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Heat transfer characteristics of micro-grooved oscillating heat pipes

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ABSTRACT

To data oscillating heat pipes (OHPs) are traditionally fabricated by wickless capillary tubes. In this work, microgroove (micro-fin) structure was introduced to OHPs to improve the heat transfer performance. The heat transfer characteristics of micro-grooved OHPs was experimentally investigated and compared with smooth-tube OHPs at vertical and horizontal orientations. All of these OHPs were made from copper tubes and deionized water was used as the working fluid at a volumetric filling ratio of 50%. The internal diameters (IDs) of three smooth-tube OHPs are 3.4, 4.0 and 4.8 mm, respectively, and the internal hydraulic diameters (IHDs) of two micro-grooved OHPs are about 2.0 and 2.8 mm. Experimental results show that the microgroove structure enable a profound improvement of OHP performance and reduce the startup power input or temperature. Besides, the average evaporator temperature could also be reduced significantly. The effective thermal conductivity of vertically tested micro-grooved OHP with 2.0 mm IHD is as high as about 86,262 W/(m·K). The mechanism responsible for these results is presented and discussed. In practice the micro-grooved OHPs could provide a promising option for prospective applications of high energy utilization and conversion efficiency.

1. Introduction

Oscillating heat pipe (OHP), or pulsating heat pipe (PHP), is a high efficiency heat transfer device invented by Akachi [1]. As a new member in the wickless heat pipe family, OHPs provide advantages of simple structure, low fabrication cost, fast response to high heat loads and good environmental adaptability. Hence, OHPs have received a growing interest in recent years and been considered as a promising solution for diverse ongoing and potential applications such as drying [2], solar energy collecting [3,4], thermal energy storage [5], cryogenics [6,7], and electronics cooling [8,9].

Aiming to improve the heat transfer performance of OHPs, many efforts have been performed both experimentally and theoretically, including the use of new working fluids [10–13], ultrasonic-assisted technology [14,15], structural change [16–19], and surface modification of internal wall [20–23]. Generally speaking, it is a simple approach to make use of novel structure to improve the heat transfer performance of OHPs. Khandekar et al. [24] investigated the effect of cross-sectional shape on the heat transfer and flow characteristics of plate OHPs. They found that an OHP with rectangular channels could reduce the thermal resistance effectively compared with that of circular tubes because of the capillary action created by channel edges. The impact of uniform and alternating tube diameter on the heat transfer performance of OHPs was experimentally investigated by Tseng et al. [16] and found that the performance could be significantly improved after using the alternating tube design. Later, their further experimental test on a double pipe OHP indicated that this novel structure enables it operation at the anti-gravity condition [17]. To ensure the directional movement of working fluid, Thompson et al. [18] proposed a derivative structure of Tesla-type check valves between channels in an OHP and found that the thermal resistance could be reduced by 15–25%. Most recently, similar work was performed by de Vries et al. [19] using a Tesla-type valve implemented in a single-turn PHP. The valve could produce diodicity, contributing to a promotion of fluid circulation in a more resistive direction and then a thermal resistance reduction of about 14% when compared to an identical PHP without valves.

Obviously, above advances mainly focused on the adjustment or change of general geometry and structure of OHPs, while the inner structure also definitely affects the heat transfer performance due to the oscillating motion of working fluid. Hence, how to improve the interaction between the fluid and internal wall of an OHP gives another possibility to enhance the heat transfer performance. Recently, superhydrophilic surface created by copper oxide (CuO) microstructure layer coated on the inner wall of a tube OHP was developed by Ji et al. [20] using chemically treated. Experimental investigation showed that the superhydrophilic treatment can sig-

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Nomenclature

A	cross-sectional area (m^2)
d	internal diameter (m)
D_h	hydraulic diameter (m)
g	gravitational acceleration (m/s^2)
I	input current (A)
l_f	micro-fin height (mm)
N	number of microgrooves
Q_a	heating power input (W)
R	thermal resistance (°C/W)
S	perimeter wetted of a single microgroove (m)
t_b	root thickness (mm)
t_w	tube wall thickness (mm)
T	temperature (°C)
u_I	system uncertainty
u_{II}	random uncertainty
U	input voltage (V)

Greek

α	helix angle (°)
γ	addendum angle(°)
ρ	density (kg/m^3)
σ	surface tension (N/m)
φ	heat loss coefficient

