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VISUALIZATION EXPERIMENT OF MINI-GROOVED FLAT HEAT PIPE FILLED WITH DIFFERENT WORKING FLUID

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ABSTRACT

Effective cooling way is required to cool the electronic devices with small space and high heat flux. Mini-grooved flat heat pipe with simple structure, high thermal conductivity and good temperature uniformity meets the requirement of electronic devices rapidly cooling. A visualization experiment was established in this paper to study the fluid flow and heat transfer performance of the mini-grooved flat heat pipe. The fluid flow and distribution were clearly observed in the visualization experiment. It was found that the flat heat pipe had better thermal characteristics than copper and obviously affected by the input heat and filling working fluid type. And the heat pipe filled with deionized water possessed better thermal conductivity and heat transfer limit than that filled with anhydrous ethanol or hexane, while the lower hydrophilic performance of deionized water with copper weakened the temperature uniformity of the heat pipe filled with deionized water compared those of anhydrous ethanol and hexane. In this way, all kinds of factors need to be consider to select the working fluid of the heat pipe for electronic devices cooling.

Keywords: Flat heat pipe, Experiment, Visualization, Working fluid, Evaluation parameter

NONMENCLATURE

Symbols	
d	wall thickness, m
h	grooves height, m
H	heat pipe height, m
Hv	vapor chamber height, m
k	thermal conductivity coefficient，$W \cdot m^{-1} \cdot K^{-1}$
l	length, mm
Q	heat power, W
Q'	heat transfer amount, W
R	thermal resistance, $K \cdot W^{-1}$
T	temperature, K
wf	grooves pitch, m
wg	grooves width, m
W	heat pipe width, m
Wv	vapour chamber width, m
Subscripts	
a	adiabat
c	condensation
e	evaporation
eff	effective
max	maximum
min	minimum

1. INTRODUCTION

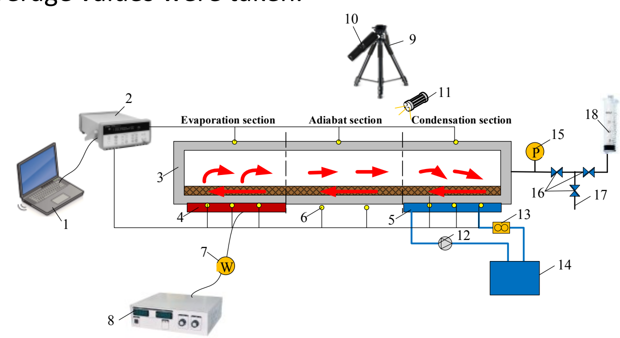
With the miniaturization and enhanced performance of electronic devices, high power has been a threat to electronics [1]. The uneven temperature distribution may cause large thermal stress inside the electronic devices, which significantly affects the working stability of electronic system. There is a challenge to develop an efficient cooling way to remove the great heat from the electronics [2]. Mini flat heat pipe has the advantages of compact structure, no additional electric drive, high thermal conductivity and good temperature uniformity, which can meet the requirement of electronic devices effectively cooling [3-4].

The main thermal resistance inside the heat pipe exists in the wick [5]. There are two ways to improve the heat transfer performance of heat pipe. One is to improve the wick structure and the other one is to choose the suitable working fluid [6]. As mini flat heat pipe chiefly uses the phase change of working fluid to transfer heat, the option of working fluid is crucial to the working ability of heat pipe. Various working fluids have been used in the heat pipe for electronic devices cooling. Wang et al. [7] used deionized water as working fluid to experimentally investigate the flat plate heat pipes with interlaced narrow grooves for CPU cooling. Chen and Chou [8] examined the effects of liquid filling ratios and leakage on the cooling performance of Al 6061 flat plate heat pipes filled with acetone.

In this paper, a visual experiment table was established to investigate the working characteristics of copper based mini-grooved flat heat pipe. Considering the working temperature of electronic devices, three common and relative environment friendly working fluids, deionized water, anhydrous ethanol and hexane, were chosen to experimentally study the heat transfer performance of mini-grooved flat heat pipe. The effects of input heating power on the heat pipe were also examined.

