Experimental Study on Thermal Performance of Closed Loop Pulsating Heat Pipe Using Azeotropic Mixture as a Working Fluid

Pallavi Chaudhari[1], Pramod Pachghare[2]

[1]M. Tech student in Thermal Engineering, Government College of Engineering, Amravati, India

[2]Assistant Professor in Mechanical Engineering Department, Government College of Engineering, Amravati, India

Abstract: ***A Closed Loop Pulsating Heat Pipe (CLPHP) is a self-excited thermally driven two phase passive heat transfer device, which transfers heat from one location to another with a negligible temperature drop. Its operation depends on the phase change of a working fluid within the loop. In this paper, experimental study on a vertical closed loop pulsating heat pipe (PHP) has been conducted having 50% filling ratio (FR). The heat power was supplied from 8 W to 96 W, in the steps of 8 W. The thermal performance is measured in terms of thermal resistance. The work explores the thermal performance of a PHP working with an azeotropic mixture of water (4.5% wt.) and ethanol (95.5% wt.) in comparison to pure ethanol and water. The various temperatures were recorded on the outer wall of the evaporator and condenser section. Overall thermal resistance at different heat inputs was calculated. It is concluded that, the thermal resistance decreases more rapidly with the increase of the heat Input power. No measurable difference has been recorded for the PHP running with azeotropic mixture of ethanol (95.5% wt.) and water (4.5% wt.) in comparison with pure ethanol, in terms of overall thermal resistance.***

Keywords: pulsating heat pipe, azeotropic mixture, thermal resistance, heat transfer, working fluid

1. Introduction

Thermal management is the challenge of the day in electronic product development. Presently, the chip heat flux level ranges between 40 to 120W/cm^2. It is expected to increase to 200W/cm^2 in the next few decades. Several cooling methods are employed to cool the electronic devices. The Pulsating Heat Pipe (PHP) is being explored for cooling electronic devices with promising results. The PHP is simple in structure with a small diameter capillary tube filled with certain working fluid in it and extended from the heat source to sink. PHP uses the technique of transporting the working fluid by means of differential pressure across liquid slugs and vapor plugs from evaporator to condenser and back from condenser to evaporator. The fluid from the evaporator is pushed towards the condenser in the form of discrete liquid slugs and vapor bubbles. The vapor gets partially condensed at the condenser and looses the heat and returns to evaporator to complete the cycle. The heat transfer in a PHP is due to the sensible heat and latent heat combination.

The pulsating heat pipe, proposed and patented by Akachi [1], 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, cell cryopreservation, the spacecraft thermal control system, etc. Recently a Zhang and Faghri [2] presented a review on effect of various parameters such as working fluids, charge ratios, inclination angles, etc. in terms of fluid dynamics and heat transfer. Charoensawan et al. [3] performed the experiments in vertical orientation for the 2.0 mm device, water filled device showed higher performance compared to R-123 and ethanol; whereas R-123 and ethanol showed comparable performance in case of 1.0 mm devices. However Mameli et. al [4] used the similar azeotropic working fluid in two turns CLPHP and conclude that no measurable difference has been recorded between the CLPHP running with the azeotropic mixture and the CLPHP running with pure ethanol, in terms of overall thermal resistance. Pachghare et. al used the pure and binary working fluid CLPHP and conclude that no measurable difference has been recorded between the CLPHP running with pure and binary mixture working fluids. Working fluid behavior is strongly depends on the thermo-physical properties, put latent heat of vaporization is main property that strongly affects the thermal performance [5, 6]. Shafi [7,8] performed the numerical modeling of PHP with multiple liquid and vapor plugs using the constant wall temperature condition. They illustrated that the gravity force has an insignifant effect on the performance. They also demonstrated that the major heat transfer mechanism is due to sensible heat and the PHP does not work at high fill ratios such as higher than 90%. Kang et al. [9] demonstrated that silver nanofluids temperature difference decreased 0.56-0.65^{0}C compared to DI water at an input power 30-50 W at the same charge volume by experiment. Qu et al. [10] performed an experimental investsigation charged with base water and spherical Al_2O_3 particles of 56 mm diameter. Compared with pure water, the maximum thermal resistance was decreased by 0.14^{0}C/W (or 32.5 %) when the power input was 58.8 W at 70% filling ratio and 0.9 % mass fraction.

