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Experimental Analysis of Pulsating Heat Pipe with Different Working Fluids

Jagadeesh S K[1], Umesh C K[2]

[1]Dr. Ambedkar Institute of Technology, Department of Mechanical Engineering, Bangalore 560056, India

[2]University of Visvesvaraya College of Engineering, Department of Mechanical Engineering, Bangalore 560001, India

Abstract: ***Pulsating heat pipe (PHP) is a passive two phase heat transfer device which does not require a pump or additional power to transport the working fluid from the region of higher temperature or vice versa. A functional PHP test rig is fabricated with well insulated evaporator and condenser. An experimental study of the performance of PHP is carried out with acetone, ethanol and methanol as working fluid. The filling ratios are varied from 40% - 60% in steps of 10% with varying heat input from 4W to 6W in steps of 1W. A comparative study is made and evaluated the performance of PHP in terms of thermal resistance.***

Keywords: Pulsating heat pipe, Thermal resistance, Experiment, Working fluids

1. Introduction

Cooling by pulsating heat pipe (PHP) is a new technique in thermal management of electronics. PHP is a passive heat transfer device that functions via thermally excited oscillating motion induced by the cyclic phase change of an encapsulated working fluid. A typical PHP consists of a train of liquid plugs and vapour bubbles which exist in serpentine-arranged, interconnected capillary tubes or channels. The PHP is partially filled with a working fluid. The internal diameter of the PHP must be small enough so that liquid plugs can be separated by vapour bubbles. Unlike conventional heat pipes, the PHP can function with no wicking structure and is easy to manufacture [1]. A typical PHP has three sections: an evaporator section, an adiabatic section, and a condenser section. In 1990, Akachi invented the PHP, schematic sketch of which is as shown in Fig. 1. This invention is responsible for the first literature, which describes how a PHP functions. In Akachi's invention, it can be found that the PHP can have different types: closed loop, open loop, check valve, tubular, and flat plate [2]. The heat added in the evaporating section produces vapourisation causing vapour volume expansion and heat removed on the condensation section generates vapour condensation causing vapour volume contraction. This expansion and contraction of vapour volume produces the oscillating motion of liquid plugs and vapour bubbles in the system. In addition, the pulsating motions of liquid plugs and vapour bubbles co-exist at the same time, deriving the name 'pulsating' heat pipe. The phase change heat transfer in the evaporator and the condenser is the primary driving force for the oscillating/pulsating motion in the system, transporting the heat from the evaporator to the condenser. The oscillating/pulsating motions in the PHP depend on the surface conditions, dimensions, working fluid, operating temperature, heat flux and the total heat load, orientation, number of meandering turns, and the filling ratio.

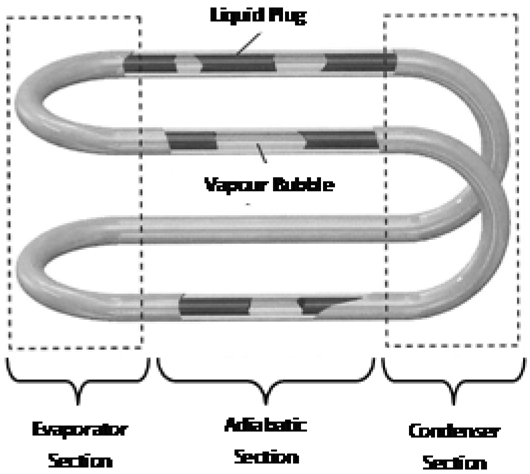


Figure 1: Schematic of a PHP [Akachi, 1990]

PHP is a novel concept which has already been tried out in some applications of micro and power electronics owing to the unique operational characteristics coupled with relatively low costs. The thermo-hydrodynamic behaviour of PHP is distinctly unique from conventional heat pipes and the present work aims to understand the fundamental thermo-fluidic operational characteristics of closed loop pulsating heat pipes (CLPHPs) through experiments and simulation studies. This paper presents the experimental studies conducted on a single turn closed loop pulsating heat pipe using different working fluids, namely, acetone, methanol and ethanol, with varying filling ratios and heat inputs.