Subscript

c	condenser section
e	evaporator section
l	liquid phase
v	vapor phase

nificantly enhance the heat transfer performance of OHP. A further experimental test on a flat-plated OHP having different hydrophilic CuO nano-layer distribution was performed by Zhang et al. [21], results showed that the condenser treated OHP has best improvement in the heat transfer performance. Similar experimental studies on a flat-plated OHP with different inner surface wettability were conducted by Ma's group [22,23]. Experimental results demonstrated that the hybrid surface (superhydrophilic evaporator and superhydrophobic condenser) is preferred to achieve heat transfer enhancement in compared with uniform hydrophilic or superhydrophobic surface, owning to the maximum oscillation amplitude and velocity of liquid-slug movement in the former OHP. In addition to the surface modification of wettability, Xu et al. [25] recently performed a numerical simulation to investigate the liquid-vapor oscillating flow and heat transfer in a vertically-orientated OHP assuming that the inner wall was covered by sintered particle wicking structure. Traditionally, OHPs are fabricated without capillary wicks, while their modeling results demonstrated that both of the latent and sensible heat transfer could be improved effectively compared to that without wicking structures. Although sintered particles seem to be useful to act as wicks to enhance the heat transfer performance of OHPs, the unique nature of serpentine small-diameter-tube structure would surely increase its fabrication complexity and cost ineffectiveness.

Actually, the micro axial groove is another important wicking structure to provide a capillary-driven pump for returning the condensate to the evaporator section in miniature heat pipes [26–29]. Compared to sintered capillary wicks, a micro axial groove has its own advantages of easy fabrication, low cost and can serve as an energy-efficient design option on the basis of recent advances in microgroove smaller-diameter copper tubes [30]. Hence, microgroove (or micro-fin) tubes were used in the present work to fabricate OHPs for performance improvement. The start-up and heat transfer characteristics of micro-grooved OHPs were experimentally investigated and compared with conventional smooth-tube OHPs. The addition of microgroove structure inside tube OHPs can significantly lower the start-up power and enhance the heat transfer performance, providing an attractive and low-cost solution for prospective high energy efficiency applications.

2. Description of the experiment

2.1. Experimental apparatus

Fig.1 presents the experimental setup, which is mainly composed of a three-turn closed-loop OHP assembly, a heating unit, a cooling unit and a data acquisition system. The OHP was fabricated by a copper capillary tube, dividing into three parts: evaporator, adiabatic and condenser sections with lengths of 70, 230 and 110 mm, respectively. As illustrated in Fig. 1, the evaporator of OHP was electrically heated by a nichrome wire with a diameter of 0.3 mm. The heating wire packaged by a soft insulating tube was wrapped uniformly around the tube surface and connected to a power supply unit, which includes an AC voltage stabilizer and a voltage transformer. The input voltage and current to the heating wire were measured by two digital multimeters (VC890D, VICTOR), respectively. The heating power input to the evaporator section was largely determined by the product of voltage and current. The condenser, embedded in a cooling chamber, was cooled by ethylene glycol aqueous solution, which was pumped continuously from a cold bath (DC-0510, Shanghai HengPing Instrument and meter). Note that both of the evaporator and adiabatic sections were well thermally insulated with aluminum foil enveloped fiberglass insulation to minimize the heat loss from these two sections to the ambience.

To measure the wall temperatures of OHP, twelve OMEGA T-type thermocouples were soldered at different locations along the OHP tube. In addition, another two thermocouples were used to measure temperatures of cooling fluid at the inlet and outlet of condenser section. All temperature measurements were collected by a data acquisition system (34970A, Agilent).

The experimental procedure was similar to our previous work [31,32]. During the experiment test, the heating power input was stepwise increased until a quasi-steady state was established. Then, the spatial temperatures and heating power input could be recorded.

In this study, five OHPs were used independently, among which three (termed as #1, #2 and #3) OHPs having smooth tube, while #4 and #5 OHPs are made from micro-grooved tubes. Table 1 lists the inner and outer diameters of these five OHPs. Fig. 2 displays the local amplificatory inner surfaces and cross sections of micro-grooved tubes that shape #4 and #5 OHPs. Although there are no specific inner diameters (IDs) of #4 and #5 OHPs, their hydraulic diameter can be estimated by [33]:

$$D_h = \frac{4A\cos\alpha}{NS} \tag{1}$$

where A is the cross-sectional area infiltrated by pipe flow inside, S is the perimeter wetted of a single microgroove and channel taken perpendicular to the axis of groove, and α and N are the helix angle and number of microgrooves, respectively. According to the geometrical parameters given by Table 2, the internal equivalent