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Research Paper

Experimental research on the start-up characteristics and heat transfer performance of pulsating heat pipes with rectangular channels

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HIGHLIGHTS

- Effects of cross-section shape on heat transfer performance of PHP were studied.
- Different start-up processes of PHP with rectangular channels were discussed.
- The thermal resistance increased with filling ratio under the same heat flux.
- The thermal resistance was (30–40)% of that of PHP with circular channels.

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ABSTRACT

As a simple and efficient heat transfer device, the pulsating heat pipe (PHP) has been considered as one of the most effective methods to meet the challenges of high heat flux. Current studies focused on the heat transfer performance of the PHP with a small diameter ($d \leq 3$ mm). However, the PHP with a relatively large diameter has better performance due to the larger heat capacity of the working fluid at the same filling ratio. Besides, compared with the PHP with circular channels, the PHP with rectangular channels has special advantages due to the unique structures. On the basis of this, an experimental setup of the PHP with rectangular channels of 4 mm equivalent inner diameter was built, and the influence of cross-section shape on the start-up characteristics and heat transfer performance of the PHP was investigated. The experimental results showed that the start-up process shifted from a "sudden start-up mode" to a "smooth start-up mode" with the increase of heating power. The start-up heating power of the PHP with rectangular channels was (1.5–2) times greater as the heating power of the PHP with circular channels. Furthermore, the thermal resistance of the PHP with rectangular channels was only (30–40)% of the PHP with circular channels, and the temperature differences between the evaporation section and the condensation section were (10–20) °C lower than those of the PHP with circular channels under the same filling ratio and heat flux. It could also be concluded from the results that the lowest thermal resistance was achieved when filling ratio was 0.3 within the range of experimental data. The experimental results will provide valuable references for the optimal design of the PHP and further studies.

1. Introduction

The pulsating heat pipe (PHP) has been considered as one of the most effective methods to meet the challenges of higher heat fluxes [1–3]. As a high efficient heat transfer device, the PHP has many distinct advantages: simple structure, low cost and strong adaptability. The PHP is made of a long capillary pipe that is bent into many turns, in which the working fluid can form the alternate distribution of vapor plugs and liquid slugs due to the effect of surface tension. In operation, heat is transferred by the oscillation motion of vapor plugs and liquid slugs. After been proposed by Akachi [4] in 1990, it has been studied and applied in areas of solar energy utilization, waste heat recovery, aerospace thermal management and electrics cooling [5–7]. The operational mechanism of the PHP is quite different from traditional heat pipes, and no wick structures are needed to help the backflow of the working fluid. Researchers have indicated that the heat transfer performance of the PHP is greatly influenced by many parameters, especially the inner diameter and cross-section shape [8]. Charoensawan and Terdtoon [9] indicated that the thermal resistance of the PHP decreased with the increase of the inner diameter

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Nomenclature

T_i	temperatures of the i-th thermocouple (°C)	R	thermal resistance (K W^{-1})
ΔT	temperature difference (°C)	d	diameter (mm)
P	heating power (W)	t	times (s)
A	area of evaporation section	δ	uncertainty
q	heat flux (W m^{-2})		

since smaller inner diameter could lead to larger flow resistance and frictional pressure drop. Yang et al. [10] compared the heat transfer performance of PHPs with inner diameters of 2 mm and 1 mm. The results showed that the thermal resistance of the former PHP was lower by about 10% than that of the latter one. Kwon and Kim [11] conducted a series of experiments to investigate the effects of a dual-diameter tube on the flow and heat transfer characteristics of the single-turn PHP. The results showed that circulating flow promoted by a dual-diameter tube reduced thermal resistance of the PHP by as much as 45%, and there was an optimum range of diameter difference to maximize the thermal performance enhancement. It can be concluded that the PHP with large diameter has better performance due to the larger heat capacity of the working fluid at the same filling ratio and smaller friction resistance of working fluid compared with PHP with small inner diameter [8]. Meanwhile, the cross-section shape of PHP has significant influence on the transition of flow patterns and the distribution of working fluids, especially when the cross-section shape is rectangle, triangle, etc., the main reason is that the strong capillary force is caused by the angled corners of those channels [12]. Khandekar et al. [13] investigated the characteristics of PHPs with rectangular channels. The experimental results provided explanations for operational characteristics and performance limits, which were influenced by capillary resistance, gravity and working fluids. Yang et al. [14] investigated the influence of filling ratio, heat flux, and operating orientation on the thermo-hydrodynamic performance for PHPs with square channels of 1 mm and 2 mm, respectively, the results indicated some peculiar performance which was attributed to the sharp angled corners of the channels compared with circular channels.