2. INTRODUCTION

The mini flat heat pipe consists of airtight container, capillary structure and working fluid, which is separated into evaporation, adiabatic and condensation sections. The schematic diagram of the experimental apparatus for copper based mini-grooved flat heat pipe was shown in Fig. 1. The experiment system consisted of heat source, heat sink, measurement and data collection, vacuum pumping and liquid filling parts. Constant heat flux was applied at the evaporation section to offer heat source. Water jacket with inlet water flow rate 400 $mL \cdot min^{-1}$ and inlet temperature 20 °C was used to provide heat sink at the condensation section of the heat pipe. The heat source area was 20*20 mm^2 and the heat sink area was 40*20 mm^2. Rectangle grooved wick was chosen for the heat pipe. The geometric structure and parameters of flat heat pipe used in this paper were shown in Fig. 2 and Table 1. The material of heat pipe upper surface was copper or glass. Copper was selected to measure the heat transfer performance of the heat pipe, while glass was chosen to observe the fluid flow inside the heat pipe [9]. As the material of heat pipe airtight container has some effect on the heat transfer performance of heat pipe, glass with low thermal conductivity was only used to observe the fluid flow inside the heat pipe for the heat pipe upper surface. Insulted cotton wrapped around the heat pipe when the heat transfer performance of heat pipe was measured. Calibrated thermistors (uncertainty lower than 0.5 °C) were used to measure the temperature of the heat pipe. Calibrated thermistors No.1-16 were used to measure the temperature of the heat pipe at the bottom surface. The distribution of calibrated thermistors 1-16 was shown in Fig. 3. Calibrated thermistors No.1-4 were used to measure the temperature at the bottom surface of the evaporation section. Calibrated thermistors No.5-8 were used to measure the temperature at the bottom surface of adiabat section. And calibrated thermistors No.9-16 were used to measure the temperature at the bottom surface of condensation section. The experiment time for every case was 1800 s. Experiments were repeated three times for every case, and the average values were taken.



1-computer, 2-data collection, 3-flat heat pipe, 4-heat chip, 5-water jacket, 6-thermocouple, 7-watt meter, 8- power supply, 9-CCD camera, 10-microscope, 11-light source, 12-water pump, 13-flowmeter, 14-cold water storage, 15-pressure meter, 16-vacuum valve, 17-vent, 18-injector

Fig. 1. Schematic diagram of the experimental apparatus.

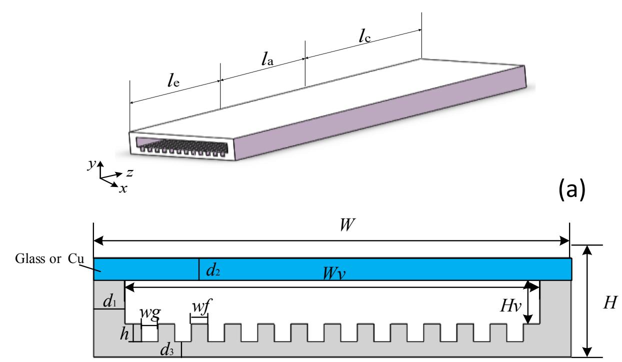


Fig. 2 Geometric structure of flat heat pipe: (a) 3D structure; (b) cross section in the *z* direction.

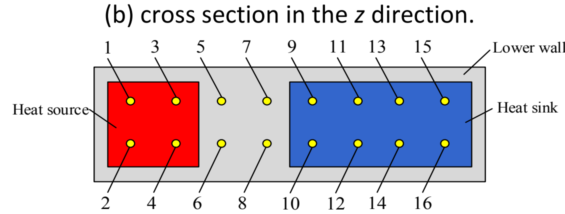


Fig. 3 Distribution of calibrated thermistors 1-16

Table 1 Geometric parameters of flat heat pipe

parameter	l_e (mm)	l_a (mm)	l_c (mm)	W (mm)	Wv (mm)	H (mm)	Hv (mm)	wg (mm)	wf (mm)	h (mm)	$d1$ (mm)	$d2$ (mm)	$d3$ (mm)
value	20.0	20.0	80.0	23	20	5	2	0.8	0.8	0.8	1.5	1.0	0.7

Thermal resistance, effective thermal conductivity, maximum temperature at the evaporation section and temperature uniformity at the condensation section are adopted to characterize the thermal performance of flat heat pipe [10]. They are defined as follows:

1) Heat transfer amount

Although insulation cotton was wrapped around the heat pipe to preserve heat, a small amount of heat from the heat pipe surface released to the outside in the form of natural convection. It mainly concentrated on the upper and lower surface of the heat pipe at evaporation and adiabat sections. The heat transfer amount is that input heating power minuses heat loss:

$$Q^{'} = Q - Q_{\text{loss}} \tag{1}$$

2) Thermal resistance:

$$R = (\overline{T}_{\text{e}} - \overline{T}_{\text{c}}) / Q \tag{2}$$

Where $\overline{T}_{\text{e}}$ and $\overline{T}_{\text{c}}$ are average temperatures at heat and cold source areas, respectively.

