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Research Paper

EXPERIMENTAL ANALYSIS OF CLOSED LOOP PULSATING HEAT PIPE WITH VARIABLE FILLING RATIO

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Increasing performance of electronic components is resulting in higher heat flux dissipation. Two-phase Passive devices are proven solutions for modern microelectronics thermal management. In this context, Pulsating Heat Pipe (PHP) cooling is the new and emerging technique in the field of thermal management of electronics. In the present work, transient and steady state experiments are conducted on a two turn closed loop PHP. Copper is used as the capillary tube material in the evaporator and condenser sections with inner diameter of 2 mm and outer diameter of 3 mm. The total length of the closed loop pulsating heat pipe is 1080 mm. The evaporator and condenser sections are 360 mm and 280 mm respectively. The experiments are conducted on vertical orientations for different heat loads varying from 10 W to 100 W in steps of 10 W. The PHP is tested on Ethanol, Methanol, Acetone and Water as working fluids for different fill ratios from 0% to 100% in steps of 20%. The performance parameters such as temperature difference between evaporator and condenser, thermal resistance and the overall heat transfer coefficient are evaluated. The experimental results demonstrate the heat transfer characteristics, lower thermal resistance and higher heat transfer coefficient of PHP are found to be better at a fill ratio of 60% for various heat input.

Keywords: Pulsating heat pipe, Fill ratio, Orientation, Working fluids

INTRODUCTION

Thermal management is the challenge of the day in electronic product development. The amount of excess heat generated by the electronic devices and circuitry has increased enormously. All electronic components from microprocessors to high-end power converters generate heat and rejection of this heat is necessary for their optimum and reliable operation. As electronic design allows higher output in smaller packages, effective heat load dissipation becomes a critical

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design factor. Many of the present days electronic devices require cooling beyond the capability of conventional metallic heat sinks. One solution to remove excess heat is by utilization of heat pipes which are employed to remove the excess heat by directly attaching them to the heat source. The Oscillating or Pulsating Heat Pipe (PHP) is another promising heat transfer device for applications like electronic cabinet cooling. These simple looking devices have intriguing thermo-hydrodynamic operational characteristics. A PHP is partially filled with working fluid which distributes itself naturally in the form of liquid slugs and vapour plugs inside the capillary tubes. One end of this tube bundle (evaporator section) receives heat, transferring it to the other end (condenser section) by a pulsating action of the liquid-vapour system. A PHP is essentially a non equilibrium heat transfer device driven by complex combination of various types of two-phase flow instabilities. The performance success of a PHP primarily depends on the continuous maintenance or sustenance of these non equilibrium conditions. The liquid slugs and vapour plugs are transported because of the pressure pulsations caused inside the system. The construction of the device inherently ensures that no external mechanical power source is needed for the fluid transport. The driving pressure pulsations are fully thermally driven.

Single and multiple loop PHP studies are widely reported in the literature. These studies highlight the influence of various design parameters of PHP on its performance.

Working of Closed Loop Pulsating Heat Pipe

The tube is first evacuated and then filled partially with a working fluid. If the inner diameter of the capillary tube is small enough such that the working fluid will distribute itself along the tube length forming liquid slugs and vapor bubbles due to the effect of surface tension. Under operating condition, the tube-bundle of a PHP receives heat at one end and is cooled at the other. Due to boiling and evaporation, bubble generation and growth continually occurs in the evaporator. Simultaneously, bubbles collapse and shrink due to condensation in the condenser. The resulting effect of the action of bubbles acts as pumping elements, providing the momentum or uneven hydrostatic pressure needed to move slugs or bubbles to locations where evaporation, boiling, and condensation can occur. Therefore, the transport of liquid slug and vapor bubble is caused by the thermally induced pressure pulsations inside the device and no external mechanical power is required. The heat transfer, essentially as a combination of sensible and latent heat portions, is caused by the transport.

