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Experimental investigation on the thermal performance of three-dimensional oscillating heat pipe

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ABSTRACT

An experimental investigation on the effect of cooling air velocities, operating orientations and heat inputs on a three-dimensional oscillating heat pipe (3D-OHP) was studied seriously. The 3D-OHP had dimensions of 90 mm × 61 mm × 150 mm, 6 total turns, 3 layers along width direction and 4 layers along length direction. Unlike traditional OHP designs, this new three-dimensional multi-layer design allows for different working conditions in thermal management such as multi-heat source cooling and higher heating fluxes cooling. The thermal performance of the 3D-OHP was studied by testing temperature variation measured at various heat inputs under different cooling air velocities and operating orientations. The results indicated both the cooling air velocities and operating orientation significantly affect the start-up, oscillation and dry-out of the 3D-OHP. The start-up temperature decreased and the dry-out limit increased with the increase of cooling air velocities and the decrease of the operating angle. Difference of thermal resistance in each layer along different directions was also calculated. It was found that only operating orientation had remarkable influence on thermal resistance of different layers along length direction. The difference between the thermal resistance of the skin layer and the inner layer increased with the decrease of operating angle.

1. Introduction

Heat pipe is an effective thermal transmission device which can be used in many fields [1]. In recent years, heat pipe has been used in the thermal management of electronics because huge amount of heat can be transmitted through it timely for its high thermal conductivity. As a kind of new type heat pipe, the oscillating heat pipe (OHP) has better thermal performance than traditional heat pipe in heat dissipation. It was first introduced into the literature by Akachi [2] in the 1990s. The OHP is made from capillary tube without wick structure which was bent into many turns and a certain ratio of working fluid was injected into it. When the evaporation section is heated, the working fluid evaporates into vapor plugs and disperse with liquid slugs in the tube because of the effect of surface tension [3,4]. The pressure imbalance in adjacent tube causes the oscillation of working fluid between the evaporation section and condensation section. No external mechanical power is required to give rise to the oscillation [5]. Compared with traditional heat pipe, OHP has not only phase change thermal transmission, but also oscillations work during the heat transfer process. The OHP has advantages of prominent thermal performance, simple structure, easy manufacture and low cost, overall.

After more than twenty years research [6–10], the OHP has been used for the cooling of power electronics (such as the diodes [11,12] and electronic chips [13–16]), solar collector [17–19], waste heat recovery [20,21] and so on. Rittidech et al. [22] have used a closed-ended oscillating heat pipe air-preheater in a dryer in order to achieving energy thrift. Arab et al. [23] have designed and constructed an extra-long oscillating heat pipe which was installed in a thermosyphon solar water heater as a heat transfer tool. Clement and Wang [24] have designed and tested an oscillating heat pipe with a working purpose of heat dissipation for a proton exchange membrane fuel cell stack. Hemadri et al. [25] have embedded oscillating heat pipes into thermal radiators and found out that the effective Biot number strongly affected the isothermalization degree of the radiators. Kargar Sharif Abad et al. [26] have used an oscillating heat pipe in a solar desalination system and increased the rate of desalinated water production markedly. Mangini et al. [27] have experimentally tested an oscillating heat pipe for space application in microgravity environment. In our previous work [28–31], oscillating heat pipes have been designed and manufactured for battery thermal management (BTM) to ensure good performance.

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Nomenclature

$R_{3D\text{-}OHP}$	thermal resistance [K/W]
Di	inner diameter [mm]
T	temperature [°C]
U	voltage [V]
I	current [A]
g	gravity acceleration [N/kg]
σ	surface tension [N/m]
Re	Reynolds number
P	density [kg/m^3]
u	velocity [m/s]
α	angle [°]
D	diameter [m]
v	kinematic viscosity [kg/(m s)]
Pr	Prandtl number
Nu	Nusselt number
ε_n	correction factor
h	convective heat transfer coefficient [W/(m K)]
λ	thermal conductivity [W/(m K)]

Subscripts

liq	liquid
vap	vapor
dis	dissipation
max	maximum
ca	cooling air
e	evaporation
c	condensation
i	number of measuring point
J, k	number of layers
f	flow
w	wall

Acronyms

BTM	battery thermal management
OHP	oscillating heat pipe
3D-OHP	three-dimensional oscillating heat pipe

