Experimental Investigation on Effect of Operating Parameters on Thermal Performance of Pulsating Heat Pipe

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Abstract- *Thermal management of electronics semiconductor technology is elixir to transform dream and imagination of the designers into reality. Inspiration and need for research in development of innovative cooling strategies for modern electronics is of paramount importance. Pulsating Heat Pipes (PHPs), an innovative research area in heat pipe science, are new two-phase heat transfer devices that rely on the oscillatory flow of liquid slug and vapor plug in a long miniature tube. This paper highlights the effects of operating parameters on thermal performance of closed loop pulsating heat pipe.*

Experiments were conducted on a CLPHP made up of copper capillary tube of 1.78mm ID & 3mm OD, the lengths of the evaporator, adiabatic and condenser sections are 100mm, 100mm and 150mm respectively. Afterwards effects of various parameters, including working fluids (Ethanol, Methanol and DI Water), the volumetric filling ratios (40%, 50%, 60% and 70%) and orientation (Vertical, Inclined at 45o with horizontal and horizontal) on thermal performance of the CLPHP investigate experimentally. Significant insight into the operational regimes of the CLPHP has been gained.

Keywords- Closed Loop Pulsating Heat Pipe, Working Fluids, Volumetric Filling Ratio, Latent Heat, Thermal Resistance.

I. INTRODUCTION

Miniaturization is in vogue today and this exhilaration has especially gripped the electronics and similar industries. Market expectations towards higher functionality at reduced package sizes have led to denser electronics and increased power. Total dissipated power is not the only problematic issue, heat flux is gratuitous to it. The solution lies in development of new materials, novel cooling strategies or devices and an architype shift in the cooling technology concepts and modes of implementation[1]. The pulsating heat pipe (PHP), proposed and patented by Akachi[2], is a new member of the wickless heat pipes. Due to its excellent features, such as high thermal performance, rapid response to high heat load, simple design and low cost, PHP has been considered as one of the promising technologies for electronic cooling, heat exchanger. A typical PHP consists of a meandering looped capillary tube with multiple turns. The internal diameter of the tube is restricted by aEötvösnumber[3], which is a fundamental requisition for PHP operation. Fig. 1 illustrates a closed-loop pulsating heat pipe, which can be fabricated by evacuating the capillary tube, and then partially filled with a phase-change working fluid. It will distribute itself naturally in the form of liquid slugs and vapor plugs inside the capillary tube. Heat is transferred from the evaporation section to the condensation section of the heat pipe through pulsating action of the liquid–vapor–slugsystem, which is mainly caused by the thermally induced pressure/density pulsations inside the device [4]. Usually, an adiabatic zone exists between the evaporator and condenser. State of art indicates that's at least three thermo-mechanical boundary conditions have to be met for the device to function properly as pulsating heat pipe. This includes the internal tube diameter, the applied heat flux and amount of the working fluid in the system. Additionally the numbers of turns of the device and thermo-physical properties of the working fluid also play a vital role in determining the thermal behavior of device[5][6].

Bhawna verma et al. [2013] performed experiment to study the effect of working fluid on the start-up performance, thermal performance and heat transfer coefficient of PHPs, Methanol/DI Water as working fluid with varying filling ratio. They tested the PHPs in vertical, horizontal and inclined at 45o orientation, experimental results indicates that in all orientations of PHPs the start-up temperature and start-up time is considerably reduces if Methanol is used as working fluid. Thermal resistance of PHPs in inclined and horizontal orientation for water are 0.55oC/W and 0.81oC/W respectively same values for Methanol are 0.52oC/W and 0.63oC/W respectively. Hence they conclude that PHPs with Methanol as working fluid is perform better than water and can be used as orientation free PHPs[7].

Piyanun Charoensawan et al.[2003] worked on design of total no of turns on CLPHPs. Experimental results indicates that there is existence of critical number of turns (Ncrit),which effects on thermal performance of CLPHPs. For

2mm ID, Ethanol as working fluid and Le=15 cm, Ncrit is 16 turns. If N< Ncrit, the CLPHP is not satisfactory operate in the horizontal orientation and higher thermal performance occurs at vertical bottom heating mode. If N> Ncrit, thermal performance of is increases with increase in inclination angle from horizontal and almost remains comparably up to 60 from horizontal[8].

Xiangdong Liu et al.[2013] performed experiment on CLPHP for analysing the start-up performance with Water, Ethanol and Methanol as working fluids with different filling ratios and analysis the effect of filling ratio on start-up performance of CLPHP. It has been observed that with increase in filling ratio all the values of evaluation criteria decreases and then increases, since there is existence of optimum filling ratio for all different fluids and with the help of experiment this has been conclude that optimum FR for Water and Ethanol are 41% & 52 % respectively[9].