Factor Affecting Closed Loop Pulsating Heat Pipe

It can be seen that six major thermo-mechanical parameters have emerged as the primary design parameters affecting the PHP system dynamics. 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,
- Working fluid thermo-physical properties.

DESCRIPTION OF THE EXPERIMENTAL SETUP

Figure 1 shows the schematic diagram of the experimental setup. In this setup, copper is used as the capillary tube material in the evaporator and condenser sections with inner diameter of 2 mm and outer diameter of 3 mm. The total length of the closed loop pulsating heat pipe is 1080 mm. The evaporator and condenser lengths are 360 mm and 280 mm respectively. In order to visualize the flow in the PHP, a glass tube is connected between evaporator and condenser sections for a length of 440 mm. In the present investigation, borosilicate glass of inner diameter 2 mm and outer diameter 5 mm is employed. Silicon rubber tubes of 2 mm inner diameter and 5 mm outer diameter are used as connectors between glass and copper tubes. The silicon rubber tubes employed here as connectors can withstand high temperatures up to 400 °C. They are also leak proof and can expand at higher temperatures. The evaporator section consists of coil heater of 0-600 W capacity with 3 mm width and 120 mm length is employed during the experiments for heating the working fluid. Eight K type thermocouples are used for the temperature measurement. The operating temperature range of these K type thermocouples is 0 to 2400 °C with a maximum error of ± 0.1 °C. Two thermocouples are fixed in the evaporator section and three in the condenser section, similarly one in the oil bath and two are measured the inlet and outlet temperature of water at condenser section. The temperatures measured by two thermocouples in the evaporator section are named as T_2 and T_3. The temperatures measured by three thermocouples in the condenser section are named as T_4, T_5 and T_6 respectively. The thermocouples are fixed on the walls of the copper tube. The thermocouples temperature is measured with help of digital temperature indicator which is mounted on control panel. The glass wool is uniformly smeared throughout the heating section for insulation purposed.

Figure 1: Experimental Schematic of the PHP

Following procedure is adopted during the present transient and steady state experimentation:

- Before filling the working fluid, air is blown inside the heat pipe to ensure that there is no fluid present inside the PHP.
- PHP is filled with working fluid using a syringe for the required amount. The experiments are conducted for different fill ratios ranging from 0% to 100% in steps of 20%.
- The PHP is heated with the help of a power source from control panel.

- The cooling water is allowed to flow through the PHP to the condenser section of PHP from the constant water bath at a flow rate of 30 ml/min.
- The required wattage is set using the dimmer and the heat load is varied from 10 W to 100 W insteps of 10 W.
- Experiments are conducted in vertical orientation of PHP with different Ethanol working.

RESULTS AND DISCUSSION

Transient and steady state experiments are conducted with Ethanol, Methanol, Acetone and Water as working fluids. The experiments are carried out at different heat loads and fill ratio, the evaporator and condenser wall temperature readings are recorded. Figures 2 to 5 show the variation of overall thermal resistance $R_{th} = (Te - Tc)/Q$ of the PHP with increasing heat input power Q for different filling ratios for various working fluid. From the literature review I am consider 20% of heat lost in the surrounding, therefore all the calculation is carried out by 20% of heat lost of total heat load. This heat is lost trough the condenser section, evaporator section and adiabatic section.

Figure 2: Typical Variation of Thermal Resistance with Heat Input Power at Different Fill Ratio for Ethanol Fill in PHP