At different situations, different pure working fluids have their advantages. Up till now, very little experimental work was reported on single loop PHP. It is also observed that only one fluid i.e. ethanol is used as the working fluid in the experiments of single loop PHP. No more data is available related to single loop PHP. Thus in the present work, fluids like water, azeotropic mixture in addition to ethanol are considered and the various experiments are carried out for single loop PHP.

1.1 Details of Azeotropic Mixture

- It is a mixture of at least two different liquids.
- The mixture has either a boiling point higher than the boiling point of the components or less than the boiling point of the components when fraction of liquids can't be altered by distillation.
- At the azeotropic point, the vapour phase composition is same as the liquid phase composition.
- It exist in the solution at a boiling point specific for that component
- e. g. 95.63% ethanol and 4.37% water

2. Experimentation

2.1 Experimental setup

Figure 1 illustrates that, the schematic of experimental set-up. The set-up comprises the CLPHP, cooling water unit, heater and a control panel.

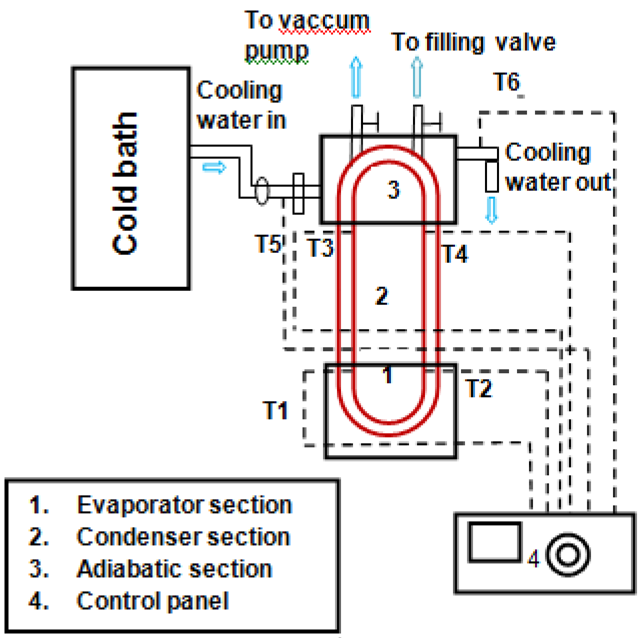

Figure 1: Schematic of experimental setup

The CLPHP is divided in three main sections:

- The evaporator zone, where the device receives a controlled heat input by means of heating coil.
- The adiabatic zone ideally insulated from the environment.
- The condenser zone where the PHP releases the heat by means of a liquid cooled heat sink.

The tubes in the three sections (i.e. evaporator, adiabatic and condenser) are made of copper in order to minimize the thermal resistance between the tube and the heat input/output zones while the straight tubes in the adiabatic section are covered with insulated material so that there is no contact with the environment. All tubes in evaporator and condenser section have inner diameter 2.0 mm and outer diameter 3.0 mm. The total length of evaporator section (L_e = 270 mm), total length of condenser section (L_c = 190 mm) and total length of adiabatic section (L_a = 300 mm). The centre distance between two tubes (pitch) was maintained 70 mm.

In the evaporator section, insulation paper is provided on the copper tube and then a nichrome wire is wound on the tube. For safety, again a layer of insulation is used. The condenser section was cooled by (coolant) normal water through a cooling box of dimension 100×20×70 mm^3 with maintained flow 3 ml/sec and inlet and outlet temperature was measured.

