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Experimental Investigation on Thermal Performance of a Closed Loop Pulsating Heat Pipe without Fin and with Fin Structure

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Abstract Pulsating Heat Pipe (PHP) is a new and emerging cooling technique in the field of thermal management especially in microelectronics. To fulfill the increasing demand of power electronic applications, PHP is a proven technology which works on principle of self-oscillation of the working fluid and phase change heat transfer phenomenon in a capillary tube. In this paper, the thermal performance of a closed loop pulsating heat pipe (CLPHP) without fin and with fin at the condenser section by using Acetone and Water as working fluid has been investigated experimentally. The effects of different parameters include the filling ratios (from 40% to 70% in steps of 10%), the inclination angles (0°, 30°, 45°, and 60°), and at various heat input (10 to 10W in the steps of 10W) has been investigated thoroughly. In this study CLPHP is made from long capillary copper tube with inner diameter of 2.0 mm and outer diameter of 3.0 mm. The heat pipe is bent into eighth number of U-turns and divided into three sections, evaporator section (50 mm), adiabatic section (120 mm) and condenser section (80 mm). Adiabatic section is maintained by using aluminum foil surrounded by appropriate insulation. The result shows that, the thermal resistance decreases as heat input increases. But at low heat input i.e. up to 60W, the thermal resistance decreases rapidly and the PHP performance is more sensitive to the inclination angle whereas high heat input i.e. above 60W, the thermal resistance decreases slowly and comparatively less independent to the inclination angle. Evaporator dry out is occurred for acetone at low filling ratio with 40% and 50% at heat input 40W and 50 W respectively. CLPHP with fin structure shows better performance than the CHPHP without fin structure at high heat input. Acetone with 70% filling ratio and water with 50% filling ratio shows the best performance at 0° inclination angle for both structures.

Keywords: *PHP, CLPHP, working fluid, filling ratio, inclination angle, thermal resistance, fin structure and without fin structure.*

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1. Introduction

Advancement is taking place in thermo-fluid engineering due to increasing demand of smaller and effective heat transfer devices. This leads to the development of Pulsating Heat Pipe (PHP), which is a self-oscillating two-phase heat transfer device for handling moderate to high heat fluxes typically suited for cooling of electronic devices, power electronics, energy saving technology and other similar applications. Due to its excellent features, PHP has been considered as one of the promising technologies for electronic cooling, heat exchanger, etc.

PHP is a passive two-phase heat transfer device which is first introduced by G. F. Smyrnov and G. A. Savchenkov (USSR patent 504065) in 1971 [1]. This PHP was based on wickless system which able to operate against gravity and incorporated his invention in refrigeration systems. Although the fundamental aspect of a PHP is contained in their patent, the exploitation of the concept from an engineering point of view was done by H. Akachi in 1990 [2]. In this Patent, (US patent 4921041) he described twenty four different loop type heat pipes.

The PHPs can be generally classified into two major categories such as closed loop pulsating heat pipe (CLPHP) and open loop pulsating heat pipe (OLPHP). The performance of PHP has been widely investigated by scientists and engineers all over the world for its excellent features such as small volume, low fabricating cost, simple structure and high heat transfer performance. The performance of a PHP depends upon many factors like the geometrical parameters of flow channel, the working fluid, filling ratio, number of turns, inclination angle and PHP configurations [3,4].

Over the years, many experimental studies have been conducted to understand the mechanism of heat transfer characteristics in PHP and the factors affecting the performance of PHP. The most of the researchers have conducted experiment mainly focused on PHP with open loop [2,3,5,6,7], closed loop PHP with check valve [2,8,9,10,11] and closed loop PHP [2,6,7,12-19]. It has been shown by the previous studies that a CLPHP is thermally more advantageous than an OLPHP because of the possibility of fluid circulation. Although a certain number of check valves has shown to improve the performance, miniaturization of the device makes it difficult and expensive to install such valve. Therefore, a CLPHP without any check valve is most favorable from many practical aspects. The most of the previous experimental studies mainly focused on the factors affecting the performance of PHP like the effects of inner diameter, number of turns, working fluids, filling ratio, operational orientation, aspect ratio, heating mode, heat load and its limitation in the form of evaporator dry-out. To enhance the heat transfer characteristics in CLPHP, fins in the condenser section can be adopted and investigated. The purpose of the present study is to explore the insight physics of heat transfer mechanism, thermal performances of CLPHP through experimental investigation using fins at the condenser section.

