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Influence of process variables on the hydrodynamics and performance of a single loop pulsating heat pipe

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ABSTRACT

An experimental investigation on the performance of closed loop pulsating heat pipe (CLPHP) is reported in this article. The chosen single loop geometry can be considered as the basic building block of a multi turn CLPHP. The loop with 4 mm internal diameter is made of quartz glass tube to facilitate the visualization of the circulation process through the entire loop including evaporator and condenser. Temperatures measured at different locations of the loop on its wall also help to understand the complex hydrodynamics. The observation reveals different operating ranges like no flow, oscillating flow and through flow depending on the loop orientation, filling ratio and input power. There also exists an optimum filling ratio (within 50–40%) and an optimum inclination angle (within 50–70°) where the thermal resistance of the loop is the minimum. From the visualization a possible explanation for the best loop performance at a typical angle of inclination has been provided. Cease of circulation at an inclination angle close to 0° has also been visualized. Finally, a flow regime map for single loop CLPHP is presented.

1. Introduction

Many of the cutting edge technologies demand devices for heat transmission which are simple, reliable, cost effective yet capable of handling very high heat flux. As Pulsating Heat Pipe (PHP) promises to meet these seemingly conflicting demands, it has drawn considerable attention from the scientific community, after its invention in early nineties by Akachi [1]. A PHP is made of a capillary tube, bent in a serpentine shape to form either a close loop (CLPHP) or an open loop (OLPHP) [2]. These loops are first evacuated and then filled partially by the working fluid which distributes itself naturally in the form of liquid slug–vapor plug combination inside the tube due to the dominance of surface tension. The fraction of the tube volume filled with the working fluid is termed as filling ratio (FR). Once this initial distribution is achieved, heating at one end and cooling at the other establish a saturation pressure gradient due to phase change phenomena (bubble generation and growth in the evaporator section; bubble condensation in the condenser section). This acts as the driving force for oscillation or circulation in a PHP. It may be noted that for this fluid motion, a PHP does not depend on any active device as the pumping power is developed due to the generation, growth, decay and collapse of the vapor bubbles. Besides, the presence of the bends and the spatio-temporal fluctuation of void-fraction provide local pressure perturbations in the device. A continuous sustenance of this non-uniform pressure distribution is responsible for the unique thermo-fluidic transport in this device. This passive, two-phase heat transfer device is a comparatively new addition to the family of heat pipes. Some characteristics of PHPs, which make them superior to the conventional heat pipes, are its simplicity of construction, orientation independent operation, no capillary limit etc. Though in the last two decades a considerable amount of experimental as well as theoretical investigations have been made [2–4], the intricate thermal hydraulics is not yet completely realized.

The state of the art information regarding PHP has been archived by review papers [2,4] time to time. Only some of the salient works on this topic are mentioned here for the sake of completeness. In literature, quite a good number of parametric studies [3,5–7] and visualization studies [7–10] could be found. Combination of parametric and visualization studies [3,11] were also reported in the literature. It has been observed that the internal diameter [3,6,12,13,17], inclination angle [3,5–7,14,15,17], number of turns [2,5–7,14], filling ratio (FR) [2,3,11,18] and working fluid [3,6,18,19] are the important influencing parameters in PHP operation. Some innovative designs of PHP [20,21] are also developed to improve its thermal performance. Charoensawan

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Nomenclature

Bo	Bond number = $D\sqrt{g(\rho_l - \rho_v)/\sigma}$
g	gravitational acceleration (m/s^2)
D	diameter (m)
$E\ddot{o}$	Eötvös number = $(Bo)^2$
ID	internal diameter (m)
FR	filling ratio
PHP	pulsating heat pipe
CLPHP	closed loop pulsating heat pipe
OLPHP	open loop pulsating heat pipe
PDF	probability density function
Q	heat input at the evaporator