3) Effective thermal conductivity:

$$k_{\text{eff}} = \frac{QA_{\text{cross}}}{(\overline{T}_{\text{e}} - \overline{T}_{\text{c}}) l_{\text{eff}}} \tag{3}$$

Where l_{eff} is the effective length of heat pipe, defined by:

$$l_{\text{eff}} = (0.5 l_{\text{e}} + l_{\text{a}} + 0.5 l_{c}) / 2 \tag{4}$$

4) Temperature uniformity at condensation section is:

$$dT_{\text{c}} = (T_{\text{c,max}} - T_{\text{c,min}}) / T_{\text{c,max}} \times 100\% \tag{5}$$

3. RESULTS AND DISCUSSION

3.1 Visualization experiment

The working fluid of deionized water, anhydrous ethanol or hexane was injected into the heat pipe. It was observed that when deionized water was injected into the heat pipe, liquid remained at the corner of the heat pipe. And deionized water still stayed at the corner of the heat pipe when the heat pipe received input heat, which decreased the liquid amount in the grooves. As a result, all the grooves were not well moistened, causing the heat pipe easily to dry out. Moreover, some liquid condensated on the lug boss between grooves at the condensation section rather than in the grooves when the heat pipe was filled with deionized water, as shown in Fig. 4. However, liquid distributed evenly in grooves when anhydrous ethanol or hexane was injected into the heat pipe. This may be chiefly caused by two reasons. On the one hand, the surface tension of water is distinctly higher than those of anhydrous ethanol and hexane and the height of vapour chamber is narrow which give rise to capillary phenomenon at the corner of heat pipe. On the other hand, anhydrous ethanol and hexane are hydrophilic with copper, while deionized water is comparatively hydrophobic with copper [11-12]. During the visual experiment, liquid droplet condensated at the glass when the heat pipe received input heat. And with the increase of input heat, the amount of liquid droplets on the glass increased and the coverage area of liquid drop enlarged from evaporation section to the whole glass. To avoid liquid droplets on the glass affecting visualization, small heat source added on the glass.

Fig. 4. Water condensates on the lug boss between grooves under input heat 12 W.

It was also observed that when the heat pipe received heat more than 8 W, boiling phenomenon appears at the evaporation section. Figure 5 displays the boiling phenomenon when the heat pipe is filled with anhydrous ethanol with heat source area 20*20 mm^2 under input heat 8 W. The boiling process took 4 s. And the liquid level continually decreases in the grooves, especially at the evaporation section. Finally, the liquid level forms slope shape along the grooves after the first 400 s. Figure 6 presents the formation of slope liquid level when the heat pipe is filled with anhydrous ethanol under input heat 8 W.

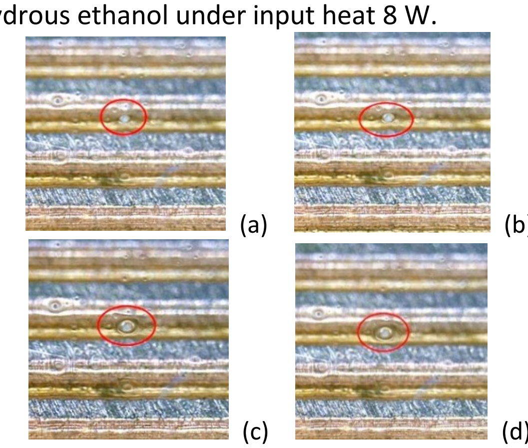
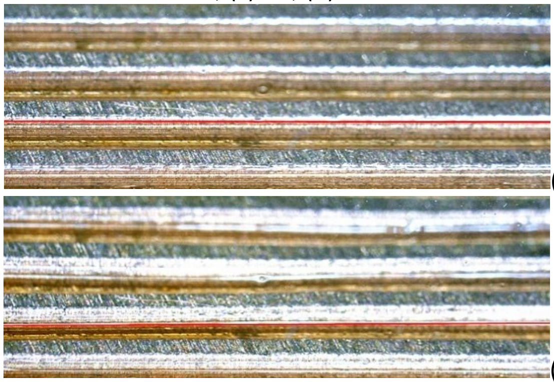


Fig. 5. Boiling process when heat pipe is filled with anhydrous ethanol with heat source 20*20 mm^2 under 8 W: (a) 1 s; (b) 2 s; (c) 3 s; (d) 4 s.