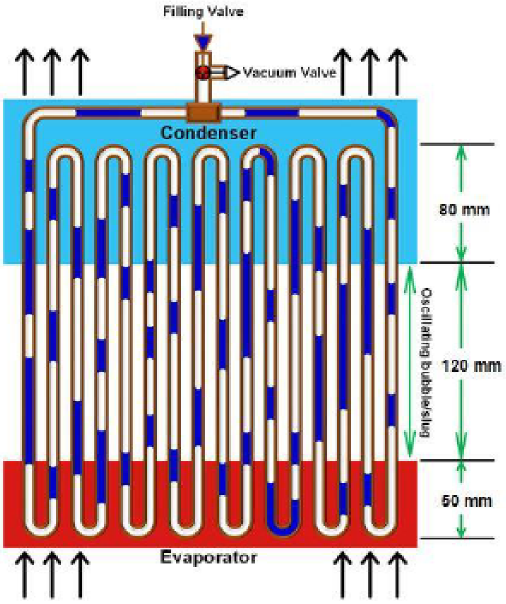

Figure 1. CLPHP without fin Structure

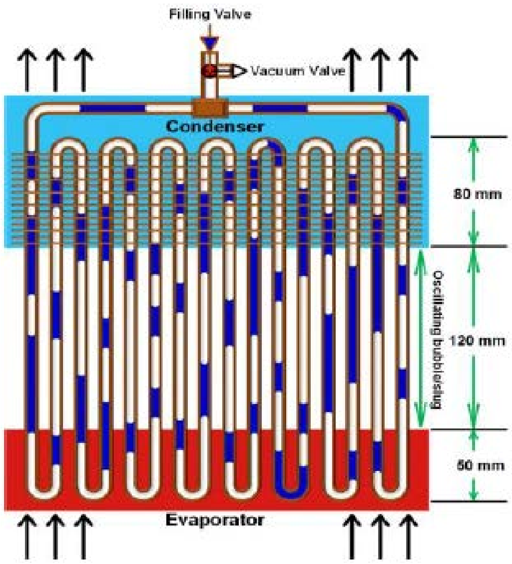

Figure 2. CLPHP with fin Structure

2. Experimental Setup

The schematic diagram of CLPHP without fin structure and with fin structure is illustrated in the Figure 1 and Figure 2 respectively. The CLPHP is made from long capillary copper tube with inner diameter of 2.0 mm and outer diameter of 3.0 mm. The pipe is bent into 08 numbers of U-turns and divided into three sections, evaporator section (50 mm), adiabatic section (120 mm) and condenser section (80 mm). Adiabatic section is maintained by using aluminum foil surrounded by appropriate insulation. The whole apparatus is set on a stainless steel and wooden frame with provision of angular movement of the CLPHP using servo motor. The overall experimental setup is shown in Figure 3. A power supply unit with voltage variac is used at the evaporator section through Ni-Chrome wire for heating the working fluids. As the copper tube is a good conductor of electricity, it is not directly connected with Ni-Chrome wire because it can cause short circuit. Ni-Chrome wire is surrounded to a mica sheet and kept at a constant distance from the copper tube. A DC cooling fan is used at the condenser section of CLPHP to enhance the cooling rate. The other accessories of the setup are adapter circuit, selector switches etc.

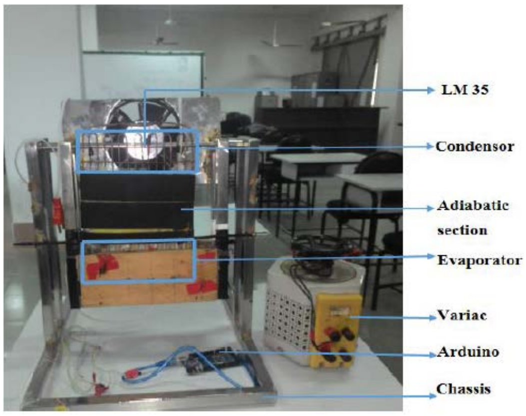

Figure 3. Experimental set-up

2.1. Experimental Procedure

The following procedure has been adopted during the experimentation and followed strictly throughout the entire period:

a. Before filling the working fluid, dry air is blown inside the heat pipe to ensure that there is no other fluid present inside the pipe.

b. CLPHP is filled with working fluid using a syringe for the required amount of filling ratios ranging from 40% to 70% in steps of 10%.

c. The required wattage is regulated by using the power supply unit and the heat load is varied from 10 W to 100 W in steps of 10W.

d. Experiment is conducted at the various inclination angles at 0^0 (from vertical), 30^0, 45^0 and 60^0 of CLPHP with Acetone and Water.

e. A digital thermometer and eight K-type thermocouples are used for measuring temperature. Four thermocouples are fixed in the evaporator section and four thermocouples in the condenser section which are covered by aluminum foil for proper temperature sensing. The thermocouples are calibrated using saturated steam and ice bath and verified with the standard calibration curve.

f. A data accusation system integrated with a computer is used for automatic data collection.

The accuracy level of MS 6514 digital thermometer and K-type Omega thermocouples is found ± (0.2%+0.5) and± .75% of the measured temperature respectively. All measurement uncertainties reported for a 95% confidence interval, uncertainty analysis was carried out based on the procedures of ANSI/ASME standard (ref.). The maximum uncertainty in the experimental results was found to be ± 2.26%.

