EFFECT OF INNER DIAMETER ON THE THERMAL PERFORMANCE OF CLOSED LOOP PULSATING HEAT PIPE

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Abstract- The concept of heat pipes has no longer remained unknown in the thermal management discipline. However a new entrant in the family of heat pipes, known as Closed Loop Pulsating Heat Pipe (CLPHP), has never ceased to be an arena of interest owing to the numerous complexities in its operation. With passing days more and more conclusive studies of the behavior of pulsating heat pipes are emerging, yet its efficient application from engineering viewpoint remains somewhat elusive. Nevertheless these two-phase passive heat transfer devices are deemed to be highly effective in light of their low thermal resistance, compactness, portability, cost-effectiveness and simplicity in constructional design. The present paper attempts to shed some light on diameter as the influential parameter on the thermal performance of closed loop pulsating heat pipe (CLPHP) with inner diameters of 1.5mm, 2.0mm, 2.5mm and 3.5mm. Meandering brass tube of total 6 turns and 0.5mm thickness was taken with ethanol as the working fluid throughout the experiment. The results depict that the CLPHP acts in pulsating mode only up to a definite diameter which is 2.5mm as per the performed experiment. The 3.5 mm pipe acts not as a PHP but as a mere heat pipe only. The thermal performance however increases with increasing diameter and hence the diameter of 2.5mm exhibits good performance.

Index Terms- Closed Loop Pulsating Heat Pipe (CLPHP), Inner Diameter, Thermal Performance

I. INTRODUCTION

There is a drive for miniaturization with micro electro-mechanical systems which creates an environment demanding an enabling thermal control system. Conventional heat pipe technology has been successfully applied in the last thirty years for the thermal management of a variety of applications like heat exchangers, economizers, space applications, and electronics cooling, to cite a few. A heat pipe is a heat transfer device with an extremely high effective thermal conductivity. Heat pipes are evacuated vessels, typically circular in cross sections, which are back-filled with a small quantity of a working fluid. They are totally passive and are used to transfer heat from a heat source to a heat sink with minimal temperature gradients. Although a plethora of designs of classical heat pipes are available, recent industry trends have frequently shown the limitations of these conventional designs. This has led to the evolution of novel concepts fitting the needs of present industry demands. A relatively new and emerging technology, Pulsating or Loop-type Heat Pipes (PHP), as proposed by Akachi et al. [1], represent one such field of investigation. This range of devices is projected to meet all present and possibly future specific requirements of the electronics cooling industry, owing to favourable operational characteristics coupled with relatively cheaper costs. Pulsating (or oscillating) heat pipes are passive two-phase cooling devices made from capillary-sized tubing that meanders in a closed-loop or open-loop channel pattern. This channel pattern is evacuated and partially charged with a working fluid and hermetically sealed. Heat is transferred by the working fluid's latent and sensible heat as vapor bubbles expand, contract, and in turn oscillate the liquid slugs. No wick structures are involved. These can be divided into 3 groups at least: (a) closed loop PHP (CLPHP); (b) CLPHP with check valves; (c) open loop PHP (OLPHP), also called closed end PHP (CEPHP) [2].

Looking into the available literature, it can be seen that six major thermo-mechanical parameters have emerged as the primary design parameters affecting the PHP system dynamics [3]. These include:

- Internal diameter of the PHP tube,
- Input heat flux to the device,
- Volumetric filling ratio of the working fluid,
- Total number of turns,
- Device orientation with respect to gravity, and
- Working fluid thermo-physical properties.