2. Review of Literature

Harshal, et. al. [3] conducted experiments with varying fill ratios of 40%, 50% and 60% and heat input of 20W to 50W in steps of 10W. Copper was selected as the tube material with inner diameter 2.15 mm and water was used as the working fluid. They reported that the difference in steady state temperatures of evaporator and condenser increased with increase in filling ratio as well as heat input. The results indicated that the PHP performed better with lower level of filling ratio for the same heat input.

Nandan, et al [4] investigated the thermal performance and flow visualisation of a single loop geometry with 4 mm internal diameter made of quartz glass tube. Temperatures were measured at different locations of the loop on its wall. The observations revealed different operating regimes like no flow, oscillating flow and through flow, depending upon the loop orientation, filling ratio and input power. There existed an optimum filling ratio, within 50-60% and an optimum inclination angle, within 50-70^0, where the thermal resistance of the loop is minimum. A flow regime map has been presented, which visualises the cease of circulation at an inclination angle of 0^0.

Udaykumar, et al [5] carried out experimental investigations on a single loop PHP and the effect of heat input, filling ratio and working fluid on the performance of PHP was studied. The results indicated that with the increasing heat input, the thermal resistance of the PHP decreased while the heat transfer coefficient and fluid circulation velocity increased. The temperature difference between the evaporator and condenser was observed to be minimum for acetone compared with ethanol, methanol and propanol. Acetone was found to give the best performance of the PHP amongst the fluids used in the experiment.

Pallavi and Pramod [6] conducted experiments on a single loop PHP with azeotropic mixture of water and ethanol as working fluid. They reported that thermal resistance decreased with increase in heat input to the PHP both pure liquids (water, ethanol) and azeotropic mixture of water and ethanol. It was also observed that the PHP with ethanol and azeotropic mixture gave better performance compared to the PHP with water as the working fluid.

Rama Narasimha, et al [7] conducted an experimental study on a closed pulsating heat pipe with single U turn. The bubble speed and the temperatures were measured at varying conditions of heat input and type of working fluid. The working fluids used were acetone, methanol, ethanol and water. The derived parameters included time constant, heat transfer coefficient and thermal resistance. The results indicated that acetone has better heat transport capability with lesser temperature drop across the evaporator and condenser. The bubble speed was higher in case of acetone compared to other fluids for varied heat inputs. The study indicated that acetone was the suitable working fluid for PHP operation at the operating temperatures studied in terms of lower thermal resistance and higher heat transfer coefficient.

R. Naik, et al. [8] conducted transient and steady state experiments on a single turn closed loop PHP. Copper was used as the capillary tube material with inner diameter 1.95 mm and outer diameter 3 mm. The evaporator and condenser sections were 185 mm and 195 mm respectively. The experiments were conducted in both horizontal and vertical orientations with head load varying from 9 to 15W in steps of 2W. The PHP was tested with acetone, methanol and ethanol as working fluids with filling ratio of 60 to 80% in steps of 10%. The experimental results indicated that the heat transfer characteristics of PHP was better at 60% filling ratio and the PHP performed fairly well with horizontal mode for all heat loads, working fluids and fill ratios considered.

3. Design and Fabrication

The experimental set up of a single turn pulsating heat pipe was developed and tested in the heat transfer laboratory at the department of mechanical engineering, Dr. Ambedkar Institute of Technology, Bangalore. A copper tube of 3 mm inner diameter and 700 mm length was bent in U shape at the two ends and they are connected using borosilicate glass tubes. The glass tubes serve to act as adiabatic section and also to visualise the movement of the liquid slugs and vapour bubbles during the working of the heat pipe. Silicon rubber tubes are used to interconnect the copper pipe and glass tube to form a single loop. One end of the U turn is wound with a Nichrome tape heater of 0-100W capacity, forming the evaporator section of the heat pipe. This portion is enclosed in a thick PVC box filled with glass wool to prevent the heat loss to the atmosphere. DC Regulated power supply was provided to control and measure the voltage and current given to the evaporator. Another end of the U turn forms the condenser section in which cold water was circulated to dissipate the heat carried by the working fluid in the heat pipe. Six K-type thermocouples were used in the test rig – four in the evaporator section, named T_1, T_2, T_3 and T_4, and two in the condenser section, named T_5, T_6, to measure the temperature of the evaporator and condenser sections, respectively.