Therefore, in this study, first a CLPHP was designed and manufactured. Then, the effect of the most important parameters, including the working fluid (Methanol, Ethanol and DI Water), volumetric filling ratio (40%, 50%, 60% and 70%), orientations and input heat power, on the thermal performance of the CLPHP were investigated experimentally.

II. EXPERIMENTAL WORK

Setup consists of three section: evaporator, condenser and adiabatic sections. Evaporator section consists of an enclosure, U PVC pipe having 100mm ID, 105mm OD and 200mm length. Evaporator section of the CLPHP is suspended inside this enclosure by a cover plate. Cover plate consists of a circular PVC sheet of 110mm diameter. 28 notches are made over the periphery of this plate to fix 28 copper tubes of 14 turn PHP. This plate is sealed to the top of the evaporator enclosure. Water is filled in evaporator enclosure. A 100mm length of cartridge hater is inserted into evaporator section. The condenser section also consists of an enclosure, U PVC pipe having 100mm ID, 105mm OD and 200mm length. The condenser section of the CLPHP is completely submerged inside the enclosure. The CLPHP is attached to the enclosure by another cover plate like evaporator section. The condenser enclosure has inlet and outlet ports for water as heat absorbing medium.

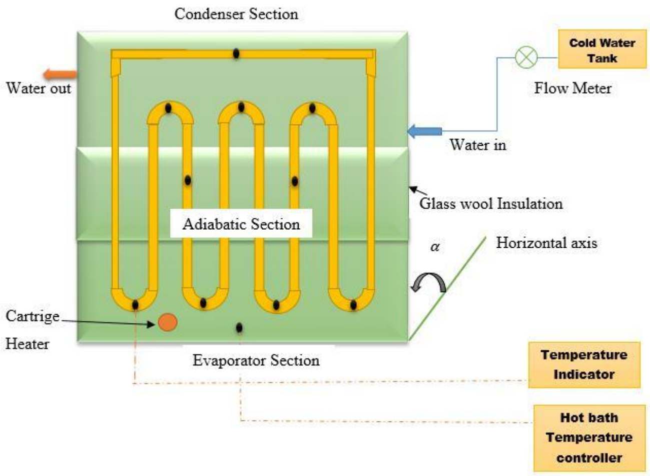

Fig. 1 Details of the Experimental set up

A schematic diagram of the device used during the experimental tests is shown in Figure 1 pulsating heat pipe configured as a CLPHP was built using a capillary copper tube with 3mm OD, 1.78mm ID, and approximately 11m length to form 28 parallel channels with 14 turns. The two end of copper tube in the manufactured PHP are connected using a three T-connector. The first T-connector provides a connection between the vacuum system and the CLPHP, second T connector provides a connection between syringe pump and CLPHP and third T connector provides a connection between vacuum gauge and CLPHP. The CLPHP consisted of three regions: a heating section (evaporator), adiabatic section, and cooling section (condenser) with a height of 100mm, 100mm, and 150mm, respectively. During the tests, the evaporator section was always below the cooling section. The total internal volume of the CLPHP was 32 cc. Copper was used for the pipe material so that supreme conduction heat transfer could be obtained in the condenser and evaporator. Pipes in the adiabatic section were also entirely insulated so that any heat losses from this part would also be minimized and so that the adiabatic assumption would be nearer to reality as shown in Image 1.

Image 1. Experimental set up of CLPHPs with insulation

12 Chromel–Alumel (K type) thermocouples were applied to measure the system's temperature during the tests. Four thermocouples were placed in four turn of the evaporator section to measure the average evaporator temperature, two thermocouples were placed in the adiabatic zone, four thermocouples were placed in four turn of the condenser section to measure the average condenser temperature, and two thermocouples measured the inlet and outlet flow temperatures of the cooling section.

When filling the pipes with the working fluid, one must make sure of the fact that no incondensable gas leftovers in the working fluid and the system because the air inside the working fluid can adversely affect the hydrodynamic properties of the two phase flow, by evacuating the air from the system, the initial pressure of the system decreases and since the process of boiling and bubble formation speeds up, the performance of the system improves. Therefore, it is imperative that the amount of air in the system is kept to a least. In order to empty this air from the system and also to fill it with working fluid, a vacuum system was designed and fabricated. This system consists of the following: (a) a vacuum pump for emptying the gases inside the system, (b) chamber for storing the working fluid, and (c), hoses, and special valves for creating connections between the heat pipe, and the vacuum pump. This system has the capability to produce and maintain a vacuum of 0.1 Pa.

