International Communications in Heat and Mass Transfer 85 (2017) 23–28

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Investigation of the evacuation pressure on the performance of pulsating heat pipe

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ARTICLE INFO

Keywords:
Pulsating heat pipe
Water
HFE-7000
Evacuation pressure
Thermal resistance

ABSTRACT

This study examines the influence of evacuation pressure on the startup and overall performance of pulsating heat pipes (PHP). The outer diameter of the copper tube is 3 mm and 2 mm (double tube design) having a wall thickness of 0.3 mm and 0.2 mm, respectively. The working fluids in this study include water and HFE-7000 with filling ratios around 50%, and the evacuation pressure ranging from 0.01 Torr to atmosphere pressure. For an evacuation pressure of 0.01 Torr at a supplied power of 80 W, the thermal resistance of the PHP filling with water is 0.928 K/W while it is 1.161 K/W for HFE-7000. However, the trend is reversed and the thermal resistance for HFE-7000 is lower than water when the evacuation pressure is increased over 100 Torr. The corresponding effective thermal conductivity of water-filling PHP reaches 51,448 W/m K in comparison with 12,692 W/m K for HFE-7000. However, the effective thermal conductivity for water-filling PHP drops appreciably with rising evacuation pressure, and the PHP is not functional at the atmosphere pressure. Conversely, although the effective thermal conductivity for HFE-7000 PHP still drops with the rise of evacuation pressure, the HFE-7000 PHP is still in operation even without any evacuation. The gigantic difference in the startup and performance of PHP is related to the solubility of non-condensable gas amid water and HFE-7000.

1. Introduction

The pulsating heat pipe (PHP) features many outstanding characteristics like wick-free, low cost, excellent heat transport capability, and flexible configurations. Hence, it shows quite promising potentials for applications in heat recovery, solar energy, aerospace, electronic cooling, and the like [1]. Moreover, its simple structure can be easily implemented to tackle high flux applications [2,3] in space-confinement applications. Normally, PHPs are consisted of small diameter tubes having vertical serpentine configurations. By filling some amount of working fluid, the PHPs are functioning with periodic expansion vapor slug from heat source in the evaporator and contracts in the condenser to give up heat. Hence unevenly distributed liquid slugs circulate to and fro amid the evaporator and condenser [4]. Converse to the conventional heat pipes, PHP is wickless that offers low capital cost during manufacturing. Moreover, the PHPs also hold many superior features such as high effective thermal conductivity, flexibility, large maximum heat transfer, and long distance transportation capability.

For effective starting up the PHPs, appropriate manipulating the size of capillary tubes and the gravity force is quite significant [5,6]. Zhang and Faghri [7] clearly indicated that raising the number of turns could lead to un-balance of pressure force alongside the tubes. The induced unstable pressure imbalance will help to startup the PHP subject to inclinations. However, the PHPs with fewer turns still face severe starting up problems for applications with horizontal arrangement or inverted heat source conditions. To tackle this problem, Chien et al. [8] proposed a copper-made PHP having alternating tube sizes to introduce more unbalancing forces like capillary and viscous forces. Their proposed non-uniform channel PHPs is functional to all inclinations provided the charge ratio is sufficient (above 50%). Tseng et al. [9] investigated the performance of closed-loop pulsating heat pipes (CLPHPs) subject to the influence of uniform and alternating diameter. The alternating design is identical to that of the uniform design but some of the tubes are compressed to an oval-like configuration. Both aforementioned studies were able to operate the PHPs horizontally with fewer turns. However, these foregoing PHPs are still unable to operate for inverted heat sources arrangement. Therefore Tseng et al. [10] further proposed a novel design having alternative double-pipe tube having different tube diameters with some extra open connections between these double-pipes. By introducing extra un-balanced pressure force, capillary force and gravity force, the PHP can easily startup even for an opposite heat source/sink arrangement while the conventional

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2017.04.005

Nomenclature

A	area, m^2
c_p	specific heat of water, J/kg K
D	diameter, m
h_{fg}	latent heat if vaporization, J/kg
k_{eff}	effective thermal conductivity, W/m K
M	figure of Merit, W/m^2
$\dot{m}$	mass flow rate of coolant water, kg/s
L_{eff}	effective length, m
Q_{out}	cooling capacity of condenser, W
R	thermal resistance, K/W
T	temperature, K
$T_{c,avg}$	average surface temperature at the condenser, K
$T_{e,acg}$	average surface temperature at the evaporator, K
$T_{w,in}$	temperature at the chilled water inlet, K
$T_{w,out}$	temperature at the chilled water outlet, K

Greek symbol

μ	dynamic viscosity, N s/m^2
ρ	density, kg/m^3
σ	surface tension, N/m

Subscript

avg	average
BC	bend tube at condenser
BE	bend tube at evaporator
cond	condenser
evap	evaporator
l	liquid
SC	straight tube near condenser
SE	straight tube near evaporator

single tube design fails to startup with this opposite arrangement.

