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Experiment research on the effect of the evaporator's configuration design of an innovative ultra-thin looped heat pipe

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ABSTRACT

Three ultra-thin looped heat pipe (ULHP) prototypes with different evaporator configurations are designed and developed, their heat transfer characteristics are compared by experiments in the aspects like the operation temperature, thermal resistance, start-up characteristic and heat leakage situation, the operating principle of the ULHPs is further explored and clearly understood. The experimental results demonstrated that the designed ULHPs meet the requirements of different thermal management systems. Specially, the thermal resistance of the one with the optimized configuration reaches as low as 0.08 K/W. The high efficient running of the ULHPs system relies on the smooth circulation of the working fluid. The choice of the suitable structure in evaporator can effectively reduce the operation temperature and the temperature difference of the evaporator, decrease the leaked heat and thermal resistance, and accelerate the start-up process.

1. Introduction

According to different application requirements of the conventional electronic cooling, the high-power LED heat dissipation and the solar heat collection, the temperature of the evaporator should be lower than 80 °C [1–3]. Specially, for the latest power battery thermal management system, the safety operation temperature is limited under 60 °C [4–8]. Loop heat pipe is a highly effective phase change heat transfer device linked by vapor line and liquid line. The heat transfer of loop heat pipe is realized by the phase change process of working fluid during circulating between the evaporator and condenser. A significant feature in structure of loop heat pipe is the separated vapor line and liquid line and the integration of the evaporator and the compensating room, which determines the characters in heat transfer such as the small carrying resistance of vapor, the quick start-up and multidirectional long distance heat transmission capability. With the fast development of electronic cooling, the micro flat loop heat pipe that can fit closely with the electronic components surface receives great attention [9,10]. However, the capillary wick core plays the role as the providing driven force for the traditional loop heat pipe, which not only increases the total thickness of the looped heat pipe, running counter to the requirement of the compact and light structure design, but also aggravates the heat leakage situation and the start-up process [11–13].

The developed ULHP prototype in this paper combines the characteristics of traditional loop heat pipe and the pulsating heat pipe (PHP), replacing the capillary core with parallel micro channels in order to reduce its total thickness but keep the high work efficiency in heat transfer.

The idea of opening micro-channel inside the evaporator of heat pipes is so practical and common that lots of researches have been conducted both in experiment and theory. The geometry parameters including the various shapes, the width/deep ratio and the size of the grooves are widely researched.

For groove shapes study, Chen et al. [14,15] concluded that the triangular channel is superior than rectangular in improving the heat transfer performance of flat plate pulsating heat pipe by experiments. Thompson et al. [16] experimentally studied the three-dimensional flat-plate oscillating heat pipe with staggered microchannels, their PHP could work high efficiently under heat flux 300 W/cm^2. Liu et al. [17] reported that the trapezoid shaped channel could work best while the triangular one operated worst in micro channel heat pipes by simulating work with ANASY. Hetsroni et al. [18] summarized the effect of the geometry, the axial conduction and the energy dissipation by analyzing the experimental data of heat transfer in circular, triangular, rectangular, and trapezoidal micro-channels whose hydraulic diameters ranged from 60 μm to 2000 μm. For the width/deep ratio and the size research, Peng et al. [19] conducted experiments to study the flow

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Nomenclature

d	inner diameter, m
g	gravitational acceleration, m/s^2
λ	thermal conductivity of air, W/m °C
L	length, m
P	pressure intensity, Pa
Q	heat, W
R	resistance, °C/W
T	temperature, °C
u	velocity, m/s

Subscripts

c	condenser
c.a	the average temperature of the condenser
drive	driven
e	evaporator
e.a	the average temperature of the evaporator
entr	entrance section
ext	external loop
f	friction
i	sequence number of the four parts of the outside loop
loop	loop thermal resistance
sink	heat sink
sys	system thermal resistance

and the heat transfer characteristic in the rectangular micro channel with the width/deep ratio ranging from 0.33 to 1. He found out that the traditional empirical correlation was not suitable for the prediction in micro-channels. Gamrat et al. [20] explored and compared the heat transfer capability of the rectangular micro-channels with various width/deep ratios. Wang et al. [21] captured the bubble growth process during flow boiling in high width/deep ratio (20/10) micro channels with visualization experiments, and figured out that the bubble growth and the correspondingly evaporative heat transfer characteristic are influenced by the micro-channel width/deep ratio and size strongly.