An eight-channel digital temperature indicator is used to display the temperature measured at various points in the evaporator and condenser sections. A channel selector switch is used to select the channels of the indicator, in turn, so that temperature of each thermocouple can be observed. All the apparatus is mounted on to a wooden board with suitable fixtures.

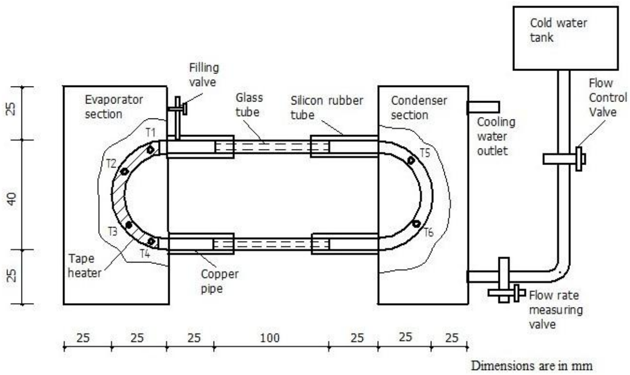


Figure 2: Schematic of the experimental test rig

4. Experimental methodology

The following methodology is adapted to conduct experiments on single turn pulsating heat pipe.

1) It is ensured that no liquid is contained in the heat pipe loop. This is done by blowing hot air through the loop by using a hair dryer.
2) For a given filling ratio, the working fluid is measured as a percentage of the total volume of the heat pipe loop.
3) The required quantity of the working fluid is then filled by using an injection syringe through the filling tube (T-tube). Since the diameter is very small, it is difficult to push the fluid through the loop. In that case, keeping the heat pipe assembly slightly inclined, open the silicon

rubber tube connector partially and push the fluid through the filling tube so that the required quantity is filled in the loop.

4) The flow of cooling water is set for a constant rate of 2 cc/sec so that the temperature rise of cooling water in the condenser does not exceed 1^0C.
5) The DC Regulated Power Supply is switched ON and required heat input is set by adjusting the current and voltage reading.
6) After some time, the working fluid starts boiling, and the vapour bubbles along with liquid slugs start moving through the loop. This movement can be seen as they pass through the glass tubes.
7) Keep observing the temperature indicator and after a steady state is reached (when there is no significant change in temperature in any channel), note down the temperature readings, T_1 through T_6, with the help of channel selector.
8) Tabulate the readings and calculate the thermal resistance and heat transfer coefficient.
9) Plot the various graphs to understand the performance of single turn pulsating heat pipe.

5. Results and Discussion

Three different working fluids, namely, acetone, methanol and ethanol were used in the experiment. The experiment was carried out at steady state conditions for each of the fluids at different filling ratios and varying the heat input given to the evaporator section. The temperatures at evaporator and condenser sections were recorded at all the six locations after the test rig reached the steady state and the performance of the heat pipe was determined by evaluating the thermal resistance, which is considered to be the performance parameter of a PHP [10]. The experimental data collected and results evaluated for each of the working fluid during the experimentation are tabulated as follows:

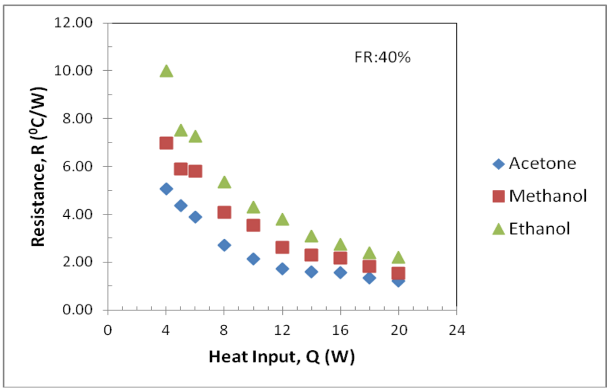
The steady state experiments are carried out with three different working fluids, namely, acetone, methanol and ethanol. The heat input is initially varied between 4W to 6W in steps of 1W and then 8W to 18W in steps of 2W. The filling ratio of 40%, 50% and 60% has been used. The evaporator wall temperature T_E is calculated by taking the arithmetic mean of the temperatures recorded at four different locations on the evaporator wall. Similarly, the condenser wall temperature T_C is calculated by taking the arithmetic mean of the temperatures recorded at two different locations on the condenser wall. The thermal resistance of the heat pipe, which is used as the performance parameter, is determined by the equation [9]

$$R = \frac{T_E - T_C}{Q} \; ({}^0C/W) \qquad (1)$$

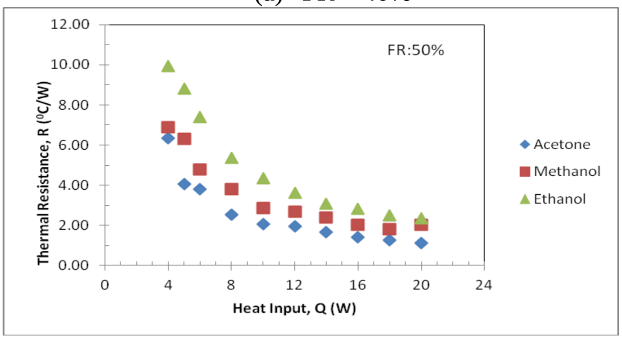
Where T_E = Evaporator temperature (^{0}C), T_C = Condenser temperature (^{0}C) and Q = Heat input (W).
The effect of heat input, filling ratio and working fluids on the performance of PHP is discussed in the following section.

5.1 Effect of heat input

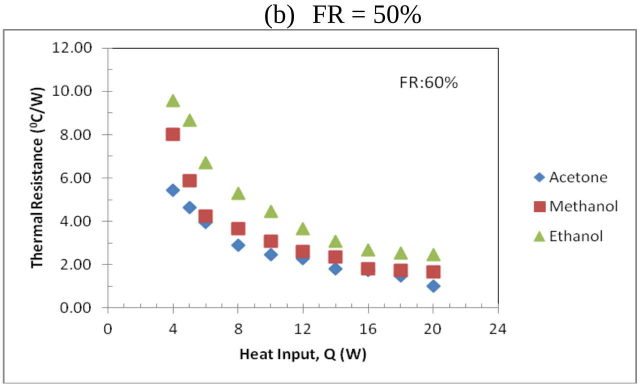
The heat input is a very important parameter to be considered for the study since the PHP may be subjected to different heat load conditions in real-life situations. In the present investigation, experiments are carried out for various heat inputs ranging from 4W to 20W in various steps. This range of heat input is given to all the working fluids with filling ratios (FR) of 40%, 50% and 60%. The performance of the PHP is measured in terms of thermal resistance and plotted for varying heat input. Fig.3 (a-c) shows the variation of thermal resistance of the PHP filled with acetone, methanol and ethanol. The variation is shown with respect to different heat inputs and at different filling ratios. It is observed that the thermal resistance of the PHP has decreased with increase in heat input at all filling ratios of all the working fluids considered. The decreased thermal resistance represents the increased heat transfer coefficient and therefore indicates that the performance of the PHP increases with the increased heat input.



(a) FR = 40%



(b) FR = 50%



(c) FR = 60%

Figure 3 (a-c): Effect of heat input on thermal resistance

5.2 Effect of working fluid

Working fluid plays a vital role in the effective functioning of a pulsating heat pipe. The thermo physical properties of the working fluid, such as surface tension, thermal conductivity, latent heat, specific heat and viscosity affect the performance of the PHP to a greater extent. Review of literature [1, 4, 5-8] suggested that acetone, methanol and ethanol are considered to be suitable working fluids for better performance of a PHP.