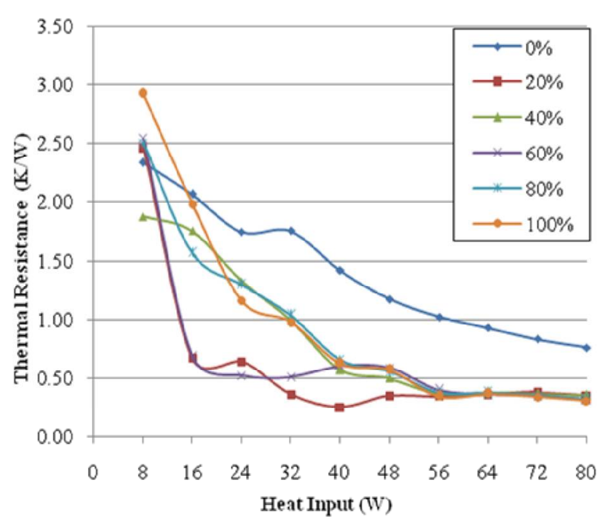


Figure 3: Typical Variation of Thermal Resistance with Heat Input Power at Different Fill Ratios for Methanol Filled PHP

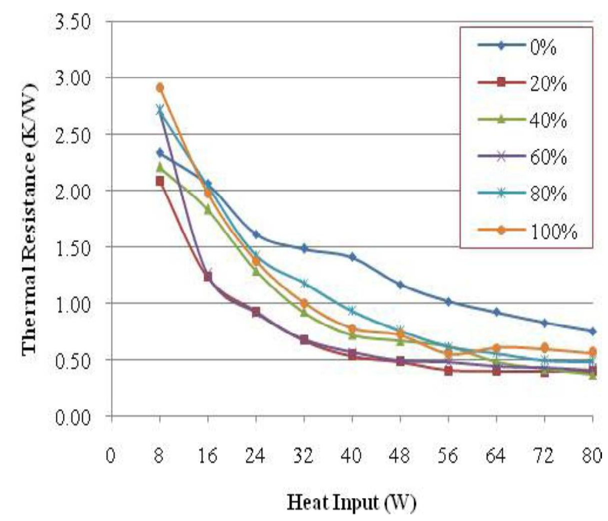


Figure 4: Typical Variation of Thermal Resistance with Heat Input Power at Different Fill Ratios for Acetone Filled PHP

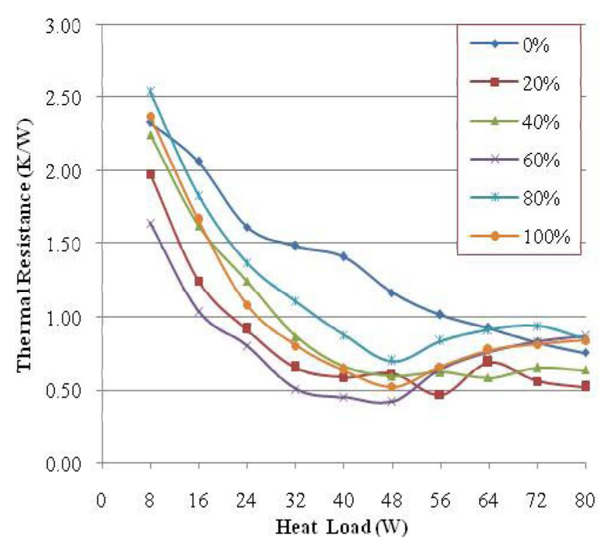
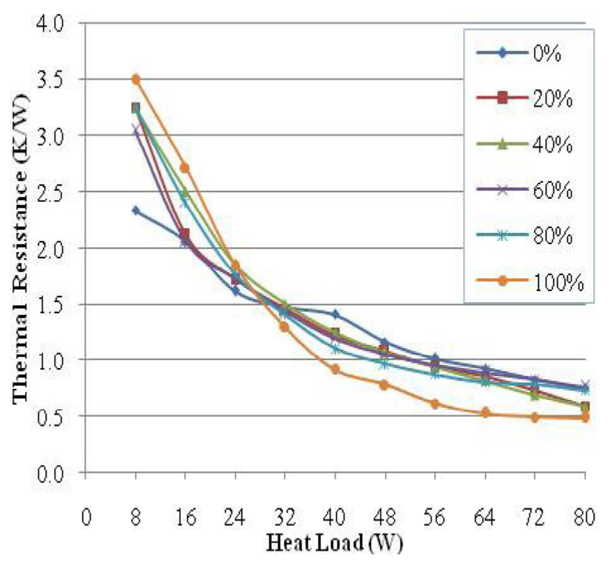