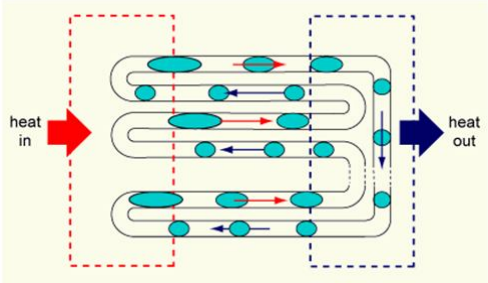


Fig.1. Liquid-vapour heat/mass transfer in an oscillating heat pipe

This paper mainly focuses on the operational regime of CLPHP on the basis of varying internal diameter. The motivation for the work comes from the fact that internal diameter is one of the most important factor for efficient working of CLPHP, so the research paper attempts to enhance further knowledge on thermal

performance exhibited by CLP under conditions of varying internal diameter and also to come up with an optimum value of the diameter at which the heat pipe functions best as 'pulsating' heat pipe. The working fluid was ethanol throughout the experiment because of its suitable thermodynamic properties.

II. EXPERIMENTAL SETUP

The experiment was conducted with two filling ratios of 50% and 60% and with fins inserted in the condenser section to enhance heat transfer. The CLPHP is first evacuated of air using a vacuum suction pump. This is done to ensure that no air is present to hinder the heat pipe operation. The low internal pressure also lowers the boiling point of the working fluid so that the PHP starts operating as soon as the heat is applied. The internal volume is next charged to the required filling ratio with ethanol using an injector syringe after which the CLPHP is sealed off at the top. DC fans are directed at the rear of the condenser section to induce forced convection over the fins. Nichrome wire is then wound round the evaporator section turns to serve as the heater coil.

The K-Type thermocouples are next attached to each of the turns in the evaporator and condenser sections to measure the temperatures in both the region simultaneously. Power to the heater is next provided from the line supply through the variac. The experiment is initially conducted with heat input of 10W and the corresponding temperature readings are recorded at regular intervals for a time span of 10 minutes. The aforementioned steps are repeated for heat input increments of 10W up to 60W. The average evaporator and condenser temperature readings are evaluated for each heat input value and corresponding graphs of thermal resistance vs heat input, temperature vs time and heat transfer coefficient vs heat input are plotted. The procedure above is repeated for the rest of the other internal diameters of CLPHP (2.0 mm, 2.5 mm and 3.5 mm) for 50% filling ratio. The whole experiment is now conducted again in the same manner but with 60% filling ratio this time.

III. RESULTS AND DISCUSSION

3.1. Effect of internal tube diameter

The internal tube diameter is one of the parameters which essentially defines a PHP. The physical behaviour adheres to the 'pulsating' mode only under a certain range of diameters. The critical Bond number (or Eötvös) criterion gives the tentative design rule for the diameter [2, 4]:

$$(\mathrm{E\ddot{o}})_{crit} = (\mathrm{Bo})_{crit} \approx \frac{D_{crit}^2 \cdot g \cdot (\rho_{liq} - \rho_{vap})}{\sigma} \approx 4 \quad (1)$$

$$D_{crit} \approx 2 \cdot \sqrt{\frac{\sigma}{g \cdot (\rho_{liq} - \rho_{vap})}} \quad (2)$$

This criterion ensures that individual liquid slugs and vapor bubbles are formed in the device and they do not agglomerate leading to phase separation, if the device is kept isothermally in a non-operating period.

3.2. Experimental outcomes and discussion

The maximum critical diameter is computed to be 3.32 mm in the experiment performed. This leads to the preliminary outcome that pipes having diameters of 1.5 mm, 2 mm, 2.5 mm act as closed loop pulsating heat pipes. Pipes of inner diameter 3.5 mm cannot be considered as a pulsating heat pipe as its diameter is more than the critical diameter. This can be explained by the $E\ddot{o}_{crit}$ criterion as given in equation (1) above. One of the requisite design criteria was that bubbles should act as pumping elements. The success of bubble pumping action depends on the formation of distinct liquid-vapor plugs and slugs and so it is obvious that diameters below 3.32 mm will definitely function as PHP.

In the following graphical analysis the 3.5 mm diameter shows unpredictable performance since it does not behave like a typical CLPHP and hence may not follow any generalized trend.