The performance of PHP depends on not just geometric configuration. In practice, the working fluids also play essential role in the startup and influence the overall performance of the PHPs. Tseng et al. [9] examined the startup and performance of PHPs between methane, water, and HFE-7100. They found that PHPs can be easily starting up at a lower heat flux when methane or HFE-7100 is used. This is resorted to a larger variation of the pressure with temperature gradient and a lower latent heat, thereby yielding a lower thermal resistance. However, after starting up, the thermal performance of water exceeds those of methane and HFE-7100 at a higher supplied power for its much superior latent heat. Yang et al. [11] studied effect of filling ratio of R-123 in typical PHPs, and suggested a filling ratio of 50% to yield for best performance. Ma et al. [12] reported that by adding nano-size diamond particle to the PHP may drop the temperature difference between evaporator and condenser from 40.9 °C to 24.3 °C. Hu et al. [13] investigated the effect of wettability on the enhancement of PHP. Their results indicated that working fluid having a higher surface tension may promote the wettability and augment the overall performance accordingly. In actual operation of PHPs, complete evacuation of the capillary tube before filling working fluids is an essential process to ensure the successful and longevity operation of PHPs. Hence, the influence of initial evacuation pressure before charging working fluid is a pivotal factor. However, there were little studies in association with this subject in the available literatures. Hence, it is the objective of this study to clarify the effect of evacuation pressure on the startup and overall performance of PHPs. Both water and HFE-7000 are used as working fluids for comparison subject to influence of evacuation pressure, and it will be shown in the subsequent discussions that there is a quite different behavior in response to evacuation pressure between water and HFE-7000. Yet the physical interpretation about the differences will be addressed accordingly (see Fig. 1).

2. Experimental setup

From the existing literatures, the PHP with fewer turns is not functional without the help of gravity. To tailor this problem, Tseng et al. [10] had developed a double pipe design to facilitate unbalance forces in application. This study also incorporates the same design concept with the experimental setup being schematically shown in Fig. 1, and two set of PHPs are made and the detailed dimensions and schematic of the test sample is shown in Fig. 2(a). The PHPs are made of copper tube with an overall size of 210 mm × 200 mm with 8 parallel channels. The nominal outer diameter of the copper tube is 3 mm and 2 mm (double tube design) having a wall thickness of 0.3 mm and 0.2 mm, respectively. The working fluids in this study include water and HFE-7000. The filling ratios of water in the test samples are 49% for water and 52% for HFE-7000. A total of 31 thermocouples are used to measure the temperature distribution alongside the PHP and the relevant locations are shown in Fig. 2(b). The supplied power into the evaporator is via a power supply with direct current heating (GWinstek, model PSM-6003). A water cooling thermostat with a Cole-Parmer gear pump drive with adjustable flowrate of 1–210 mL/min is used to control the condenser. The water flowrate is measured by a Cole-Parmer flowmeter having a calibrated accuracy of ± 2%. Some further details of the experimental apparatus and description can be found from Tseng et al. [8–10].

3. Data reduction

The cooling capacity of condenser is calculated from the following equation:

$$Q_{out} = \dot{m}c_p\left(T_{w,out} - T_{w,in}\right) \tag{1}$$

where $\dot{m}$, c_p, $T_{w,out}$ and $T_{w,in}$ represent the mass flowrate, specific heat, outlet temperature, and inlet temperature of chilled water, respectively. The total thermal resistance is obtained from the following equation:

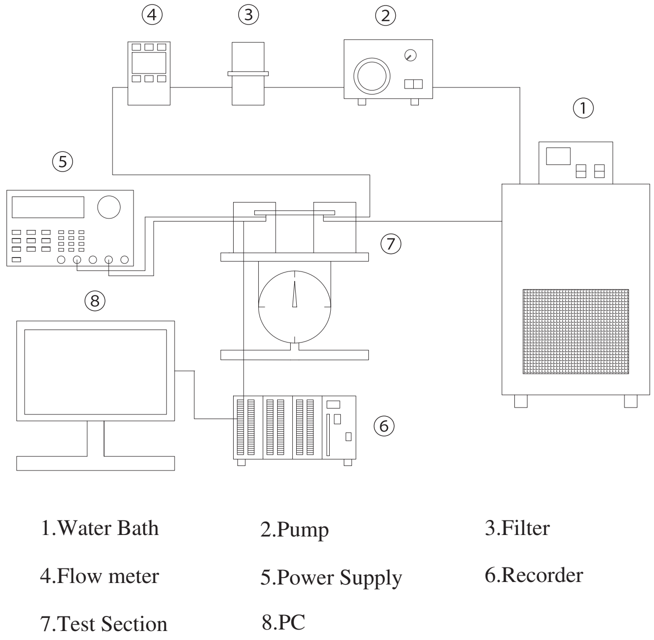

Fig. 1. Schematic of the test apparatus.