The control panel comprises of power measuring and temperature measuring equipment as shown in fig. 1. The heat input is measured in terms of electrical power supply through Dimmerstat (0 – 1000 W). The voltmeter (0 – 300 V) and Ammeter (0 – 3 A) was connected in line for the input power measurement. The output of the experimental setup is calculated in terms of thermal resistance, for that, the various temperatures were recorded at different location by means of thermocouple wires (Chromel-Alumel, K-type, accuracy ± 0.2^{0}C). The position of the thermocouple wires are shown in fig. 2. With the help of knob eight different temperatures can be noted. Water, ethanol and azeotropic mixture of water (4.5% wt.) – ethanols (95.5 % wt.) are selected as working fluids for experimentation.

2.2 Experimental Procedure

- The primary requirement of CLPHP is to create a vacuum inside the tube. In order to create vacuum inside the PHP, a reciprocating vacuum pump is connected to the filling valve.
- Thereafter the device is fill with the desired working fluids and closed the valve.
- Water was supplied from storage tank to the condenser section.
- Wait till the condenser tank is completely filled. Then flow rate was measured with beaker and stop watch.
- Power was supplied to the control panel and checked well for the data collection.
- Control panel was connected to the PHP setup with the help of power cord, the nichrome wire starts heating. This in turn heats the evaporator section.
- Provide a constant heat input to the heater up to steady state reached and temperature at different points of CLPHP note down between 10 minute intervals. The heat input is increased with step of 8 W input powers after steady state reached.
- After a quasi-steady state was reached, note down the readings. At steady state from the inlet - outlet temperature and mass flow rate of the coolant, the heat transfer could be calculated. Above procedure was repeated for the different working fluids.

3. Data Reduction

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

$$\dot{Q}_{out} = \dot{m}\, C_P\, (T_{out} - T_{in}) \quad (1)$$

where m, C_P, T_{out} and T_{in} represents the flow rate, specific heat at constant pressure, outlet temperature, and inlet temperature of chilled water, respectively. The total thermal resistance is obtained from the following equation:

$$R_{th} = \frac{\Delta T}{\dot{Q}} = \frac{T_e - T_C}{\dot{Q}} \quad (2)$$

where T_e and T_c is the average temperature of evaporator and condenser, and $\dot{Q}$ is represents the average of the heat removal form of the condenser and supplied input power ($\dot{Q}$= I×V). Normally the difference amid the heat removal from condenser and the supplied power is less than 5%.

4. Results and Discussion

4.1 Pure working fluids PHP

A typical plot shows the effect of different pure working fluids on average evaporator, average condenser wall temperature, evaporator-condenser wall temperature difference and thermal resistance with different heat inputs are shown in fig. 1, 2, 3 and 4 respectively. With increasing heat input to the device, the evaporator temperature rises resulting in a greater density gradient in the tubes. Simultaneously the liquid viscosity also drops diminishing the wall friction and it proportional to heat input therefore thermal resistance decrease with increase in heat input for all working fluids.

From the Fig. 1, it can be seen that the evaporator wall temperature is higher in case of water and lower in the case of ethanol due to higher saturation temperature and high specific heat for water. It is also observed that the system takes more time to reach the steady state in case of water. Figure 2 concludes that the condenser temperature of water and ethanol is nearly equal at low heat input but as the heat input increases, the condenser temperature of ethanol is higher than the water.

There is no quantifiable difference in all working fluids for high heat inputs after input heat power 56 W. The temperature difference between the evaporator and the condenser is less for ethanol and more for water. This is due to the fact that the saturation temperature of ethanol is lower compared to water.