3.3. Effect of heat input on thermal performance for 50% and 60% filling ratio

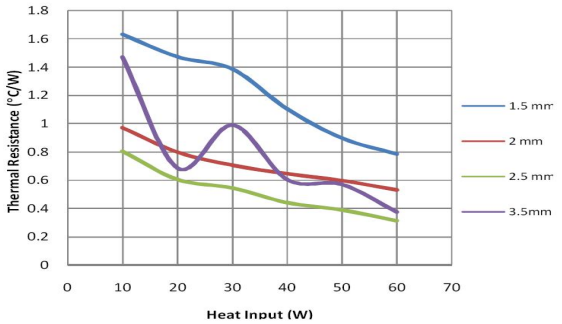


Fig.2. Variation of thermal resistance with heat input for different diameters at 50% FR for Ethanol

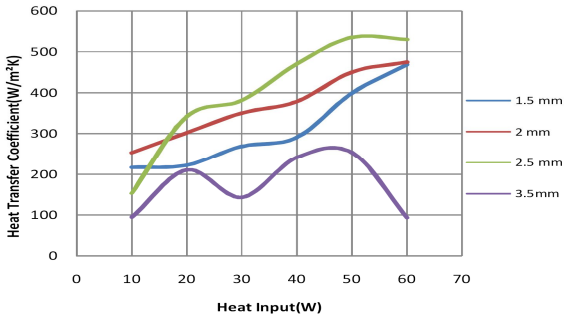


Fig.3. Variation of heat transfer coefficient with heat input for different diameters at 50% FR for Ethanol

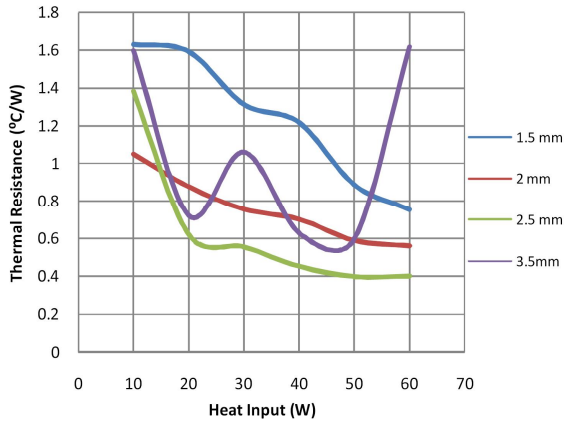


Fig.4. Variation of thermal resistance with heat input for different diameters at 60% FR for Ethanol

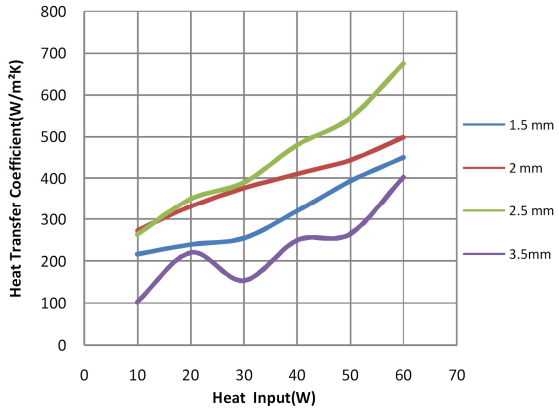


Fig.5. Variation of heat transfer coefficient with heat input for different diameters at 60% FR for Ethanol

Thermal performance of any heat transfer device may be effectively measured in terms of two main parameters which are (1) thermal resistance and (2) heat transfer coefficient.

$$R_{th} = \frac{(T_e - T_c)}{Q} \qquad h = \frac{Q}{A\,(T_e - T_c)}$$

- The thermal resistance is inversely proportional to heat input. So it can be said that for a given inner diameter the thermal resistance decreases with increasing heat input, indicating greater heat pipe effectiveness. This is also exhibited by **Fig.2** and **Fig.4**. Low input heat fluxes at the beginning could not generate enough perturbations and the resulting bubble pumping actions were extremely restricted. Overall this scenario resulted in poor thermal performance (i.e. very high thermal resistance). With the increase in heat input the bubbles no longer oscillated about their mean stagnant positions but started rising p through the adiabatic section. On their way they definitely might have coalesced with other bubbles and grown in size that resulted in increased buoyancy, causing the bubbles to rise further and ultimately collapse in the condenser section. The heat transfer coefficient improved to a marked degree with increase in power input.

