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Experimental investigation on thermal performance of multi-layers three-dimensional oscillating heat pipes

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An experimentally investigation on the effect of heating powers, layer number, operating orientations and filling ratios on three-dimensional oscillating heat pipe (3D-OHP) was studied in detail. Each layer of 3D-OHPs had the similar shape of single layer OHP with 90 mm wide, 150 mm high and 2turns. The distance between adjacent tubes and adjacent layers were both 26 mm. The thermal performance was studied by testing the start-up power, temperature and thermal resistance. Another 2D-OHP with same turns and similar geometry size as 3D-OHP was also tested to compare the difference between two OHPs. The results showed that the 4 layers 3D-OHP had the smallest start-up power and temperature among single layer to 5 layers 3D-OHPs under the similar heating powers both vertically and horizontally placed. It also had the smallest thermal resistance after start-up, which indicated that 4 layers 3D-OHP had the best thermal performance under the similar working conditions among 3D-OHPs. The 4 layers 3D-OHP with 50% filling ratio had the lowest start-up power and temperature and good heat transfer ability both vertically and horizontally placed. Compared with 2D-OHP, the thermal resistance of 3D-OHP was lower under high heating power in horizontal orientation. In general, the 3D-OHP had its unique advantages because of its multi-layer structure.

1. Introduction

With the continuous miniaturization and high integration levels trend of microelectronic components' development, the thermal management system with small and highly efficient heat-transport devices are needed to ensure reliable operation condition [1,2]. Heat pipes are among these devices. The oscillating heat pipe (OHP), also called pulsating heat pipe (PHP), is remarkable as a new kind of heat pipe. The OHP was first introduced into literature by Akachi in 1990 s [3]. An OHP consists of a single meandering capillary tube without wick structure between evaporation section and condensation section. The tube is evacuated and injected a certain ratio of working fluid. 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 [4,5]. 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 [6]. So the OHP has different heat transport mechanism from conventional heat pipe and has attracted considerable attention for advantages of prominent thermal performance, simple structure, easy manufacture and low cost.

After more than two decades research, OHPs with different novel structures were designed, manufactured and tested to obtain good heat transfer performance under different required working conditions. Some researchers designed OHPs with different tube diameters. Wang et al. [7] have tested the thermal performance of an OHP with uniform and alternating tube diameters. The results showed that the alternating tube designed OHP could start up at a low heat input with a small thermal resistance. Kim et al. [8] have designed a flat PHP with various asymmetric and aspect ratios channels and found out the optimum asymmetric ratio and aspect ratio under different heat inputs. Shyu et al. [9] have also designed a PHP with alternate channel width and found out the new design could obtain an extremely low Bond number. Kim [10], Wu [11,12] and Wang [13,14] et al. have also done related works. Some researchers designed OHPs with different geometrical structures to adopt different requirements. Qu et al. [15] have designed a hybrid flexible oscillating heat pipe (FOHP) for some spatial complicated energy utilization systems and tested its thermal performance with different structural styles under filling ratios of 50%, 60% and 70%. The results showed that the FOHP could function well and had acceptable heat transfer performance. Frijns et al. [16] have proposed a PHP with a Tesla-type valve and compared its

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Nomenclature

D	diameter [mm]
σ	surface tension [N/m]
ρ	density [g/cm^3]
g	gravity acceleration [N/kg]
R	thermal resistance [°C/W]
T	temperature [°C]
U	voltage [V]
I	current [A]
$\varDelta P$	pressure [N/cm^2]

Acronyms

FR	filling ratio
OHP	oscillating heat pipe
PHP	pulsating heat pipe
FOHP	flexible oscillating heat pipe
3D-OHP	three-dimensional oscillating heat pipe
3D FP-OHP	three-dimensional flat-plate oscillating heat pipe
2D-OHP	two-dimensional oscillating heat pipe

Subscripts

max	maximum
liq	liquid
vap	vapor
e	evaporation
c	condensation
q	quantity of heat
f	friction
g	gravity

thermal performance with an OHP without valves. The results showed that the exist of valves provided a 14% decrease in thermal resistance. Shafii et al. [17] have designed an flat OHP with interconnecting channels and found out that the interconnecting channels enhanced flow circulation and heat transfer in OHP. Shafii et al. [18] have also designed a rotating OHP and experimentally researched the charging input powers, filling ratios and rational speeds influence to the thermal performance. OHPs with other novel structures have also been proposed by other researchers [19–23].