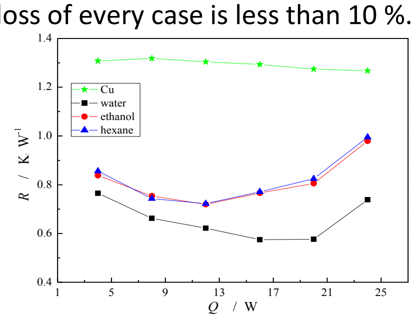
(a)

(b)

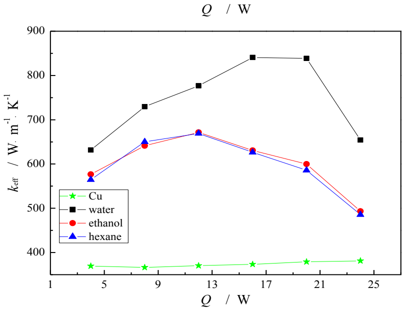
Fig. 6. Formation of slope liquid level when heat pipe is filled with anhydrous ethanol under 8 W: (a) 1 s; (b) 400 s.

3.2 Heat pipe heat transfer performance with different working fluid

Figure 7 shows the thermal resistance, effective thermal conductivity, maximum temperature at evaporation section and temperature uniformity at condensation section of pure copper and mini-grooves flat heat pipe filled with deionized water, anhydrous ethanol, hexane as working fluid under different input heating power with working fluid filling ratio 1.2. And the heat loss of every case is less than 10 %.



(a)



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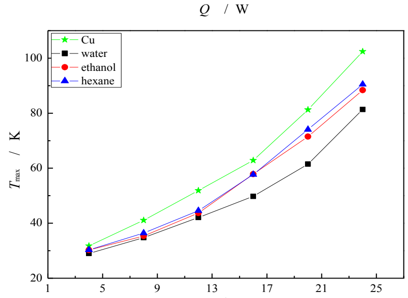

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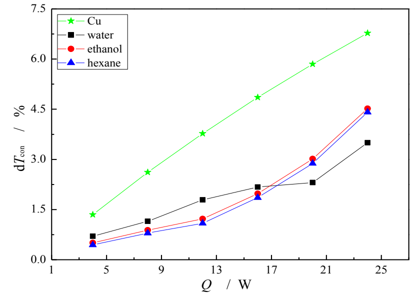

(d)

Fig. 7. Evaluation parameters of heat pipe heat transfer performance under different input heating power with different working fluid: (a) thermal resistance; (b) effective thermal conductivity; (c) maximum temperature at evaporation section; (d) temperature uniformity at condensation section.

It can be found in Fig.7 that the heat pipes filled with working fluid have obviously better heat transfer performance than copper, with lower thermal resistance, maximum temperature and higher effective thermal conductivity, temperature uniformity at condensation section. Compared with heat pipes filled with anhydrous ethanol or hexane, the heat pipe filled with deionized water has lower thermal resistance, maximum temperature and higher effective thermal conductivity. And when the input heating power is higher than 12 W, the thermal resistances of heat pipe filled with anhydrous ethanol and hexane rise up sharply and the effective thermal conductivity and temperature uniformity of heat pipe filled with hexane descends intensely. It indicates that the heat pipes filled with anhydrous ethanol and hexane reach heat transfer limit at input heat 12 W because of the capillary limit [13]. Meanwhile, the heat transfer limit of heat pipe filled with deionized water is about 20 W. These phenomena are due to the more excellent physical properties of water than those of anhydrous ethanol and hexane. In comparison with anhydrous ethanol and hexane, deionized water has higher surface tension to provide capillary force, larger liquid density to decrease fluid flow pressure drop and higher latent heat to absorb/release heat at the evaporation/ condensation section, which improves the heat transfer limit and enhances the heat transfer ability [14].