- The thermal resistance generally therefore follows a downward trend with 1.5 mm giving the poorest performance and 2.5 mm giving the best performance.

- The performance of CLPHPs is comparatively better for 50% FR than 60% FR because the temperature difference in case of 60% is greater that causes the R_{th} to also increase, yielding poorer performance.

- The applied heat flux affects the following [5,6]:
(a)Internal bubble dynamics, sizes and agglomeration/breaking patterns,
(b) Level of perturbations and flow instabilities, and
(c)Flow pattern transition from capillary slug flow to semi-annular and annular.

- With increasing heat input the flow also gets transformed from oscillating slug flow to annular flow, thereby improving performance. This is logical since the evaporator U-sections experience convective boiling through the thin liquid film rather than nucleate type boiling in slug flow regime.

- The convective heat transfer coefficient can be thought of as the reciprocal of thermal resistance, so it follows a general trend of increasing with rising heat input as depicted by the **Fig.3** and **Fig.5**. The best performance is shown by 2.5 mm diameter with the worst performance being exhibited by 1.5 mm.

- Further increase in heat flux will lead to some sort of evaporator dry-out phenomenon. 'Dry out' means almost all the liquid available is in pulsating action i.e. in bubble form and there is very little liquid available which does not have the ability to compensate the high amount of heat input. In this experiment there was no dry out which means that ethanol works well up to 60 W.

CONCLUSIONS

The following conclusions have been drawn from the experiment:

- The cooling philosophy of CLPHP draws inspiration from that of the heat pipes except it is not equipped with any wick structure to bring back the fluid to the evaporator. This requirement is met by the self-driven thermal oscillations of the bubbles that generate as a result of nucleate boiling.

- For a specified heat input and maximum allowable evaporator temperature and all other geometry remaining fixed, a decrease in diameter from optimum value decreases the performance. This happens because of an increase in the frictional head.
- Diameters above an optimum value lead to stratification of phases and so a PHP loses its fundamental character. It no longer adheres to the pulsating mode.
- In general, the performance increases with increasing diameter and so 2.5 mm functions the best. The optimum diameter in this case is 3.32 mm which is exceeded by 3.5 mm and hence this pipe will lose its pulsating mode of operation.
- Two different filling ratios such as 50% & 60% were experimented. PHP containing these two filling ratios shows almost same performances, with 60% FR being comparatively lower in performance grade.
- The performance of CLPHP is linked with the internal flow pattern of working fluid (Ethanol) as net heat transfer is a combination of sensible heat of liquid plugs and latent heat of vapor bubbles. These flow patterns can be achieved by varying heat input.
- The better heat transfer performances are observed at higher heat inputs for a specific diameter.
- Comparatively higher rise in evaporator temperature than condenser temperature has been observed for the same heat input.
- On the basis of the above experimental investigations, CLPHP having higher inner diameters at both 50% and 60% FR are the best choice. But lower diameters can also be recommended according to the amount of heat transfer.
- CLPHPs are extremely efficient heat transfer technology, which due to its simple design, cost-effectiveness and thermal performance are expected to find wider applications in the electronic industry in the future.

ACKNOWLEDGMENTS

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NOMENCLATURE

Bo: Bond number
D : tube diameter (m)
Eö: Eötvös number
FR: Filling Ratio (volume of liquid/inner volume of PHP at room temperature)
g : acceleration due to gravity (m/s²)
Q : heat power (W)
h : heat transfer coefficient (W/m^2K)
R : thermal resistance (°C/W)

Greek symbols

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

Subscripts

a : adiabatic section
c : condenser section
crit : critical
e : evaporator section
liq, vap : liquid, vapor
max : maximum

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