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Thermal characteristics and flow patterns of oscillating heat pipe with pulse heating

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ABSTRACT

In this paper, a pulsed direct current regulated power supply instead of normal continuous power supply was applied to heat the oscillating heat pipe through transparent electrical heating film which was evenly coated on the evaporation section. Simultaneous visualization and temperature measurement experiments were performed to investigate the impact of pulse heating on the temperature difference between evaporation section and condensation section, temperature fluctuation and flow behaviors of oscillating heat pipe. The experimental results indicated that the temperature difference between the evaporation section and the condensation section under pulse heating mode is highly dependent on the pulse duration and heating power. Furthermore, it was found that the pulse duration and pulse interval play an important role on the oscillating period of the temperature. Under pulse heating, instantaneous formed large amplitude oscillation is observed due to a phenomenon termed as 'injection–contraction' phenomenon, which simultaneously reinforces both the sensible heat transfer and latent heat transfer. When heating power equals to or is larger than 90 W, pulse heating accelerates the liquid reflux to evaporation section as the heating is stopped during pulse interval. Under pulse heating mode, the regions corresponding to the safe operations of oscillation heat pipe can be also extended.

1. Introduction

Recently, rapid development of electronic industry leads to high heat flux inside electronic devices, affecting their efficiency and reliability. Air, the most widely used cooling medium, limits its heat transport capability below 100 W/cm^2 [1]. As a two-phase thermal management system, conventional heat pipes possesses high heat transport capability and have been applied to many fields, such as computer and aerospace industry. However, their performance suffers various limitations [2], e.g. capillary limit, boiling limit, entrainment limit, sonic limit and viscous limit. Seeking to overcome those limitations, oscillating heat pipe (OHP) was introduced by Akachi [3] in the middle of 1990s. A typical oscillating heat pipe is a capillary tube bent into meandering tube, being vacuumed and partial filled with working fluid as shown in Fig. 1. Comparing with conventional heat pipe, OHP has many advantages, e.g. no wick structure, available miniaturization, easy fabrication and better heat transfer ability. Hence, OHP has been widely studied and applied to various fields by researchers, e.g. hybrid vehicle [4], fuel cell cooling [5], integral thermal spreader [6], wire-on-tube heat exchanger [7].

Numerous experimental and theoretical work have been conducted by many researchers over decades, shedding light on the complex characteristics of heat transfer and dynamic oscillating behavior inside OHP at a capillary level. For theoretical studies, many models describing dynamics inside OHP have been proposed, such as 'single spring–mass–damper' [8], 'multiple spring–mass–damper system' [9] and 'mass, momentum and energy conservation' [10]. Recently, effects of phase change, surface tension [11] and bubble generations [12,13] were also incorporated into the numerical models.

For experimental research, the influential parameters on the heat transfer performance of OHP have been widely studied [14–19]. The paramount parameters affecting the heat transfer capability of OHP identified in the previous investigations [14–19] are cross section, inner diameter of the tube, number of U-turn, working fluid and filling ratio respectively. Furthermore, it was found that the self-rewetting fluid and nano-fluid can also further promote the performance of OHP [20,21].

As the distinctive flow patterns and unique oscillating behaviors inside OHP could significantly affect the heat transfer of OHP, many visualization experiments have been conducted with the aid of high

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Nomenclature

Q	heating power at evaporation section (W)
U	voltage (V)
R	electrical resistance of heating film (Ω)
OHP	oscillating heat pipe
ΔT	average temperature difference between evaporation section and condescension section
t	time (ms)

Subscripts

pulse	pulse heating
continuous	continuous heating
e	evaporation section
c	condensation section