This shows that ethanol can transfer heat with less temperature difference compared to water up to 24 W heat input. Figure 4 shows the variation of thermal resistance with heat input for different working fluids. From figure 4, it is clear that up to 40 W heat input power thermal resistance decrease with increase in heat input for all working fluids, because in high power inputs, the temperature of the evaporation section is high enough to keep the working fluids of high boiling points can boil vehemently and smoothly flow in one direction. Thermal resistance of ethanol PHP is lower than water PHP for all heat input. After heat input power 32 W thermal resistance for ethanol and water smoothly decrease with heat input.

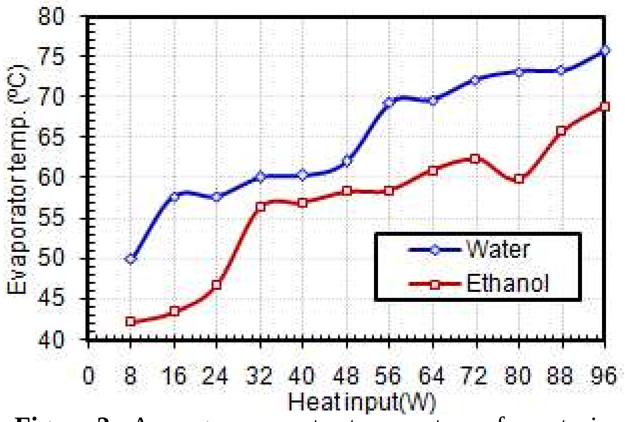

Figure 2 : Average evaporator temperature of azeotrpic mixture PHP

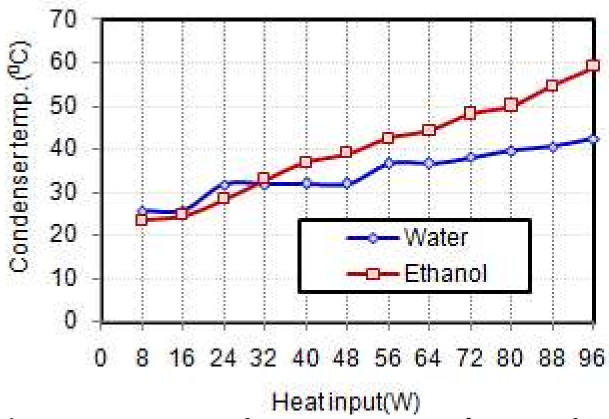

Figure 3: Average condenser temperature of pure working fluid PHP

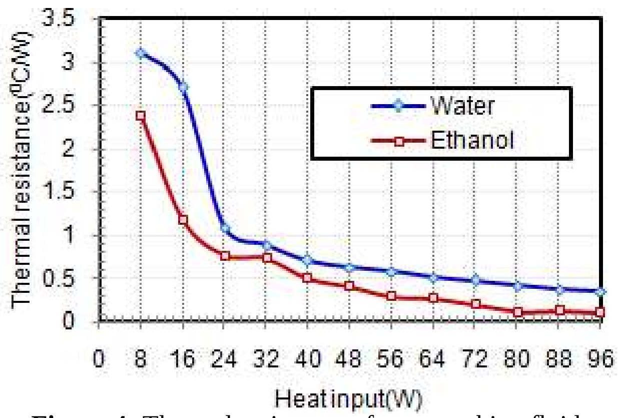

Figure 4: Thermal resistance of pure working fluid

4.2 Ethanol/Water PHP (Azeotropic mixture)

Figure 5 and 6 shows the effect of Azeotropic mixture (water-ethanol binary working fluids) on the average evaporator and average condenser temperature respectively.

From fig. 5, it is clear that the evaporator temperature for pure ethanol and azeotropic mixture of ethanol (95.5% wt.) and water (4.5% wt.) is lower as compared to water. Fig. 5 also shows that the evaporator temperature for ethanol PHP and azeotropic mixture of water and ethanol PHP is nearly same at all heat inputs. Fig. 6 presents that the average condenser temperature is nearly same for the three fluids i.e. water, ethanol and water+ethanol between the heat input 8 W to 24 W. After 24 W, condenser temperature for water is lower than the ethanol PHP and azeotropic mixture PHP. The evaporator and condenser temperature difference is nearly equal for azeotropic mixture and pure ethanol but for pure water the temperature difference is very high and hence more thermal resistance shown in fig. 6.

