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Local heat transfer measurement and thermo-fluid characterization of a pulsating heat pipe

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ABSTRACT

A compact Closed Loop Pulsating Heat Pipe (CLPHP), filled with ethanol (65% v/v), made of four transparent glass tubes forming the adiabatic section and connected with copper U-turns in the evaporator and condenser sections respectively, is designed in order to perform comprehensive thermal-hydraulic performance investigation. Local heat transfer coefficient is estimated by measurement of tube wall and internal fluid temperatures in the evaporator section. Simultaneously, fluid pressure oscillations are recorded together with the corresponding flow patterns. The thermal performances are measured for different heat input levels and global orientation of the device with respect to gravity. One exploratory test is also done with azeotropic mixture of ethanol and water. Results show that a stable device operation is achieved (i.e. evaporator wall temperatures can reach a pseudo-steady-state) only when a circulating flow mode is established superimposed on local pulsating flow. The heat transfer performance strongly depends on the heat input level and the inclination angle, which, in turn, also affect the ensuing flow pattern. The spectral analysis of the pressure signal reveals that even during the stable performance regimes, characteristic fluid oscillation frequencies are not uniquely recognizable. Equivalent thermal conductivities of the order of 10–15 times that of pure copper are achieved. Due to small number of turns horizontal mode operation is not feasible. Preliminary results indicate that filling azeotropic mixture of ethanol and water as working fluid does not alter the thermal performance as compared to pure ethanol case.

1. Introduction

The present industry demand of high heat transfer capability coupled with relatively cheaper component costs catalyses evolution of novel two-phase passive devices. A conceptually similar to the Pulsating Heat Pipe (PHP), was introduced by Smyrnov and Savchenkov in 1971 [1]. More practical design variation of this concept, from an engineering stand-point, was proposed in the early 90s by Akachi [2,3], which subsequent fuelled several investigations to better understand this device (as summarized in Refs. [4,5]). In contemporary times too, the qualitative, as well as quantitative investigations of several design variants of Pulsating or Oscillating Heat Pipes, for potential passive thermal management applications in nuclear, defense and space are emerging at a rapid pace; this has indeed become one of the most interesting and vibrant fields of investigation. The PHP design variants being proposed and studied have the potential to meet all the present and possibly future specific requirements from electronics cooling [6,7], heat recovery [8,9] and passive cooling of reactor containments, to name a few.

A PHP usually consists of a copper capillary tube bended in a serpentine-shape closed loop (CLPHP), evacuated from within and partially filled with a working fluid, typically in its liquid-phase. As the filling volume of the fluid is less than the total internal volume of the PHP tube, the liquid-phase and vapor-phase co-exist inside the tube in the form of alternating liquid plugs and vapor bubbles, typically as a Taylor bubble train. The capillary tube diameter is chosen in such a manner that surface tension dominates over gravity forces, resulting in no bulk stratification of the phases. During heat transfer operation, one end of the serpentine tube bundle receives heat (acting as an evaporator) while the other end is kept at a lower temperature (acting as a condenser). Heating causes the thin liquid film surrounding the vapor bubbles to evaporate; bubbles thus expand and push the adjacent Taylor bubble train towards the condenser zone, where heat gets rejected to the cold source. The shrinking of vapor bubbles in the condenser

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Nomenclature

Variables

A	area [m^2]
d	diameter [m]
EF	enhancement factor [−]
$\tilde{h}$	convective heat transfer coefficient [W/m^2 K]
k	thermal conductivity [W/m K]
L	length [m]
n	number of parallel channels [−]
$\dot{Q}$	heat power [W]
q''	heat flux [W/cm^2]
R	thermal resistance [K/W]
T	temperature [K]

Subscripts

cr	cross-section
ev	evaporator
eq	equivalent
max	maximum
out	outer
s	substrate
tot	total
w	wall
$w-f$	wall to fluid
∞	cooling medium

also provides additional motive force for the working fluid. Thus, a self-sustained thermally driven oscillating flow is set up due to the applied temperature difference, leading to enhanced passive thermal transport.