Ma et al. [24–26] have proposed several three-dimensional flat-plate oscillating heat pipes (3D FP-OHP) with different novel designs and tested the thermal performance under different working conditions. The experimental results showed that the 3D FP-OHP had better performance than conventional FP-OHP. Ma et al. [27] have also designed two three-dimensional tubular oscillating heat pipes and tested their thermal performance, respectively. The results found out that the two-dimensional OHPs (2D-OHP) could not transfer heat with a bigger heat flux. In our previous works, a three-dimensional oscillating heat pipe (3D-OHP) with three layers was designed, manufactured and tested. The 3D-OHP had good thermal performance and thermal resistance uniformity[28].

For advantages of big heat flux transfer ability, thermal resistance uniformity, centralized configuration and easy design, multi-layers 3D-OHP deserves more attention. In the previous studies on the thermal performance of 3D-OHP were always focus on one or two certain shapes [24–27]. In this paper, to study more about the 3D-OHP, especially the effect of layers ‘stack’, 3D-OHPs with different layers were manufactured and tested under different heat inputs both vertically and horizontally placed in present work. The start-up characteristics and heat transfer performance of 3D-OHPs were analyzed. Furthermore, thermal performance of the 3D-OHP with different filling ratios (30%, 50% and 70%) was also experimentally studied. To compare the thermal performance difference of 2D-OHP and 3D-OHP with same turns and similar geometry size, a 2D-OHP with 8turns was also manufactured and tested.

2. Experimental setup

2.1. Experimental apparatus

The schematics of OHPs with single layer, 2 layers, 3 layers, 4 layers and 5 layers are shown in Fig. 1(a) and the schematic of the 2D-OHP is shown in Fig. 1(c). All the 2D-OHP and 3D-OHPs were fabricated by the red copper with inner diameter and outer diameter measuring 2 and 3 mm, respectively. All the 2D-OHP and 3D-PHPs were designed, bent, welded, cleaned and injected in the laboratory. Each layer of 3D-OHPs had the similar shape of single layer OHP with 90 mm wide, 150 mm high and 2turns. The distance between adjacent tubes was 26 mm. The spacing between two layers was also 26 mm. The 2D-OHP had similar geometry size as 3D-OHP with 438 mm wide, 150 mm high and 8-turns. The distance between adjacent tubes was also 26 mm. Water was chosen as the working fluid. A simple formula [29] is derived for calculating the theoretical maximum inner diameter of OHP:

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

where D is the inner diameter of OHP. ρ_l and ρ_v represent the density of liquid and vapor, respectively. σ represents the surface tension and g represents the gravity acceleration. After calculation, the inner diameter of the OHPs fitted this formula.

Fig. 1(b) shows the experimental apparatus of OHPs test system. The 3D-OHP, a DC power supply (served as evaporation section), a low temperature thermostat (served as condensation section), the data acquisition system and a PC were involved in the experimental elements. The resistance wire was twined around the evaporation section of the 3D-OHP and heated by the DC power supply. The condensation section of 3D-PHP was cooled by the aluminum cold plate with internal 15 °C water flow provided by the low temperature thermostatic bath. The whole 3D-OHP was wrapped in asbestos to minimize influence of environment temperature. Thermocouples were individually placed on the evaporation section and condensation section of the 3D-OHP to measure the surface temperature, as shown in Fig. 1(a). These data signals were separately recorded and then averaged. All the temperature measurements were collected through the OMEGA K-type thermocouples (diameter, φ = 0.127 mm) and the data acquisition system (34,970 A data acquisition/switch unit and 34,901 module, Agilent).

2.2. Experimental procedure

The thermal performance of 3D-OHPs with different layers and 50% filling ratio was tested under different heating powers, respectively. The 3D-OHPs at two most common placement modes in practical application, vertically and horizontally placed, were studied. Furthermore, the 3D-OHP with different filling ratio, 30%, 50% and 70%, was also tested. The thermal performance including start-