However, the configuration of the grooves and its effect on the heat transfer capability as well as the system operation are seldom explored so far.

In this paper, we design three different types of configuration including rectangle, parallelogram and trapezoid, and conduct series of experiments under the same conditions to test the ULHPs' performances. By comparing the operation temperature and the temperature difference, the start-up process and the heat leakage situation, and the thermal resistance of these three samples, we figure out the characteristic of the ULHPs operation, understand the work mechanism and the specific effects of the different adjustments in the arrangement form of the evaporator.

2. The ULHP prototype

The ULHP we studied is shown in Fig. 1. The evaporator is a flat plate with micro-channels inside it. There is no traditional sintered capillary core inside the evaporator, which reduces the total thickness as well as the weight of the heat pipe. The total thickness of the ULHP is only 1.5 mm. The evaporator is welded by two copper plates. One plate with thickness 1 mm is used as the base plate where the parallel micro-channels are milled, the other one plate is the cover plate and 0.5 mm in thickness with smooth surface. The evaporator and the loop line are all made of copper. Details of the parameters of the ULHP are all listed in Table.1. Water is chosen as the working fluid. The pressure level of ULHP system is 13,000 Pa and the corresponding boiling point is about 52 °C.

With the parallel micro-channels instead of the capillary structure inside the evaporator, the designed ULHP system has both characteristics of traditional LHP and PHP. In the micro-channels inside the evaporator, the heat transfer and flow characteristics are quite similar with that of the PHPs. Increasing the heat load, the flow pattern develops from the bubble flow to the slug flow, during which the flow state is mainly affected by the capillary hysteresis resistance. Once the vapor-water slug flows out from the exit of the evaporator and flow inside the loop pipe, the motion is like that of the LHPs. The outside loop line can be divided into 4 parts, including the vapor line, the condensation section, the liquid line and the entrance section. Similar as the definition of the LHPs, we define the vapor line as the line started from the exit of the evaporator to the entrance of the condenser. Meanwhile, the section from the exit of the condenser to the bottom level elbow export is named as the liquid line, and the level section ahead the entrance of the evaporator is defined as the entrance section. The entrance section is similar with the storage chamber of the LHPs, playing the role as storing and supplying the complementary reflux liquid for the evaporator.

According to the operating principle of the LHPs, when the driven pressure is greater than the loop pressure loss, the working fluid is forced to form a forward circulation. Namely, Eq. (1) is satisfied.

$$\Delta P_{\text{drive}} = P_{\text{e}} - P_{\text{entr.}} = \left.\frac{dP}{dT}\right|_{T=T_{\text{entr.}}} (T_{\text{e}} - T_{\text{entr.}}) \geqslant \Delta P_{\text{ext}} \tag{1}$$

As general, $T_{\text{e}} - T_{\text{entr.}}$ is defined as the degree of superheat. Known as Eq. (1), when the total loop pressure loss is at certain, reducing the temperature of the fluid at the entrance of the evaporator $T_{\text{entr.}}$, namely, increasing the degree of subcooling of the liquid, can reduce the temperature of the evaporator T_{e}. Similar with the LHPs, the temperature of the liquid at the entrance section $T_{\text{entr.}}$ is influenced by the heat leaked out from the evaporator. That is to say, decreasing the heat leakage and ensuring the degree of subcooling of the liquid guarantees the effective operation of the ULHPs in a relatively low temperature.

The loop pressure loss ΔP_{ext} includes the capillary hysteresis resistance inside the channel, the inverse gravity flow resistance, and the friction loss along the vapor line, liquid line and the entrance section.

The loop thermal resistance and the system thermal resistance of the ULHPs are defined as Eqs. (2) and (3) respectively.

$$R_{\text{loop}} = (T_{\text{e.a}} - T_{\text{c.a}})/Q_{\text{in}} \tag{2}$$

$$R_{\text{sys}} = (T_{\text{e.a}} - T_{\text{sink}})/Q_{\text{in}} \tag{3}$$

According to the working process of the working fluid in the ULHP, the pressure–temperature figure is showed. As Fig. 2 showed, the working liquid in the evaporator absorbs heat and turns into overheating vapor with high pressure (A) and flows out from the exit of the evaporator (B). At the end of the vapor line, namely, the entrance of the condenser (C), the pressure of the vapor decreases because of the friction loss. The vapor is condensed into subcooled liquid (D) after flowing via condenser. Point E is at the entrance of the evaporator. Before the totally positive