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Dynamic performance analysis on start-up of closed-loop pulsating heat pipes (CLPHPs)

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ABSTRACT

The control theory (system identification theory) is introduced to quantitatively analyze the start-up *performance* of the closed-loop pulsating heat pipes (CLPHPs) based on an experimental investigation with various working fluids under different working conditions. A preliminary dynamic relationship between the 'input' (heat load) and 'output' (evaporator temperature) and corresponding six evaluation criteria are proposed to realize the quantitative characterization of the dynamic performance of two most common types of start-up, respectively, which provide a prerequisite for the further simulation and control design of the CLPHPs' start-up. Based on such analysis, it is indicated that the optimal liquid filling ratio for start-up is about 41% for water, 52% for ethanol, and falls within the range from 35% to 41% for methanol. The start-up performance is improved with increasing inclination angle from 0° to 90°. With the increasing heat load, a faster start-up speed and a better relative stability are observed while the start-up temperature is increased. Moreover, the working fluid with small dynamic viscosity, small specific heat, and especially large saturation pressure gradient versus temperature is beneficial to the start-up performance of the CLPHPs.

1. Introduction

As a result of the good performance, simple structure and low fabrication cost, the pulsating heat pipe (PHP) has been introduced as an attractive option for electronic cooling applications, especially where strict limitation of space and operating costs are applied [1]. The PHP can be classified as close looped and open looped, and the former usually has smaller thermal resistance than the latter due to circulation of working fluid in the loop [2]. Conventional closed-loop pulsating heat pipe (CLPHP) usually exists as a continuous capillary tube arranged in a planar serpentine manner, which is first evacuated and then filled partially with a working fluid. The diameter of the tube is small enough to allow the working fluid to distribute itself naturally in the form of liquid–vapor plugs and slugs inside the CLPHP due to the surface tension. The CLPHP must be heated in at least one section (evaporator) and cooled in another (condenser). Due to the temperature difference established on the CLPHP and the non-uniform distribution of liquid–vapor plugs and slugs, the saturation pressure difference with non-uniform pressure oscillation will be produced among the CLPHP, making the working fluid undergo complex displacements of both oscillatory and circulatory characteristics [3].

During the past decades a great deal of interest has been focused upon the flow patterns, thermal performance, and feasibility of CLPHPs with different structures [3–18]. Bubbly flow, slug flow, and semi-annular/annular flow were observed in CLPHPs. It is indicated that the thermal performance of CLPHPs depends on many parameters such as geometric parameters, working fluid properties, heat load, inclination angle, filling ratio, number of turns, etc. The optimal design of CLPHPs is based on an overall consideration of these parameters.

In addition to the thermal performance and flow characteristics, the start-up performance is another important problem in the practical application of CLPHPs. The start-up of CLPHPs is a dynamic process from the application of heat load to evaporator until to the attainment of quasi-steady thermal state when CLPHPs are able to transport the imposed heat load without overheating [2]. Therefore, several experimental studies have been conducted to investigate the start-up performance of CLPHPs. The early experimental results involving the start-up performance were reported by Kadoguchi and Tashiro [19] and Tong et al. [3]. It was found that during the initial start-up period, at the moment when heat was applied to the evaporator, a sharp noise produced by nucleate boiling was heard. In addition, Tong et al. [3] observed a large amplitude oscillation of

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working fluid during start-up process. Xu and Zhang [20] performed an experimental study on the start-up performance of a 2.0 mm inner diameter multi-turn CLPHP with FC-72 as the working fluid. Two types of the start-up process were observed: a sensible heat receiving start-up process with a temperature overshoot followed by the steady thermal oscillation at low heat load, and a smooth sensible heat receiving start-up process accompanying a smooth oscillation period at high heat load. Subsequently, Khandekar et al. [21] conducted a visualization investigation on the start-up process of a single loop CLPHP with the inner diameter of 2.0 mm. Similar to Xu and Zhang's results, two types of loop start-up called 'sudden start-up' and 'gradual start-up' were observed. However, the effects of the factors such as the geometric parameters, working fluid properties, heat load, inclination angle, filling ratio, and number of turns on the start-up performance were less investigated in the above experimental investigations. For this reason, Charoensawan and Terdtoon [22] experimentally investigated the influence of the turn's number on the start-up performance of a horizontal CLPHP. They found that the start-up of the horizontal CLPHP depends greatly on the evaporator temperature that relates to the number of turns. The start-up temperature decreases with the increasing turns. Xian et al. [23] conducted the experiments for the influence of inclination angle on the start-up characteristics of a CLPHP with water as the working fluid, which indicated the start-up temperature under horizontal operation is significantly higher than those under other inclination angles but the importance of inclination angle is weakened with the decreasing filling ratio. Recently, Lin et al. [24] experimentally studied the start-up of miniature CLPHP with various inner diameters, and this investigation indicated that the increasing inner diameter or decreasing heat transfer length is beneficial to CLPHP's start-up, based on the recommended optimum size of inner diameter and heat transfer length. Ji et al. [25] experimentally investigated the start-up performance of the CLPHP charged with Al_2O_3 nanofluid. It was suggested that the Al_2O_3 nanoparticles added in the CLPHP can help to start-up the oscillating motion.