Figure 5: Typical Variation of Thermal Resistance with Heat Input Power at Different Fill Ratios for Water Filled PHP



Operational Extremities

For 0% filling ratio, the PHP runs without any fluid inside it and this serves as the reference Measurement. Obviously the mode of heat transfer is by pure conduction in PHP. The other extreme is when the PHP is fully filled with the working fluid (FR = 100%). In this mode the heat transfer is due to the single-phase buoyancy induced liquid circulation in the PHP. In this case the local heat transfer coefficient in the tubes is only a function of fluid Grashof and Prandtl numbers. There is a smooth decrease of the thermal resistance with increasing heat power input. Similarly low input heat fluxes were not capable of generating enough perturbations and the resulting bubble pumping action was extremely restricted. Over all, this scenario results in poor performance (i.e., very high thermal resistance).

As the heat input was increased, it improved the heat transfer coefficient to marked degree. Still higher input heat fluxes resulted in bulk flow taking a fixed direction that did not reverse with time. This circulation was manifested as adjacent tube becoming alternately hot and cold. Interestingly, in such a case lowest thermal resistance was observed.

Effect of Filling Ratio on Performance Limit

The filling ratio is defined as the fraction by volume of heat pipe, which is initially filled with the liquid. The optimum filling ratio is determined experimentally when the maximum heat transfer rate is achieved at the given temperature. As we know that below FRH ≈ 10%, there is no enough working fluid in the system for substantial sensible and latent heat transfer. The evaporator trends to dry out. The heat transfer performance is poor with high thermal resistance and low heat transfer limit. Above FRH ≈ 80% there are not enough bubbles to provide the pumping action, so the thermal performance drastically deteriorates. Between about 20% to 80% fill ratio, the PHP functions is in a true pulsating mode, and the thermal resistance is clearly lower than that of 100% filled mode. Otherwise, the heat transfer limit increases with the filling ratio. Similarly if the heat input increased from lower to higher, the fluctuation of thermal resistance is continuously decreased. At 40% and 80% filling of PHP give the higher thermal Resistance. The optimum fill ratio for the PHP in the experiments is about 60%, which most adequately combines the advantages of the following two aspects: the latent heat along with the pumping action of the bubbles, and the sensible heat transport of the liquid slugs. The Figures 6 to 9 show the thermal performance of tested closed loop pulsating heat pipe with respect to the filling ratio.

Figure 6: Typical Variation of Thermal Resistance with Filling Ratio at Various Input Power for Ethanol Filled PHP

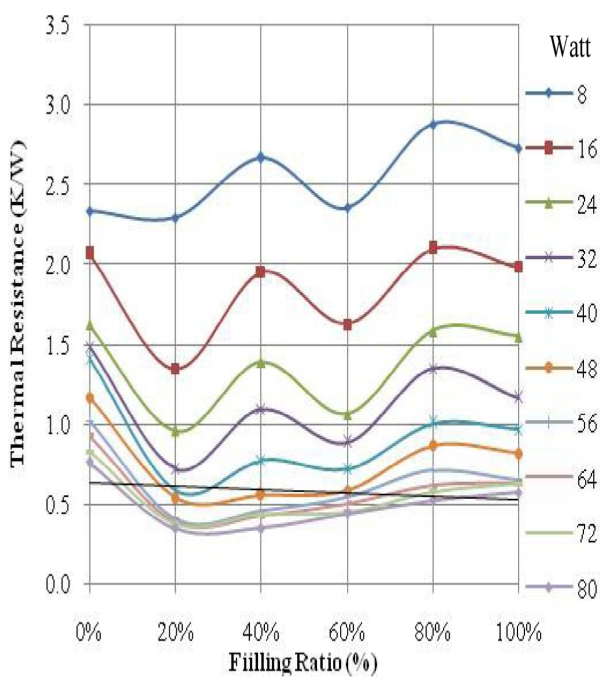


Figure 7: Typical Variation of Thermal Resistance with Filling Ratio at Various Input Power for Methanol Filled PHP