speed camera. For example, Tong et al. [22] visualized the flow inside the closed-loop oscillating heat pipe using a charged coupled device. It was observed that during the start-up period, the working fluid oscillates with large amplitude while at steady operating state and the working fluid circulates inside the whole OHP. Phenomena such as nucleation boiling, coalescence of bubbles, formation of slug and propagation of inertia waves have been also observed in the closed-loop OHP. Xu et al. [23] identified the existence of bulk circulation flow inside OHP and they found that the bubble displacements and velocities in methanol-filled and water-filled OHP displayed different kind of waves. Khandekar et al. [24] identified that the flow patterns of the working fluid and the performance of OHP were affected by the inner diameter, heating power, inclination angle and number of turns. Recently, Qu and Cheng [25] investigated three silicon-based micro oscillating heat pipes with the trapezoidal cross-section and different hydraulic diameters. Their results revealed that heat transfer performance of OHP was also affected by the working fluid and the inclination angle. At the same time, nucleation boiling bulk circulation flow and injection flow were observed. Yoon et al. [26] conducted an experimental investigation using neutron imaging to analyze the volume fraction of the liquid phase in different sections of OHP. Their results illustrated that the volume fraction distribution of the liquid phase was always less than 2.5% in the evaporator section and greater than 80% in the condenser during steady oscillating state. Furthermore, there is a notable synchronization between the entrance of liquid into the evaporate section of OHP and temperature oscillations.

Based on literature survey, it can be seen that a continuous constant power source was often adopted by the majority of researchers and thermal characteristics and flow behaviors inside OHP under continuous heating mode have been revealed. As a passive heat transfer device, the heat transfer capability of OHP fundamentally origins from its oscillating motion and phase change induced inside OHP. Different heating mode, such as pulse heating, may affect the pressure and temperature oscillation to further enhance the heat transfer of OHP. In our previous work, Xian et al. [27] found that pulse heating can enhance the heat transfer of OHP and there exists an optimized pulse heating parameters (e.g. pulse duration and pulse interval). Recently, Kim et al. [28] numerically simulated the effects of temperature fluctuations of heating and cooling section on the oscillatory flow inside OHP. They discovered that periodic fluctuation of wall temperature affects the oscillations of liquid slug while the random fluctuation does not. Thus pulse heating is an effective method to enhance the heat transfer of OHP with great research significance.

In this paper, the effect of pulse heating on the heat transfer performance and oscillating behaviors inside OHP are investigated experimentally with the aid of high speed image capture system. A pulsed direct current regulated power supply with square waves of adjustable pulse duration and pulse interval time was applied to heat the oscillating heat pipe. During the experiments, the temperature inside working fluid of the OHP was measured. The thermal performance, temperature fluctuation and flow patterns of OHP under pulse heating were also analyzed and discussed.

2. Experimental setup

Fig. 1 shows the experimental setups including oscillating heat pipe, heating and cooling devices, temperature data acquisition system and high speed image capture system. The structural parameters of OHP are introduced in Table 1.

For a clear visualization, OHP was made of heat resistant glass with high transmittance and outlets at both left and right sides for convenience of vacuum and filling of high-purity distilled water. The OHP is vacuumed by high vacuum molecular pump (KYKY Technology development Ltd.). The transparent electric heating film made with SnO_2 was coated on the whole evaporation section evenly. Thus the filing ratio (about 49%) can be calculated

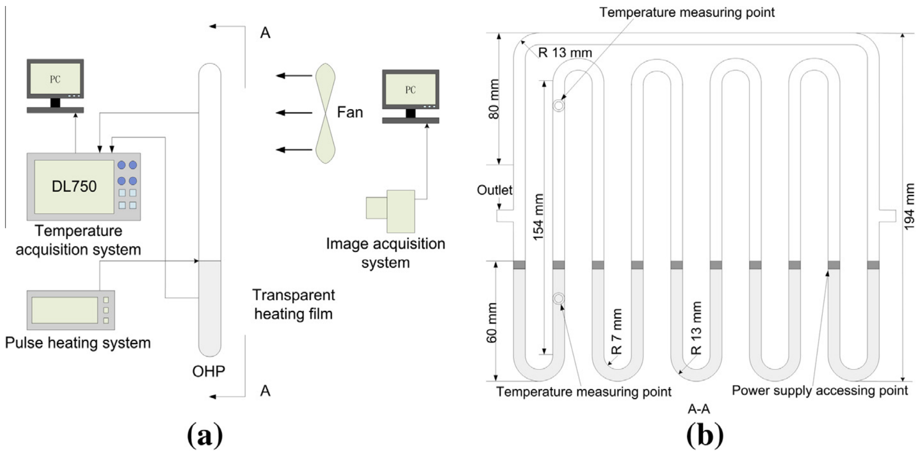

Fig. 1. The outline of experimental system (a) and a detailed introduction of oscillating heat pipe (b).