The thermal resistance of the PHP using different working fluids at different filling ratio and with varying heat input is shown in Fig. 3(a-c). It is observed that the thermal resistance of the PHP decreased with increase in heat input for all the three working fluids considered in the present investigation. Acetone is observed to have the least thermal resistance for all the filling ratios considered, indicating that acetone-filled PHP performs better than methanol- and ethanol-filled PHP. The saturation temperature of acetone, 56^0C, being lowest of the three fluids and with the condenser temperature maintained nearly constant, the temperature difference between the evaporator and the condenser decreased with increase in heat inputs. This decreased temperature difference across the evaporator and the condenser resulted in low thermal resistance of the acetone-filled PHP. Hence, the performance of acetone-filled PHP was better compared with PHP with methanol and ethanol being used as working fluids.

5.3 Effect of filling ratio

Filling ratio is the ratio of the amount of liquid present in the PHP by its volume percentage. 0% filling ratio indicates that the PHP works in the pure conduction mode and 100% filling ratio indicates that the PHP works as thermosyphon. The PHP works as a true pulsating device when the filling ratio is maintained in the range of 20%-80%. However, the exact range varies with the working fluid, operating temperatures and construction [10]. Fig.5 shows the variation of thermal resistance at different filling ratios of 40%, 50% and 60% for the case of acetone-filled PHP. At the entire filling ratio considered, the thermal resistance has decreased with increased heat input. It is also observed that at lower filling ratios of 40% - 50%, the thermal resistance has decreased with increased heat input. This may be attributed to the fact that there are more vapour bubbles at lower filling ratios and they initiate the pumping action leading to enhanced performance of the PHP. On the other hand, at higher filling ratios 50%-60%, the thermal resistance has increased due to the fact that there is more liquid and reduced bubble generation leading to less perturbations and hence reduced performance of the PHP. Thus, it is clear that there exists an optimum filling ratio with increase in heat input, at which the PHP performs the best [10]. In the present investigation, acetone-filled PHP has reached the optimum filling ratio of 50% at which the performance is the best compared to 40% and 60%.

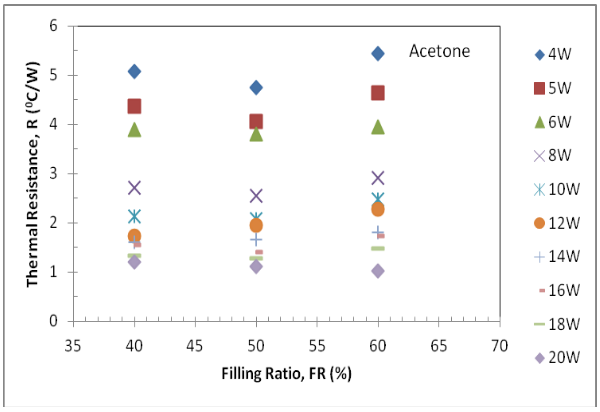


Figure 4: Effect of filling ratio on thermal resistance

6. Conclusion

1) The thermal resistance of the PHP at given filling ratio decreases with increase in heat input for all the working fluids considered. It indicates that the performance of the PHP is higher at higher heat inputs.
2) Among the working fluids tested, acetone-filled PHP performed the best at different heat inputs and at the filling ratios considered.
3) The performance of the acetone-filled PHP was higher at the filling ratio of 50%.

7. Acknowledgements

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Author Profile

Jagadeesh S.K., received the M.Tech. degree in Mechanical Engineering from National Institute of Technology, Calicut, 1998. At present, he is pursuing his doctoral studies under the guidance of Dr. C.K. Umesh, in the area of pulsating heat pipes at University Visvesvaraya College of Engineering, Bangalore.

Umesh, C.K., received his PhD from Bangalore University, Bangalore. At present, he is working as the professor of mechanical engineering at University Visvesvaraya College of Engineering, Bangalore. His areas of interest are computational fluid dynamics, heat pipes, micro channels and heat transfer.