However, as is shown in Fig. 7(d), the temperature distribution at condensation section of heat pipe filled with anhydrous ethanol or hexane is more uniform than that of heat pipe filled with deionized water before the input heat reaches the heat transfer limit, especially for the heat pipe filled with hexane. The reason is that the mini-grooved wick of heat pipe utilizes the meniscus at the narrow corner of grooves to offer capillary force, so that the hydrophilic performance of working fluid with wall is important. As is explained in Section 3.1, anhydrous ethanol and hexane with fine wettability are more hydrophilic with copper than deionized water with copper. Condensed anhydrous ethanol and hexane can evenly spread over the grooves. They can flow back from condensation to evaporation section easily, leading to the uniform temperature distribution at the condensation section. In addition, since the liquid density and kinetic viscosity of hexane are lower than those of anhydrous ethanol and deionized water, liquid hexane flows back quickly in the grooves, contributing to the high temperature uniformity at condensation section for heat pipes filled with hexane. Therefore, working fluid to be chosen for heat pipe needs to possess excellent surface tension, latent heat, wettability and low viscosity.

Furthermore, from Fig. 7, with the increase of input heating power, the maximum temperature at evaporation section, effective thermal conductivity and temperature uniformity of the heat pipe increase, while the thermal resistance decreases a bit, before the heat pipe reaches the heat transfer limit. Heat pipe possesses better heat transfer performance under a relatively higher input heat.

4. CONCLUSION

High heat flux with small space has been a great threat to the electronic devices working under steady condition. Mini flat heat pipe, with small size, excellent heat transfer ability and uniform temperature distribution, can transfer the huge heat to the outside rapidly and weaken the hot spot on the chips, which is pretty suitable for the electronic devices. In this paper, a visual experiment was established to study the fluid flow and heat transfer in the mini-grooved flat heat pipe. It was found that flat heat pipe had better thermal characteristics than copper and the heat transfer coefficient and temperature uniformity of heat pipe were obviously affected by the input power and working fluid filling type. As the option of working fluid is crucial to the working ability of heat pipe, all kinds of factors need to be consider to select the working fluid in the heat pipe for electronic devices cooling.

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REFERENCES

[1] Khalaj AH, Halgamuge SK. A review on efficient thermal management of air- and liquid-cooled data centers: from chip to the cooling system. Appl Energ 2017;205:1165-88.
[2] Mcglen RJ, Jachuck R, Lin S. Integrated thermal management techniques for high power electronic devices. Appl Therm Eng 2004;24(8):1143-56.
[3] Zaghdoudi MC, Maalej S, Mansouri J, Sassi MBH. Flat miniature heat pipe for electronics cooling: state of the art, experimental and theoretical analysis. Int J Eng & Appl Sci 2011;38:166-89.
[4] Franchi G, Huang X. Development of composite wicks for heat pipe performance enhancement. Heat Transf Eng 2008;29:873-84.
[5] Lu MC. Exploring the limits of boiling and evaporative heat transfer using micro/nano structures. Dissertations & Theses - Gradworks; 2010.
[6] Morris SJS. The evaporating meniscus in a channel. J Fluid Mech 2003;494:297-317.
[7] Wang C, Liu Z, Zhang G, Zhang M. Experimental investigations of flat plate heat pipes with interlaced narrow grooves or channels as capillary structure. Exp Therm Fluid Sci 2013;48:222-9.
[8] Chen JS, Chou JH. Cooling performance of flat plate heat pipes with different liquid filling ratios. Int J Heat Mass Tran 2014;77:874-82.
[9] Wong SC, Chen CW. Visualization and evaporator resistance measurement for a groove-wicked flat-plate heat pipe. Int J Heat Mass Tran 2012;55(9-10):2229-34.
[10] Chen JS, Chou JH. Cooling performance of flat plate heat pipes with different liquid filling ratios. Int J Heat Mass Tran 2014;77:874-82.
[11] Faghri A. Heat pipe science and technology. First ed. Washington DC: Taylor & Francis; 1995.
[12] Wong SC, Chen CW. Visualization and evaporator resistance measurement for a groove-wicked flat-plate heat pipe. Int J Heat Mass Tran 2012;55(9-10):2229-34.
[13] Jiao AJ, Ma HB, Critser JK. Evaporation heat transfer characteristics of a grooved heat pipe with micro-trapezoidal grooves. Int J Heat Mass Tran 2007;50:2905-11.
[14] Patankar G, Weibel JA, Garimella SV. Working-fluid selection for minimized thermal resistance in ultra-thin vapor chambers. Int J Heat Mass Tran 2017;106:648-54.