Greek symbols

ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscript

l	liquid
v	vapor
crit	critical
dry	dry-out

[6] found that with the increase in diameter, the performance of PHP improves irrespective of the working fluid used, but there exists an upper limit of diameter defined by Bond number [12,13]. Khandekar & Groll [3,16] pointed out that for a single turn PHP, the optimum inclination angle is in between 45–60° where the thermal resistance is the lowest. Orientation independent operation of PHP is only possible if both the criteria of the required minimum number of turns and the heat flux [5–7,14,17] are satisfied simultaneously. This required minimum number of turns is dependent on the working fluid used. It is also established in the literature [11,14] that an optimum filling ratio (FR) specific to the working fluid exists where the thermal resistance is the lowest. Selection of working fluid depends on the geometry and the operating conditions [3,6]. The thermal performance of PHP strongly depends on the internal fluid flow characteristics. Although a number of internal flow patterns have been observed by different research groups [8–11], the predominant flow pattern inside a PHP is oscillatory slug flow [3]. As all the influencing parameters are interdependent, it is wise to reduce the complexity first. In line with this thought, Khandekar et al. [16] studied a two-phase loop with a capillary tube of ID 2.0 mm having no internal wick structure and found that it truly depicts the behavior of a multi-turn CLPHP. The set-up was a semi-visualization set-up and the research mainly concentrates on the internal flow patterns and the preliminary parametric measurements.

The above literature survey shows that the visualization of the flow phenomenon inside the entire CLPHP over a wide range of operating parameters is rare. Further, most of the visualization studies have been done in isolation to any parametric measurements. This provides only a partial picture of the complex operating mechanism in a CLPHP. There could be no doubt that a combination of visualization and parametric measurement is essential for a proper assessment of the thermo-hydraulics. This has been the motivation of the present investigation. Accordingly, a scheme of experimental investigation has been planned to facilitate unobstructed and simultaneous flow visualization of different sections of a single loop pulsating heat pipe. Further, the observation is supplemented by the concurrent measurement of different performance parameters. Important conclusions regarding the working principle of CLPHP are drawn combining the outcome of these two modes of investigations. The study provides important insight regarding the internal fluid movement, different flow patterns and their transition as well as various regimes of loop operation and effect of these hydrodynamic features on the loop performance.

2. Experimental set-up and procedure

For a combined visualization and parametric measurements a single loop CLPHP, made of quartz glass has been used. The ID and OD of the quartz capillary tube are 4.0 mm and 6.0 mm respectively. The geometrical details of the single loop CLPHP and the details of the experimental facility have been shown in Fig. 1. The axial length of the CLPHP is 150 mm and the distance between two straight arms is 20 mm. Each of the adiabatic sections of the loop is 60 mm long. For other dimensions one may refer Fig. 1. For heating, a nichrome resistance wire is spirally wrapped around the capillary tube in the evaporator section. This facilitates the visualization of bubble generation and growth in the evaporator. The condenser section of the loop is kept inside a closed tank of rectangular cross-section with a single inlet and an outlet. The tank is made of transparent acrylic (poly-methyl methacrylate) sheet to facilitate visualization of the two-phase hydro-dynamics in the condenser section. Distilled water at ambient temperature was used as the coolant. Forced flow of cooling water at a high rate was adopted to maintain an isothermal condition in the condenser.

Five T-type (copper–constantan) thermocouples were used to record temperature at different locations of CLPHP. All the thermocouples were attached on the outer wall of the loop. Out of them, two thermocouples were fixed at the condenser section, two more thermocouples were used at two adiabatic sections and one thermocouple was used at the evaporator section. The temperature data were continuously recorded by a data acquisition system (Agilent-34970A) and stored in a computer, through a RS-232 data cable. The data recording frequency was 1 Hz, with a resolution of 0.1 °C. A high speed camera (MotionBLITZ, cube5), connected to a computer through a 1 Gbps LAN wire was used to capture the video. In all the experimental runs recording speed was in between 500 and 1000 fps. A high quality digital camera (Sony cyber-shot) with resolution 10.8 Mega-pixel and 18x zoom was used to take still snapshots.

For charging (or discharging), a brass valve is attached to the CLPHP. In the junction between copper pipe connected to the valve and the quartz CLPHP, a silicon adapter is used to make the junction leak-tight. Evacuation and filling was done through this valve. The CLPHP is first evacuated with a vacuum pump and then desired amount of working fluid is filled through a syringe. In all the experimental runs the working fluid was distilled water. During the experiment applied heat flux was varied by regulating the input voltage through an auto transformer. Starting from 5 V, input voltage was increased in the step of 2.5 V until applied voltage reaches 12.5 V and the corresponding wattage of the input power was estimated. Above 12.5 V heating was not done for the safety of the silicon adapter joint. The set-up was tested at the filling ratios of 30%, 40%, 50%, and 60% and the inclination angles of 0°, 10°, 30°, 50°, 70° & 90° from the horizontal position.

The design of the PHP loop along with the adopted techniques for heating and cooling makes the visualization of the hydrodynamics throughout the loop possible. The spatio-temporal fluctuation in different two-phase regions can also be recorded readily.