The OHP has been applied in many fields, but so far three-dimensional OHP has not been used widely. Ma et al. [32–34] have proposed several three-dimensional flat-plate oscillating heat pipes (3D FP-OHP) with different novel designs and tested the thermal performance under different conditions. The experimental results show that the 3D FP-OHP has better performance than conventional FP-OHP. Ma et al. [35] have also designed two three dimensional tubular oscillating heat pipes and tested their thermal performance, respectively. The result found out that the two-dimensional OHPs cannot transfer heat with a bigger heat flux. The thermal transmission direction of two-dimensional OHP is limited in a plane. Using the two-dimensional OHP for cooling may cause uneven temperature tendency of the electronics. In general, multiple two-dimensional OHPs are needed in the thermal management of an electronic component. Each OHP needs one injection process which really very inconvenient. The three-dimensional OHP has its unique characteristics to surmount these deficiencies. In this paper, a three-dimensional oscillating heat pipe (3D-OHP) only need one time injection was proposed to applied in thermal management of electronic component. Its three-dimensional structure produces more thermal transmission directions than two-dimensional oscillating heat pipe, which causes the temperature of the electronics more uniform. And the 3D-OHP has a longer flow path than two-dimensional heat pipe in the same plane size when both of the OHPs go to steady oscillation.

In this work, the 3D-OHP was designed, manufactured and tested. The platform was set up to study the thermal performance of the 3D-OHP for incremental heat inputs in evaporation section under different velocities of cooling air in condensation section. The thermal performance with different operating orientation was also tested. The thermal resistances of 3D-OHP in each layer were compared under different air velocities and orientations. The heat transfer mechanism was also presented and elaborated.

2. Experiment

2.1. Experiment setup

The 3D-OHP was fabricated by the red copper with inner diameter and outer diameter measuring 2 and 3 mm, respectively. The 3D-OHP was designed, bent, welded, cleaned and injected in the laboratory. The overall size of the 3D-OHP is 90 mm in length, 61 mm in width and 150 mm in height. The 3D-OHP has total 6 turns, 3 layers along width direction and 4 layers along length direction. Ethanol was employed as the working fluid because of its low boiling point. The filing ratio of the 3D-PHP was 50 ± 5%. A simple formula [36] is derived for calculating the theoretical maximum inner diameter of OHP:

$$D \leqslant D_{max} = 2\sqrt{\sigma/(\rho_1 - \rho_2)g} \qquad (1)$$

where D is the inner diameter of the OHP. ρ_2 and ρ_2 represent the density of liquid and vapor, respectively. σ represents the surface tension and g represents the gravity acceleration.

Fig. 1 shows the injection-cleaning platform consists of a vacuum pump, a vacuum meter, a steam water separator, a dryer, a three-way valve and an injection syringe. The valve I is opened and the valve II is closed when the vacuum pump is operating to clean the tube and ensure the vacuum, firstly. Then the valve I is closed and the valve II is opened at the same time, certain volume of working fluid flow into the tube driving by the vacuum force. In this study, the filling ratio was chosen as 50% [37]. The injection process needs to be repeated several times to clean the tube before the final injection.

Fig. 2 illustrates the experimental apparatus and the temperature measuring points of the 3D-OHP. The test system of the 3D-OHP was shown in Fig. 2(a). In addition to the 3D-OHP, a heating section, a fan (which served as a condenser), a rotating vane anemometer, measuring devices and data acquisition system were involved in the experimental elements. The heating component composed of the resistance wire and the asbestos is shown in Fig. 2(b). The resistance wire was twined around the bottom of 3D-OHP and heated by the electric power from the DC power supply. The evaporation section of 3D-OHP twined with the resistance wire was wrapped in asbestos to minimize heat loss from the heater to the environment. The condensation section of 3D-OHP was cooled by the fan. The velocities of cooling air were tested by a revolving vane anemometer. Working conditions under three cooling air velocities, 3.5 m/s, 5.5 m/s and 7.5 m/s, were selected and tested respectively. The operating orientation was changeable by changing the angle α. When α was 0°, the 3D-OHP was vertically placed and when α was 90°, the 3D-OHP was horizontal. Fig. 2(c) and (d) shows the total size of 3D-OHP and the placement of the thermocouples. A total of 18 K-type thermocouples were individu-