The PHP with large inner diameter and angled cross-section shape has special advantages which can strengthen the heat transfer performance and broaden the applications. However, most researchers focused on the performance of PHPs whose inner diameter was less than 3 mm, and few results about PHPs with a relative large inner diameter were reported, especially when the cross-section shape was rectangle. On the basis of this, the start-up characteristics and heat transfer performance of the PHP with large inner diameter and rectangular channels were experimentally investigated in this work. By comparing with the PHP with circular channels of 4 mm inner diameter [15], the characteristics of the tested PHP was illustrated by experimental results, and the results will provide valuable references for the optimal design of the PHP and further studies.

2. Experiment

2.1. Experimental setup

The experimental setup in this work is shown in Fig. 1, very similar to that from Wang et al. [16]. A copper tube with rectangular cross-section was bent into ten "U" shape turns to form a closed PHP with 4 mm hydraulic diameter, which was regarded as the equivalent inner diameter. Deionized water was selected as the working fluid. For deionized water, the influence of surface tension of the working fluid would be stronger than that of the gravity when the diameter of PHP is less than is 4.98 mm [17], so a stable oscillation of liquid slugs and vapor plugs could be formed when the diameter is 4 mm. The outer surface size of the tube was 6 mm × 9 mm, and the thickness of the wall was 1.5 mm. The length of the evaporation section, adiabatic section and condensation section were 80 mm, 90 mm and 80 mm, respectively. A nickel-chrome wire with a length of 10.6 m and a diameter of 0.3 mm was wrapped outside of the tube in the evaporation section, and the voltage was controlled by a transformer to get different heating power (80–360) W. Furthermore, the adiabatic section and the evaporation section were both insulated by polyurethane foam material. Nine thermocouples were located in the evaporation section and the condensation section and the locations were shown in Fig. 1. The inclination angle of the system is 90° in this work. The accuracies of these thermocouples were calibrated to ±0.1 K. The temperature of the cooling water was set at 19 ± 0.1 K. All the experiment data were recorded by the Agilent 34970A ($6^{1/2}$ digits) which was connected with a PC. Before the experiment, the impurity inside of the tube was blown away by high-pressure nitrogen (1.5 MPa) for about 1 h to ensure the cleanliness of the channels. In this experiment, the filling ratio was changed from 0.3 to 0.7 in turn.

2.2. Experimental procedure

The experimental procedures of this work were described as follows:

(1) The PHP with rectangular channels was charged with dried nitrogen to 1.5 MPa after the impurities in the PHP were blown away. In the following 48 h, the pressure in the PHP almost remained unchanged, then the PHP was evacuated to about 1 Pa.
(2) The PHP was connected with the wattmeter, thermocouples and the other components. Before the experiment, these measuring devices were calibrated strictly. Then the certain amount of deionized water was charged into the PHP by using a syringe.
(3) The condensation section was immerged in the cooling water. The temperature of the cooling water was set at (19 ± 0.1) K. The cooling water was pumped from the inlet to the outlet of the cooling tank by a cooling pump.
(4) The power supply of the nickel-chrome wire was switched on, and the heating power was adjusted from 0 W until the PHP started up. The temperatures and the heating power would be recorded for about 30 min after the temperatures of the evaporation section oscillated steadily within a certain range.
(5) The heating power of the evaporation section was changed to ((80, 120, 160, 200, 240, 280, 320 and 360) W) respectively and the responding data were recorded as step 4.
(6) The PHP was charged with different filling ratios and the steps 1–5 were repeated.