III. RESULTS & FINDINGS

In the present experiment, three working fluids were employed, which were Methanol, Ethanol and DI Water. Tests were conducted for filling ratios of 40%, 50%, 60% and 70% for three working fluids in vertical ($\theta = 90^o$), inclined ($\theta = 45^o$) and horizontal ($\theta = 0^o$) orientations with three evaporator temperatures 50°C, 60 °Cand 70 °C. The CLPHP was partially filled by working fluid, then the evaporator temperature maintain constant at 50°C, 60 °Cand 70 °C, in condenser section constant mass flow rate is maintain by adjusting the outlet valve, as a result, the heat flux raises the temperature and pressure in the evaporator region. Therefore, the slugs and plugs moved within the pipe and transferred heat from the evaporator to the condenser. Thus, the system will reach a semi-steady state after a certain period of time and the evaporator temperature will not change much. For different input heat powers, working fluids, and filling ratios and orientations, the average temperature differences between the evaporator and condenser were recorded.

From the working principle of the PHP, the oscillation in the PHP relies on three driving forces: gravity force, surface tension, and oscillating force, which comes from the pressure fluctuating between the evaporator and condenser. These forces are influenced by many factors. The gravity force is influenced by the inclination angle of the device, the physical features such as channel size and shape can have a significant effect on the surface tension, and the heat flux has great effect on the oscillating force. For the two-phase flow pattern existing in the PHP, the liquid along the tube blocks the motion of the vapor. So, it's also a parameter which has effect on the thermal operation of the PHP, and this is embodied by the fill ratio.

The overall thermal resistance is used to estimate the performance of the PHP, and it is defined as: $R = \frac{T_e - T_c}{Q}$, where T_e and T_c being the average wall temperature of the evaporator and condenser respectively and Q is the input power.

A. The effects of heat input

The heat received in the evaporator is the energy source that provides the driving force to cause fluid flow. Fluid motion begins when the liquid slug, which is adjacent to the plug in the evaporator section, is pushed due to the high pressure of the plug, and the motion is enhanced when the vapor shrink in the condenser region**.**

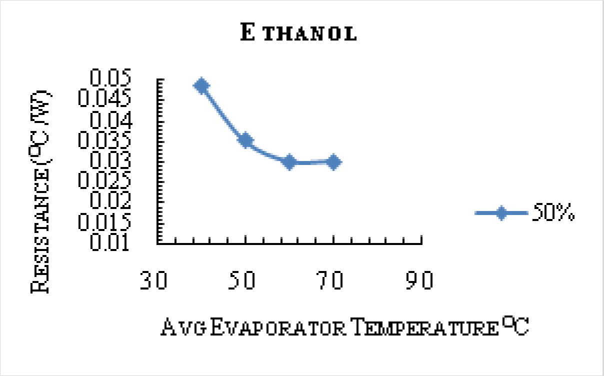

Fig. 2 The typical variation of thermal resistance with heat input power for Ethanol

Fig. 2 illustrates the effect of heat input on the overall thermal resistance for ethanol in vertical orientation of device. As shown, the overall thermal resistance is decreased considerably when the heat input is increased. When heat is added to the evaporator, the pressure and the temperature of the vapor are increased, and the force on the adjacent slug is increased, which initiates the motion of the fluid. The mass of the liquid slug vaporized becomes the mass influx for the adjacent plug. As a result, the density of the plug increases and subsequently, a pressure rise is expected, and the heat carried by the vapor is increased, so the overall thermal resistance is decreased, similar results were observed for Methanol and DI water as working fluids.

B. The effects of Volumetric filling ratio

The filling ratio is defined as the ratio of available working fluid (by volume) inside the PHPs to the total volume of PHPs (by volume). Fill ratio also has a significant influence on the characteristic of heat transfer[1].

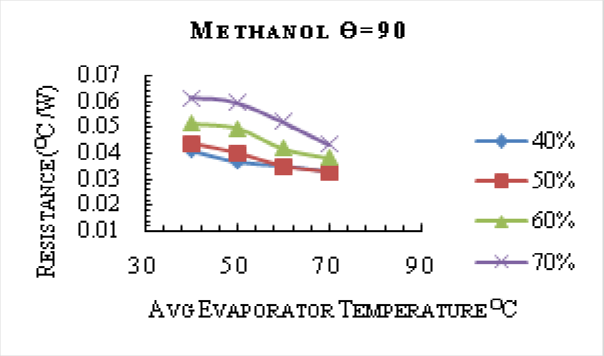

Fig. 3 Effect of filling ratio on thermal resistance for Methanol in vertical orientation