The subtle complexity of the internal thermo-fluidic behavior of the oscillating/pulsating two-phase flow is indeed quite unique, offering both opportunities and challenges for fundamental research outlook on passive two-phase transport phenomena. Design rules need to emerge from these efforts so that challenging engineering targets in the field of passive thermal management may be achieved. Paucity of design rules and lack of clarity in the fundamental operational characteristics of this intriguing system has been the major thrust of many experimental programs and supporting modeling efforts in the recent past. While most researchers have focused on the experimental study to understand the working principle of CLPHPs and delineate its driving parameters, some modest beginning has also commenced on the mathematical modeling front [10,11]. However, modeling at this stage is highly simplistic with gross assumptions. This is because all the nuances of the underlying physics of the PHP operation are still not clear and requires more experimental efforts.

Maezawa and Gi [12] investigated the temperature oscillations for PHPs operated in several heat modes (bottom heated, horizontal, top heated), two different tube diameters (1 mm and 2 mm in inner diameter) and two working fluids (water and R142b) and concluded that the random factor in the chaotic internal dynamics increases with the heat input level. Detailed flow visualization was conducted by Tong et al. [13] in a glass CLPHP: bubble nucleation and coalescence, internal two-phase flow patterns and directions were described. It was showed that the meanderings turns, uneven distribution of liquid plugs and vapor bubbles and non-concurrent boiling at the evaporator, contributed to the driving and restoring force for fluid oscillation and circulation. Kim et al. [14] performed a similar study on a flat brass plate with engraved capillary channels covered with a transparent acryl plate and reported that the liquid film surrounding the vapor plugs was approximately about 100 μm thick. They showed that the flow pattern in the evaporator region may change from capillary slug flow to a pseudo-slug flow resembling intermittent annular flow. Charoensawan et al. [15] and Khandekar et al. [16] have performed both thermal characterization and visualization of a wide number of PHP systems providing critical information on the parameter dependency of their thermal performances. It was shown that the internal diameter of the PHP tube/channels, as well as the global orientation of the devise with respect to gravity, affects the heat throughput. To overcome the effect of gravity on the thermal performance, a minimum number of serpentine turns coupled with a minimum radial heat flux are essential. Khandekar et al. [17] generated valuable information by showing the effect of different fluids, filling ratios and inclination angles on the thermal performance of PHPs. Subsequently, they also tested and characterized a single capillary loop, the primary building block of a PHP [18]. It was experimentally demonstrated that even such a simple loop exhibits multiple quasi-steady-states, which is directly correlated to the type of flow pattern inside the system [19]. Yang et al. [20] have investigated the operational limits of CLPHP and found that depending on the inner tube diameter, the minimum thermal resistance and maximum heat load are obtained when the filling ratio is between 0.4 and 0.6.

Recently Lips et al. [21] conducted several tests on a single liquid–vapor meniscus located inside a straight capillary tube which was made to oscillate by (i) adiabatically, only due to mechanical forces, and (ii) thermal gradients imposed on the length of the tube. The adiabatic experiments focused on the importance of the asymmetry between the advancing and receding contact angle during the oscillation of the meniscus. The non-adiabatic experiments showed that at low heat flux, the flow gets disturbed by bubble nucleation process, while, at a high heat flux, the main heat transfer mechanism is thin film evaporation. Both situations lead to considerable change in the thermal-hydraulic behavior. Yoon et al. [22] determined the volume fraction of the liquid-phase in different portions of the PHP tube by using neutron imaging technique. The results showed that the liquid volume fraction was always less than 2.5% in the evaporator and greater than 80% in the condenser zone.

As stated in the review by Zhang and Faghri [23] so also by others [4,5], most research efforts have been dedicated to explain the working principle of PHPs. However, a comprehensive theory of operation and a reliable database or tools for the design of PHPs still remain unrealized. Nevertheless, as the device is fully thermally driven, passive, cheap, versatile and relatively easier to build, the prospects of such systems for potential applications are too promising to be ignored.

In this background, the present work describes the complete thermo-fluid dynamic investigation on a CLPHP with four parallel transparent branches, where the fluid pressure as well as the fluid temperature are recorded, by means of a pressure transducer and two thermocouples integrated inside the tube, respectively. The local measurement of the two-phase flow temperature, together with the wall temperature at the same location and the heat input flux, provides an unprecedented estimate of the local heat transfer coefficient in a chaotic flow boiling process. Start-up fluxes as well as critical heat fluxes are monitored; the effect of heat input level, the inclination angle and the working fluid on the flow pattern and on the thermal performance are analyzed and discussed. Finally, the frequency analysis on the fluid pressure signal is performed.