International Communications in Heat and Mass Transfer 94 (2018) 1–13

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Startup and transport characteristics of oscillating heat pipe using ionic liquids

Qianqing Liang[a,b], Tingting Hao[a], Kai Wang[a], Xuehu Ma[a,*], Zhong Lan[a], Yaxiong Wang[b]

[a] *Liaoning Key Laboratory of Clean Utilization of Chemical Resources, Institute of Chemical Engineering, Dalian University of Technology, Dalian 11624, China*
[b] *School of Chemical Engineering, Inner Mongolia University of Science & Technology, Baotou, Inner Mongolia, Baotou 014010, China*

ARTICLE INFO

Keywords:
Ionic liquids
Oscillating heat pipe (OHP)
Startup
Pulsation characteristics
Thermal performance

ABSTRACT

This paper attempted to investigate the effects of ionic liquids (ILs) addition on the startup, operation and thermal performance of a closed loop copper oscillating heat pipe (OHP, four turns). The liquid slug oscillation characteristics and flow pattern of the OHP with various heat input were also experimentally examined utilizing high-speed camera. The experimental results showed that for higher ILs mass fractions, the OHP behaved a lower startup power (decrease of 29 W) and startup temperature (decrease of 11 °C), which are favorable of not only facilitating a faster startup of the OHP but also effectively avoiding the "dry-out" problem. When the mass fraction of ILs was 0.67%, the ILs-water based OHP substantially had the same amplitude and the velocity as water-based OHP. When the ILs addition was respectively 19.1% and 44.4% (mass fraction), the oscillation liquid slug displayed a high frequency and small amplitude characteristics. In case of a low mass fraction of ILs, ILs-water based OHP nearly perform the same heat transfer performance as the water based OHP presented. However, the heat transfer performance of the ILs-water based OHP showed a slight decrease of 10% at higher heat input (> 220 W), which in general did not affect the overall thermal performance and operational stability of the OHP. A modified correlation of Kutateladze number (*Ku*) was established and could basically predict the thermal performance within approximately ± 10% deviation in the vertical closed loop OHP at a filling ratio around 65% considering the effects of ILs addition.

1. Introduction

Oscillating heat pipe (OHP) firstly introduced by Akachi [1], gradually shows a promising applications in the heat dissipation field especially for compact electronic devices with high heat flux, owing to its simple wickless structure and effective thermal conductivity [2]. The OHP mainly depends on the oscillation and circulation of the gas bubble and the liquid slug to realize its stable operation, its driving force comes from the difference between the vapor expansion of the evaporation section and the vapor condensation of the condensation section [3]. Recently, related studies on the OHP mainly focused on the following aspects: (1) geometrical parameters of the OHP, i.e., inner diameter [4] and the cross-sectional structure [5]; (2) length of condensation section and the evaporation section [6]; (3) number of turns [7]; (4) inclination angle (i.e. Gravity) [8,9]; (5) filling rate of working fluid [10,11]; (6) thermo-physical properties of working fluids [12–14], including surface tension, latent heat, partial derivative of the saturation pressure with respect to temperature, specific heat capacity, viscosity, compatibility with pulsating heat pipe material, thermal stability and wettability. Based on factors analysis aforementioned, the influence of the working fluid on the startup, operation and thermal performance of the OHP cannot be neglected.

The OHP startup performance is remarkably affected by surface condition, vapor bubble type, working fluid, and filling ratio. There is a generally accepted hypothesis that nucleate boiling may be the physical phenomena that marks the onset of OHP oscillation, leading to a great change in thermal resistance. Therefore, the working fluid significantly influenced the startup characteristics for the OHP operation. Qu and Ma [5] considered that heat transfer primarily occurs through the liquid film as the pure conduction before the bubble formation, and thus the maximum heat transfer rate through the liquid film can be obtained by

$$q'' = \frac{\lambda_l \Delta T_{Taylor}}{r_{inner} \ln[r_{inner}/(r_{inner} - \delta_l)]} \quad (1)$$