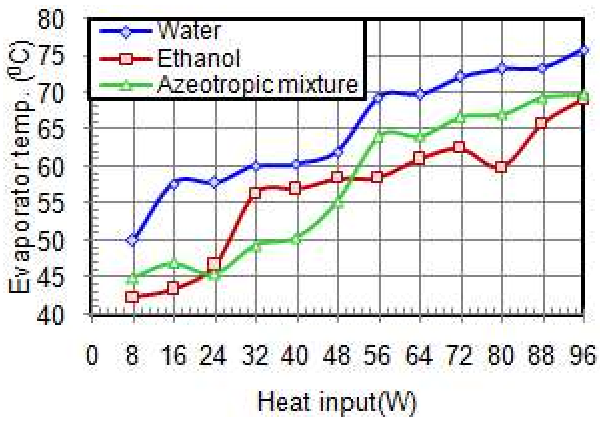

Figure 5: Average evaporator temperature of azeotrpic mixture PHP

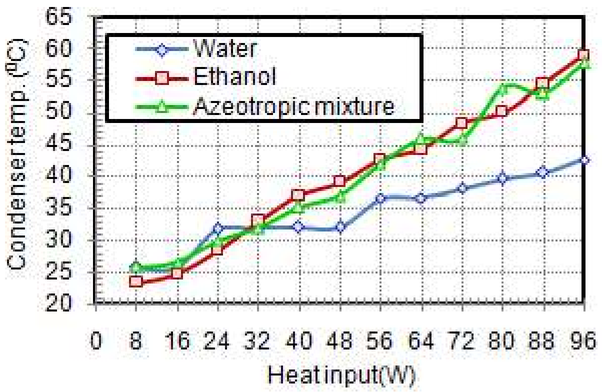

Figure 6: Average condenser temperature of azeotropic mixture PHP

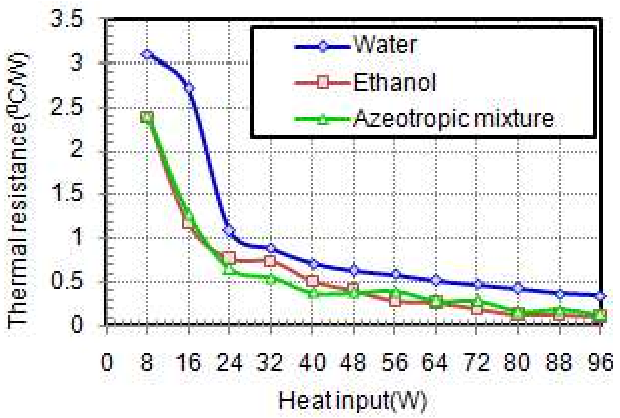

Figure 7: Average thermal resistance of Azeotropic mixture PHP

Figure 7: concludes that the thermal resistance for ethanol PHP and azeotrope PHP is same between heat input 8 W to 24 W.

Thermal resistance of water PHP is more than the azeotrope PHP and ethanol PHP for all heat inputs. From fig. 8, it is found that no measurable difference has been recorded for the PHP running with azeotropic mixture and the PHP running with pure ethanol. Hence, the ethanol PHP and azeotropic PHP is more effective than water PHP.

5. Conclusion

From these experimental studies, following conclusions are drawn:

- For all pure and Azeotropic mixture PHP thermal resistance decreases with increase heat input.
- Thermal performance of PHP strongly depends on thermo physical properties of working fluids.
- No measurable difference has been recorded for PHP running with azeotropic mixture of water (4.5% wt.) and ethanol (95.5% wt.) and PHP running with pure ethanol, in terms of overall thermal resistance.
- Thermal performance of PHP strongly depends on thermo physical properties of working fluids.
- No measurable difference observed for all working fluids at low heat input but measurable difference observed at high heat input.
- Ethanol PHP and azeotropic PHP gives the good themal performance than water PHP.