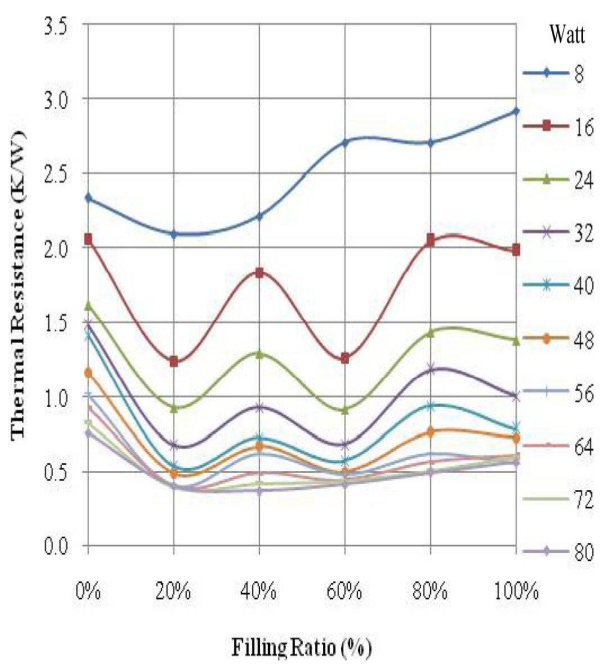


Figure 8: Typical Variation of Thermal Resistance with Filling Ratio at Various Input Power for Acetone Filled PHP

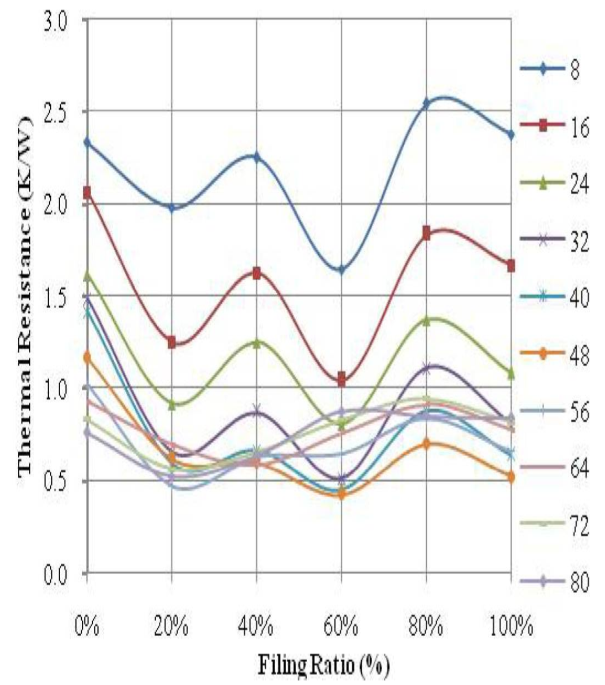
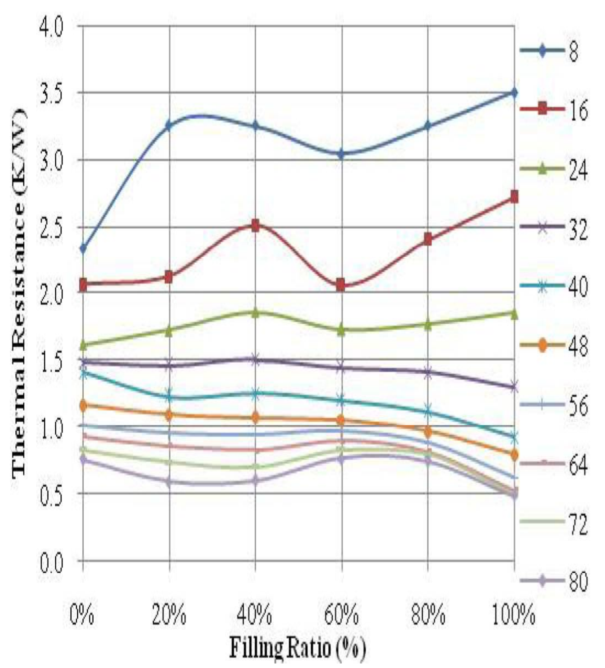