Bubble formation is directly related to the startup of an OHP, thus Eq. (1) could be utilized to determine the heat flux for an OHP to start up an oscillating motion. Note that, ΔT_{Taylor} represents superheat of Taylor flow bubble exactly after startup of the OHP. Yin et al. [15]

---

[*] Corresponding author.
E-mail address: xuehuma@dlut.edu.cn (X. Ma).

https://doi.org/10.1016/j.icheatmasstransfer.2018.03.004

proposed a mathematical model for the startup of oscillating motion in the OHP and accounted that the difference of pressure wave speed propagation between the liquid phase and the vapor phase generated an exciting driving force, in other words, a pressure difference in the OHP system producing an driving force to start up the oscillating motion of the liquid plugs and vapor bubbles. Yin et al. also concluded that heat input required to start up the oscillating motion predominantly depends on the filling ratio. Specifically, an increase of the filling ratio leads to a larger heat input to start up the oscillating motion.

For a typical OHP, convection heat transfer plays a key role in the thermal performance of the OHP. In other words, most of the heat transferred from the evaporator to the condenser is by sensible heat. Therefore, the thermal-properties, i.e. thermal conductivity, viscosity, and heat capacity of the working fluid play an important role. Accordingly, Khandekar et al. [16] proposed a reasonable selection of working fluids with high $\partial p_{sat}/\partial T$, low viscosity, low latent heat, low surface tension and high specific heat capacity based on thermodynamic principles. However, the process intensification mechanism with various working fluids for the start-up and thermal performance in the OHP is not yet fully understood. Recently, the research on the start-up and heat transfer characteristics for the OHP mainly concentrates on the following working fluid: mixture working fluid [17], refrigerant [18] (ammonia, R-134a, Hfo-1234yf, R-141b, R123, Flour inert [19]), microcapsule fluid [20] (FS-39E, FC-72), self-rewetting fluid [21], nanofluids [22–27]. Wang and Cui [16] investigated thermal resistance characteristic of the OHP using a mixture of two substance (methanol, ethanol, acetone, water) as working fluid, and found that the OHP with the mixture of methanol and water presented the best thermal performance. Brent et al. [18] investigated the design, start-up and operation performance of the OHP with five working fluids, including water, acetone, ammonia, R-134a and HFO-1234yf, and indicated that R-134a and its replacement, HFO-1234yf, were well suited for incorporation into OHP based heat spreaders. Wang et al. [20] experimentally investigated three typical working fluids, i.e., FS-39E microcapsule fluid, Al_2O_3 nanofluid and pure water of the OHP, and found that the thermal resistance could be reduced by 0.35 °C/W using 1 wt% FS-39E microcapsule fluid. Fumoto [20] et al. found that the self-rewetting fluid improved the heat transfer characteristics of the OHP, i.e. a lower thermal resistance could be obtained using self-rewetting fluid solution of 1.0 wt% of less as the working fluid. Among these working fluids, nanofluids could also significantly affect the heat transport capability in an OHP. *Ma* et al. [22,23] found that the addition of nanoparticles into the base fluid could effectively improve the heat transport capability, specifically, the OHP could reach a thermal resistance of 0.03 K/W at the power input of 336 W as well as significant reduction of the temperature difference between the evaporator and condenser with 5–50 nm diamond nanoparticles. Li et al. [25] and Wu et al. [26] respectively showed significant enhancement of OHP performance with SiO_2 nanoparticles with the diameter of 15 nm and with Al_2O_3 nanoparticles with the diameter of 56 nm. Recently, the role of nanoparticles combined with the dominant heat transfer modes (sensible/latent) in each section had been characterized and clearly identified [27], thus it was found that the OHP performance was dominantly affected by evaporator heat transfer performance and also observed that poor heat transfer performance with nanofluid at the evaporator section led to lower operating pressure of OHP. Su et al. [28] combined nanofluid and self-rewetting fluid together forming a ternary working fluid system, and found that OHP with self-rewetting nanofluid displayed excellent heat transfer performance over the entire heat load range. Based on flow visualization results for flow patterns within a closed-loop OHP with Fe_2O_3/kerosene as the working fluid, Goshayeshi [29] revealed that bubble generation and bubble growth induced a large driving force which contributed to the random motion of liquid slugs and vapor plugs. Wu [30] experimentally investigated on heat-transfer performance of a flat-plate closed loop pulsating heat pipe (FCLOHP) with a mixture of ethanol and C_{60} nano-particles, and found that increasing C_{60} nanofluid concentration could improve the thermal performance of the FCLOHP, but reduce the critical heat load.

