Reports,* vol. 8, pp. 4274-4281, 2022.
[4] H. Jouhara, A. Chauhan, T. Nannou, S. Almahmoud, B. Delpech, and L. C. Wrobel, "Heat pipe based systems - Advances and applications," (in English), *Energy,* vol. 128, pp. 729-754, Jun 1 2017.
[5] M. J. Gibbons, M. Marengo, and T. Persoons, "A review of heat pipe technology for foldable electronic devices," (in English), *Appl Therm Eng,* vol. 194, Jul 25 2021.

[6] T. Jaipurkar, P. Kant, S. Khandekar, B. Bhattacharya, and S. Paralikar, "Thermo-mechanical design and characterization of flexible heat pipes," (in English), *Appl Therm Eng,* vol. 126, pp. 1199-1208, Nov 5 2017.
[7] S.-S. Hsieh and Y.-R. Yang, "Design, fabrication and performance tests for a polymer-based flexible flat heat pipe," *Energy Conversion and Management,* vol. 70, pp. 10-19, 2013.
[8] C. Oshman, Q. Li, L.-A. Liew, R. Yang, V. M. Bright, and Y. C. Lee, "Flat flexible polymer heat pipes," *Journal of Micromechanics and Microengineering,* vol. 23, no. 1, 2013.
[9] C. Liu, Q. Li, and D. Fan, "Fabrication and performance evaluation of flexible flat heat pipes for the thermal control of deployable structure," *Int J Heat Mass Transf,* vol. 144, 2019.
[10] Z. Kang, D. Shou, and J. Fan, "Numerical study of a novel Single-loop pulsating heat pipe with separating walls within the flow channel," *Applied Thermal Engineering,* vol. 196, 2021.
[11] J. Lim and S. J. Kim, "Fabrication and experimental evaluation of a polymer-based flexible pulsating heat pipe," *Energy Conversion and Management,* vol. 156, pp. 358-364, 2018.
[12] O. Der, M. Marengo, and V. Bertola, "Thermal Performance of Pulsating Heat Stripes Built With Plastic Materials," *J Heat Transfer,* vol. 141, no. 9, 2019.
[13] J. Qu, X. Li, Y. Cui, and Q. Wang, "Design and experimental study on a hybrid flexible oscillating heat pipe," *Int J Heat Mass Transf,* vol. 107, pp. 640-645, 2017.
[14] J. Qu, C. Wang, X. Li, and H. Wang, "Heat transfer performance of flexible oscillating heat pipes for electric/hybrid-electric vehicle battery thermal management," *Appl Therm Eng,* vol. 135, pp. 1-9, 2018.
[15] Z. Kang, S. Jiang, Y. Hong, and J. Fan, "Squid - like soft heat pipe for multiple heat transport," *Droplet,* vol. 1, no. 2, pp. 182-191, 2022.
[16] Z. Kang, Y. Hong, S. Jiang, and J. Fan, "Composite filament with super high effective thermal conductivity," *Materials Today Physics,* vol. 34, p. 101067, 2023.
[17] E. R. Babu, H. N. Reddappa, and G. V. G. Reddy, "Effect of Filling Ratio on Thermal Performance of Closed Loop Pulsating Heat Pipe," (in English), *Mater Today-Proc,* vol. 5, no. 10, pp. 22229-22236, 2018.