Fig. 3shows the effects of fill ratio on the overall thermal resistance for methanol in vertical orientation. The overall thermal resistance increases with the fill ratio. When the fill ratio is low, vapor plug is more than liquid slug. As a result, the driving force is larger. On the contrary, the mass of fluid is small, and the heat carried by the fluid is less, so the temperature difference between the evaporator and condenser is small, and the overall thermal resistance of the device is small, too. On the other hand, the flow friction between the fluid and the wall is increased as increasing of the fill ratio. The driving force for the oscillation and transportation of the heat from the evaporator to the condenser is decreased. The overall thermal resistance is increased in the result of the increasing of the temperature difference. Similar results were observed for Ethanol and DI water.

C. Optimum fill ratio

The heat transfer rates at different fill ratio for methanol in vertical orientation were shown in *Fig. 4* and similarly trends were observed for Ethanol and DI water as working fluids. The heat transfer rate increases with the fill ratio, and it reaches the maximum heat transfer rate at the fill ratio 40% to 50%. The heat transfer performance decreases as fill ratio increases when the fill ratio is over 50%.

When the fill ratio is high enough, there are only few bubbles in tubes, and the effective oscillation can't be achieved

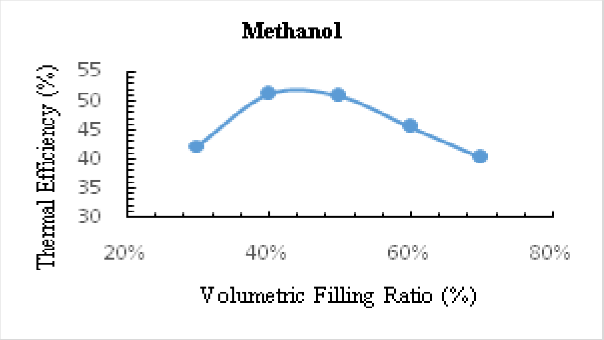

Fig. 4 Optimum filling ratio for methanol in vertical orientation

D. The effect of Orientation.

In absence of gravity effect in horizontal orientation, Surface tension dominates. Which is responsible driving force behind the performance of CLPHP in horizontal orientation. The high surface tension of water creates additional friction and restricts the flow of liquid bubbles and vapor slugs formation, which directly reduce the pulsating action of working fluids inside the CLPHP. This problem can be overcome with the help of working fluids whose surface tension is lower than water like Methanol and Ethanol, from Fig. 5 it can be conclude that as in vertical orientation thermal resistance is minimum and hence CLPHPs performs better with respects to other orientations. Same trends were observed for Ethanol and Methanol as working fluids.

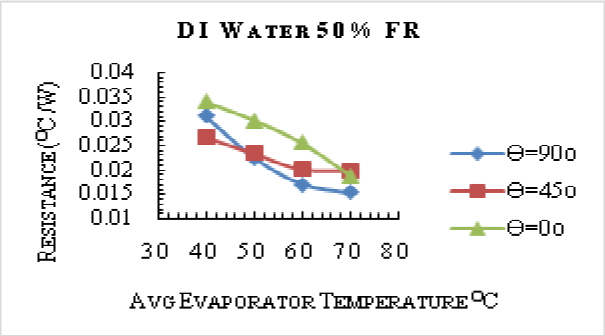

Fig. 5 Effect of orientation on thermal resistance for DI Water at 50% FR

VI. CONCLUSION

The working range of close loop pulsating heat pipe is experimentally investigated to study the effects of various influencing parameters on performance. In this paper, attempted has been made to describe the effect of filling ratio and orientation of device on thermal resistance of CLPHP. The following conclusions can be drawn from the experimentation.

1. Different fluids are beneficial under different working conditions. In present work lower surface tension fluids are dominant in orientation free performance with respect to higher surface tension fluid.
2. For higher filling ratios, very less bubbles are presents, heat transfer occurs only by convection of working fluid inside the Tube, which hinder the pulsation of working fluids hence heat transfer efficiency is not very good.
3. Lower filling ratios are responsible for fast dry out in evaporator section and hence not advisable, hence each device has its optimum filling ratios with given working fluid.
4. In this experimentation optimum filling ratio for minimum thermal resistance was found to be 40% for Ethanol and 50% for DI Water and Methanol.
5. The thermodynamic attributes of water makes it better than any other fluids for the pulsating heat pipes. Its high latent heat spreads more heat with less fluid flow. This result in low pressure drops and high power throughout. Its high thermal conductivity minimizes the temperature difference associated with conduction through the two phase flow in the PHP. Water is also a safe substance.

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