Figure 9: Typical Variation of Thermal Resistance with Filling Ratio at Various Input Power for Water



Effect of Fill Ratio on Temperature

The Figures 10 to 13 shows the temperature difference between evaporation and condenser section for different filling ratio at

Figure 10: The Temperature Difference in Evaporator and Condenser Section at Different Heat Input for Ethanol as Working Fluid

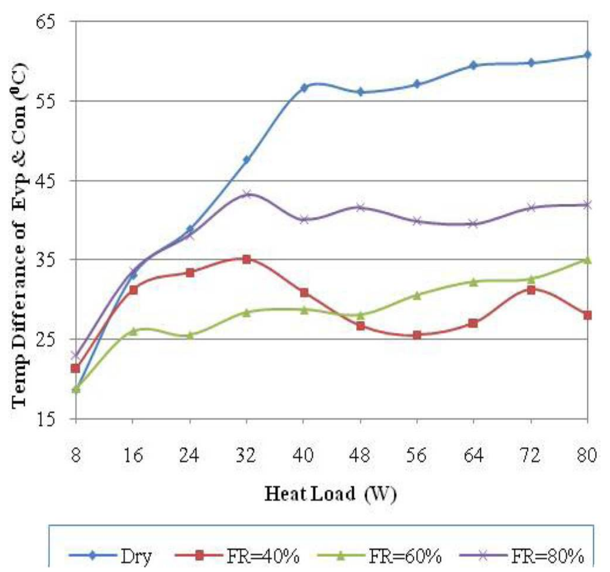


Figure 11: The Temperature Difference in Evaporator and Condenser Section at Different Heat Input for Acetone as Working Fluid

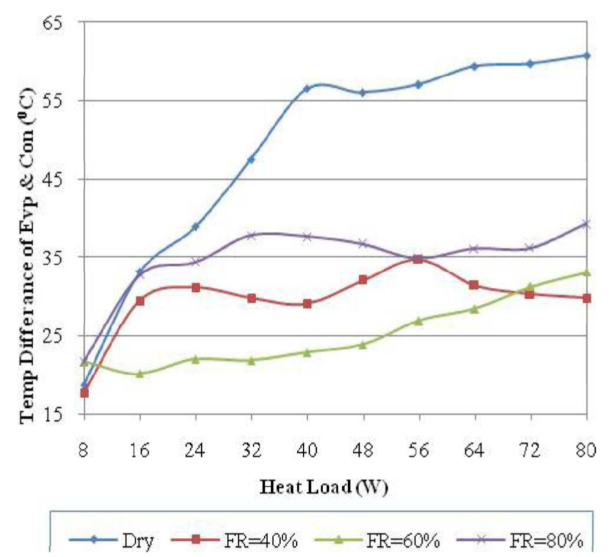


Figure 12: The Temperature Difference in Evaporator and Condenser Section at Different Heat Input for Acetone as Working Fluid