Ionic liquid (ILs) has attracted much attention as a novel solvent [31–33], and can have a liquidus range approaching 400 °C [34], almost no vapor pressure [35] and higher volumetric heat capacity [32].These favorable physical properties give ILs a potential advantage to be utilized as a thermal fluid or energy storage material [36,37], especially as a viable heat transfer fluid for concentrating solar power systems [38–40]. According to the aforementioned reports, a reasonable working fluids should behave low viscosity, low latent heat, low surface tension and high specific heat capacity. However, there is no such a perfect working fluid with all the advantages at present. Compared to water, although ionic-liquid has a high viscosity at the room temperature, it behaves a comparable volumetric heat capacity and a lower surface tension. Although the viscosity of ionic-liquid was large at room temperature, it is decreased apparently with the increasing temperature. Simultaneously, ionic-liquid with good surface wettability could be effectively conducted heat. And ionic-liquid with no phase change and high specific heat could temporarily store heat and increase the amount of energy which liquid slugs can transport in the vertical OHP. Consequently, this work conducted a tentative exploration on the start-up and heat transfer performance of closed-loop pulsating heat pipe (CLOHP) with four turns by introducing a series of mass fraction ionic-liquid as working fluids. Based on the visualization results from high-speed camera and heat transfer experiments, the analysis and comparison of the influence of the ILs addition on the operation stability, pulsation characteristics of liquid slugs and heat transfer characteristics of the OHP was simultaneously carried.

2. Experimental test program and uncertainty analysis

The prepared flat-plate oscillating heat pipe were made from copper with a 2 mm × 2 mm square cross-section and covered by transparent PC plate for visualization of slug oscillating motions using high speed camera (CCD) (Photron, Fastcam Apx-Rs). The dimensions of condensation section, adiabatic section and evaporation section was $57 \times 36\ mm^2$, $57 \times 42\ mm^2$, and $57 \times 28\ mm^2$, respectively. Twelve T-type thermocouples with a maximum uncertainty of ± 0.05 °C were located to measure the wall temperature of the OHP as shown in Fig. 1. The temperature measurements were collected by using the Agilent 34970A data acquisition system.

The channel diameter should be small enough to ensure the oscillations motion. The maximum and minimum diameter is respectively calculated using the modified Bond number [18]. When the temperature is 20 °C, channel diameter is in the range of 1.9–5.0 mm for deionized water while 1.1–2.8 mm for pure ILs, therefore 2 mm diameter is accessible to produce a oscillating flow. Fig. 2 shows the schematic of the experimental setup as our previous work [41] including four-turn copper plate OHP, heating, cooling, and data acquisition system. It can be seen from Fig. 2 that operational orientation presents a vertical bottom heating mode. The heating block was manufactured with copper block with dimensions of $80 \times 40 \times 40\ mm^3$ and connected to a direct current power (SMPS 5000) to supply a total maximum input power of 360 W. While the cooling block was also made from copper block with dimensions of $80\times 60 \times 40\ mm^3$ and the cooling water flow rate was 60 L/h and maintained a constant temperature of 15 °C controlled by a constant temperature bath (DFY-10/25) and rotor flowmeter (LZB-6) during the experiment. The cooling block and heating block were attached the plate oscillating heat pipe by bolts and the thermal conductive silicon grease (HZ-KS101, $> 0.21\ W/m^2{\cdot}K$) was used to reduce the thermal contact resistance between blocks and the FPOHP. The whole testing setup was insulated to maintain a negligible heat loss of < 5% in this paper. A vacuum pump (Leybold D8C) connected to the OHP was used to achieve the vacuum requirement and found that the experimental system could keep a pressure variation of 5–10 Pa for 12 h monitored by a McLeod vacuum gauge (PM-2, China).