Nomenclature

Q heating power input(W)
FR filling ratio
R thermal resistance (^{0}C/W)
T temperature (^{0}C)
T_e temperature of evaporation section (^{0}C)
T_c temperature of evaporation section (^{0}C)
Ts temperature of boiling point (^{0}C)
Tc temperature of condenser section (^{0}C)
C heat capacity (J/m^3·K)
C_p specific heat (KJ/kg·K)
H_{fg} latent heat of evaporation (KJ/kg)
t time (s)

Greek Symbols
ρ density (kg/m^3)
σ surface tension(N/m)
υ dynamic viscosity (Pa·s)
λ thermal conductivity(W/m^{0}C)

Subscripts
l liquid
v vapor
sat saturation state
e evaporation section
c condensation section

References

[1] A. Akachi, Structure of a heat pipe. US Patent No. 4921041, 1990.

[2] Y. Zhang, A. Faghri, 2008, Advances and unsolved issues in pulsating heat pipes, Heat Transfer Eng. 29, 20-44.

[3] Charoensawan P., Khandekar S., Groll M. and Terdtoom P., 2003, "Closed Loop Pulsating Heat Pipes Part A: parametric experimental investigations:", Applied Thermal Engineering, Vol. 23, , pp.2021-2033.

[4] Mameli M., Khandekar S. and Marengo M., 2011, "An Exploratory Study Of a Pulsating heat pipe Operated With a Two Component Fluid Mixture", Proceedings of the 21st National and 10th, ISHMT-ASME Heat and

Mass Transfer conference, December 27-30, IIT Madras, India, Paper ID: ISHMT-IND-16-033,2011.

[5] Pachghare P., Mahalle M., Khedkar S., 2012, "Effect of Working Fluid on Thermal Performance of Closed Loop Pulsating Heat Pipe: A Review," International Journal of Computer Applications, pp. 27-31.

[6] Pachghare P., Mahalle M., 2012, "Thermal performance of closed loop pulsating heat pipe using pure and binary working fluids," Frontiers in Heat Pipes (FHP), 3, 033002.

[7] Shafii M. B., Faghri A., Zhang Y.W., "Thermal modeling of unlooped and looped pulsating heat pipes".ASME Journal of Heat Transfer,Vol. 123, 2001, pp. 1159– 1172.

[8] Shafii M.B., Faghri A., Yuwen Z., "Analysis of heat transfer in unlooped and looped pulsating heat pipes".International Journal of Numerical Methods Heat Fluid Flow, Vol. 123, 2001, pp. 589-609.

[9] Shung-Wen Kang, Wei-Chiang Wei, Sheng-Hong Tsai, Chia-Ching Huang., 2009: "Experimental investigation of nanofluids on sintered heat pipe thermal performance". Applied Thermal Engineering, Vol. 29, pp. 973-979.

[10] Qu J., Hui-ying Wu, Ping Cheng., 2010: "Thermal performance of an oscillating heat pipe with Al2O3-water nanofliuids". International Communications in Heat and Mass Transfer, Vol.37, pp. 111-115Dadong WANG, Xiaoyu. CUI, Experimental research on Pulsating heat pipe with different mixtures working fluids", The 21st International Symposium on Transport Phenomenon.

[11] Borkar R., Pachghare P., 2012, "State of The Art on closed loop pulsating heat pipe," International Journal of Emerging Technology and Advance Engineering (IJETAE), ISSN 2250-2459, Volume 2, Issue 10, IJETAE_1012_95.

[12] Dadong WANG, Xiaoyu. CUI, Experimental research on Pulsating heat pipe with different mixtures working fluids", The 21st International Symposium on Transport Phenomena.