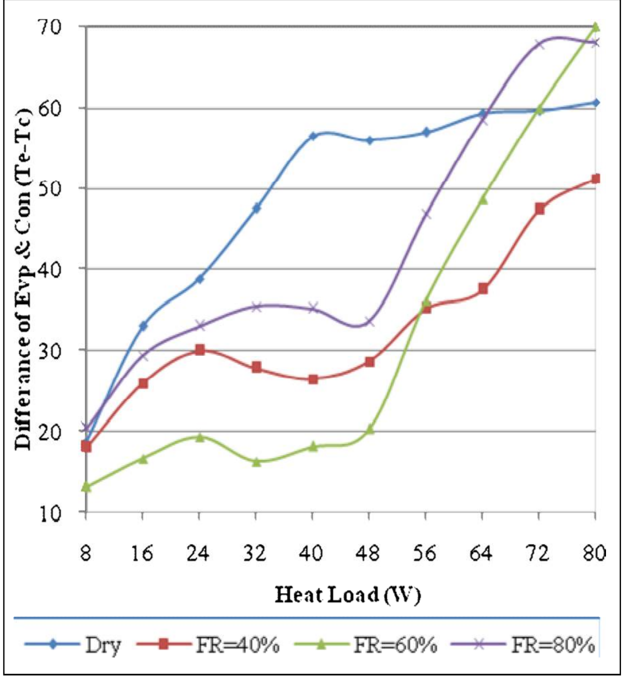
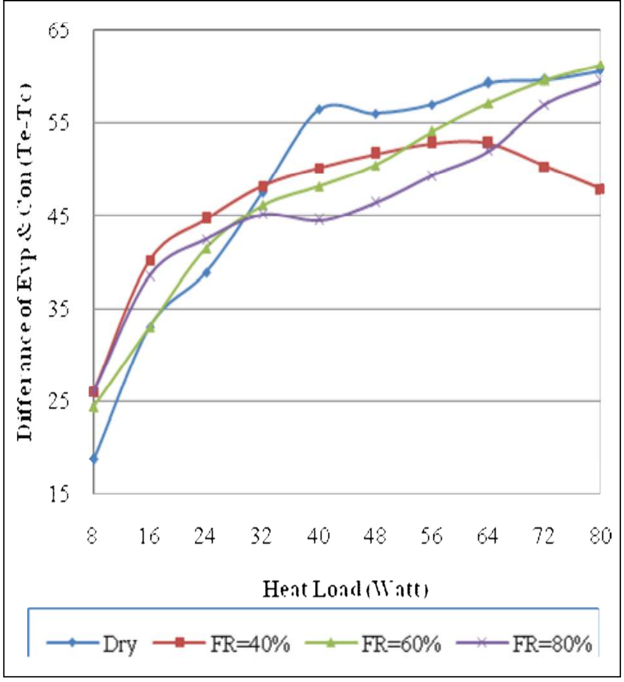


Figure 13: The Temperature Difference in Evaporator and Condenser Section at Different Heat Input for Acetone as Working Fluid



various heat input. The vapour bubbles formation is regulating the pumping action in the PHP. If the bubbles higher in PHP, the heat transfer rate also higher from evaporator section to condenser section. The figure show that at 60% filling ratio of PHP give the lower temperature difference as compare to other filling ratio. Therefore we can say that at 60% filling of PHP give the higher heat transfer rate and lower thermal resistance. When we used the Acetone as working fluid in PHP, the PHP give the better result as compare to other working fluid up to 48 watt.

CONCLUSION

The results from model are summarized as follows:

- The thermal resistance of closed loop pulsating heat pipe decrease with the increase of heat input. At the lower heat input ($Q \leq 60$ W) the thermal resistance is decreased slowly and at higher heat input ($Q \geq 60$ W) the difference is smaller.
- The thermal resistances have the results of $R_{acetone} < R_{methanol} < R_{ethanol} < R_{water}$. This condition is occurs up to 48 W and above the 48 W the thermal Resistance of Acetone is increased slightly.
- The filling ratio is a critical parameter, which needs to be optimized to achieve maximum thermal performance and minimum thermal resistance for a given operating condition. From this experimental setup we are conclude that at 60% filling of PHP give the optimum result.

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