In addition to these original experimental investigations, several theoretical investigations involving start-up performance of CLPHP have also been conducted. Qu and Ma [26] developed a model based on solving global vapor bubble dynamic equations to analyze the start-up of CLPHP and found that the CLPHP with capillary inner surface coated or fabricated with cavities or roughness can be readily started up. More recently, Liu and Hao [17] proposed a three-dimensional unsteady model of vapor–liquid two-phase flow and heat transfer in a CLPHP, taking into consideration of the vapor–liquid interface and process of condensation and evaporation. Based on this model, the flow pattern transition and heat transfer performance during start-up process of CLPHP were numerically investigated, and the fast increase in total vapor volume fraction was detected. Soponpongpipat et al. [27] developed a mathematical model to predict the suitable temperature for start-up of CLPHP by using the visualization data and thermodynamics theory. A large temperature difference between the evaporator and condenser is found to be necessary for reaching a successful start-up in the case of a fixed evaporator temperature and a small filling ratio, as well as vice versa for large filling ratios. Cheng et al. [28] proposed an one-dimensional unsteady model to investigate the heat transfer of flat-plate pulsating heat pipes and found that the existence of gravity is a source of disturbance depending on the heating mode for the flat-plate pulsating heat pipes, which could help the heat pipe to easily start-up the oscillating motion.

As mentioned above, several theoretical and experimental investigations of start-up performance have been conducted in recent years. However, there is still a lack of quantitative analysis of such a complex dynamic thermal response. As for the dynamic behavior analysis, a number of commonly used evaluation methods have been proposed in control theory. Surprisingly, these evaluation methods have not been systematically applied in the quantitative analysis of start-up performance of heat pipe. Therefore, based on a comprehensive experimental study on the start-up performance of CLPHP, the system identification theory (an important part of control theory) is introduced to quantitatively characterize the start-up performance. By this means, the effects of filling ratio, inclination angle, heat load, and especially the thermophysical properties of working fluid on start-up performance are investigated. Additionally, this study can also provide a prerequisite for the further simulation and control design of the CLPHPs' start-up.

2. Experimental setup

In general, the CLPHP operates on the basis of the movement of liquid slugs and vapor plugs, which is governed by surface tension and buoyancy [1]. Therefore, the inner diameter must be small enough so that the working fluid will distribute itself inside the tube length and form the liquid slugs and vapor plugs due to the effect of surface tension. The theoretical maximum inner diameter D_{max} for a CLPHP is suggested as [1]:

$$D \le D_{max} = 2\sqrt{\frac{\sigma}{(\rho_l - \rho_v)g}} \tag{1}$$

where D is the inner diameter of CLPHP tube, ρ_l, ρ_v are the density of liquid and vapor, respectively, σ is the surface tension, and g is the gravity acceleration. In order to study the influence of thermophysical properties on the start-up performance of CLPHP, three working fluids such as ethanol, methanol and water are used here. As suggested by Eq. (1), the appropriate scales of the CLPHP tubes for ethanol, methanol and water with a saturation temperature of 20 °C are $D \le 3.6$ mm, $D \le 3.4$ mm, and $D \le 5.4$ mm, respectively. In order to make the tube diameter to fit all the three working fluids, the CLPHP is fabricated by bending a copper capillary tube with the inner diameter of 2.6 mm and outer diameter of 4 mm.

Fig. 1 illustrates the schematic of the experimental setup. As shown in the figure, the CLPHP with the dimension of 300 mm × 174 mm has 10 turns, and the inner radius of each turn is 6.75 mm. The lengths of evaporator, adiabatic section and condenser are all 100 mm. The heat load is applied by Ni–Cr wire with a diameter of 0.4 mm which is wrapped on the outer wall surface of the evaporator, and it is dissipated from the condenser by cooling water with a constant inlet temperature of 20 °C. The input heat load is measured by a power meter (HIOKI 3332) with an accuracy of 0.2%. Both the evaporator and adiabatic section are well thermally insulated by aluminum silicate fibers. According to the analysis of heat balance between the evaporator and the condenser, the heat loss from the evaporator and adiabatic section to the ambience in this experiment is within 5.5% of the heat load. The inclination angle can be adjusted from horizontal plane ($\theta = 0°$) to vertical plane ($\theta = 90°$). The temperature distribution of the CLPHP is measured by thermocouples (diameter of 0.125 mm, OMEGA K-type with ±0.1 °C, $T_1 \sim T_8$ for evaporator, $T_9 \sim T_{18}$ for adiabatic section, $T_{19} \sim T_{26}$ for condenser) and recorded by the data-collecting instrument. Furthermore, according to the Nyquist–Shannon sampling theorem, a high-speed sampling rate for acquiring the temperature oscillation signals is set to be 50 Hz, which is far higher than two times of the highest frequency of original temperature oscillations [29]. In the current experiment, the Fourier number of tube wall, $Fo = a_w \tau_d / \delta_w^2$, has a range of 10.1–11.2, where a_w is the thermal diffusivity of tube wall, τ_d is the typical duration of sampling (here $\tau_d = 0.02$ s), δ_W is the thickness of the tube wall. And thus it can be concluded that the inner and outer