3. Results and Discussion

Thermal performance in terms of thermal resistance and temperature difference between evaporator and condenser section of CLPHP has been investigated with different working fluids (acetone and water), filling ratios and inclination angles. The heat transfer characteristics with CLPHP fin structure have been studied and compared with CLPHP without fin structure. Thermal resistance (R) can be expressed as:

$$R = \frac{T_e - T_c}{Q} \quad (1)$$

Where, T_e and T_c being the average wall temperatures of the evaporator and condenser respectively and Q is the input power. The thermal performance of a CLPHP depends strongly on filling ratio, inclination angle and PHP configuration. The influences are illustrated in the subsequent sections.

3.1. Effect of Filling Ratio on Thermal Performance

(a) CLPHP without Fin Structure for Acetone:

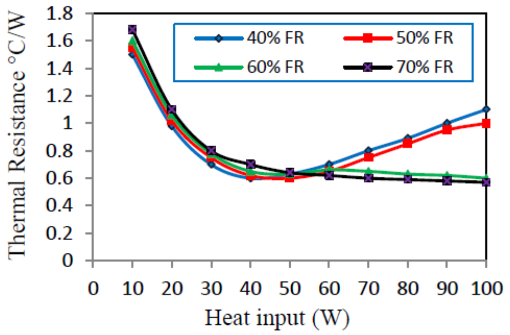

Figure 4. Variation of thermal resistance with heat input for different filling ratio at 0º inclination angle

(b) CLPHP without Fin Structure for Water:

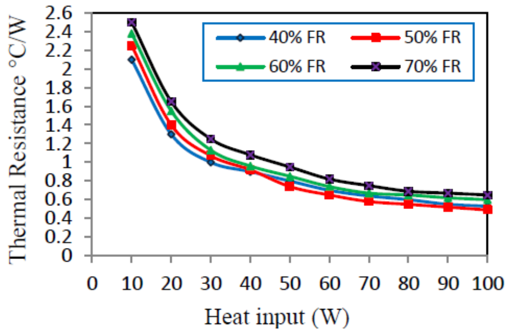

Figure 5. Variation of thermal resistance with heat input for different filling ratio at 0º inclination angle

Figure 4 and Figure 5 show the variation of thermal resistance with heat input with different working fluids at various filling ratios. From the figure it is observed that for Acetone the thermal resistance decreases with the increase in heat input at all filling ratios considered. Acetone with 70% filling ratio shows the lowest value of thermal resistance. Since the temperature difference between evaporator and condenser section is less at higher filling ratio of 70%, the magnitude of thermal resistance is less. On the other hand at lower filling ratios of 40% and 50% evaporator dry out is evident because there is not enough liquid inside the tube to perpetuate oscillating slug flow. As a to overcome the flow friction between the working fluid and the tube wall. Consequently, the rate of heat transferred decreases. Due to rapid increase in temperature difference between the evaporator section and the condenser section, the overall thermal resistance is increased. From the figure, it is also observed that for water with 50% filling ratio shows the best performance for both structures.

3.2. Effect of Inclination Angle on Thermal Performance

(a) CLPHP without Fin Structure with Acetone:

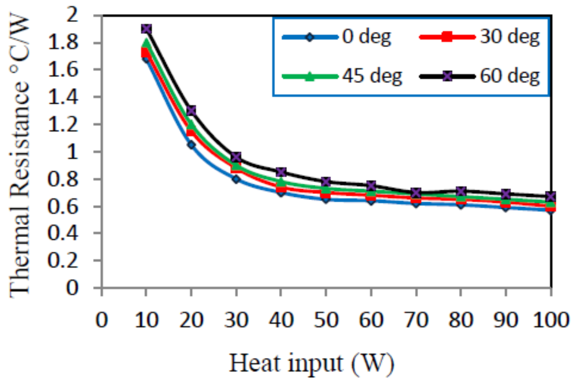

Figure 6. Variation of thermal resistance with heat input at different inclination angle with 70% filling ratio

(b) CLPHP without Fin Structure for Water:

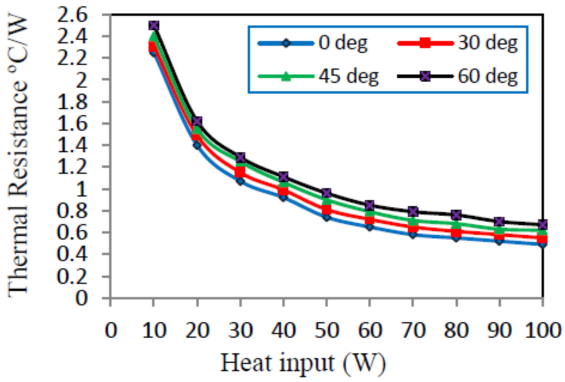

Figure 7. Variation of thermal resistance with heat input at different inclination angle with 50% filling ratio

Inclination angle has a significant role on the thermal performance of CLPHP. The effects of inclination angles have been analyzed through Figure 6 and Figure 7. The result shows that thermal resistance increases with the increase in inclination angles for both the working fluids and structures. With the increase of inclination angle, the working fluid is subjected to higher wetting angle. This affects the fluid in terms of lower capillary pressure difference and the gravitational force dominates over the surface tension force. This reduced capillary pressure difference is unable to push the liquid slug from evaporator section to condenser section. Consequently higher temperature difference between the evaporator and condenser section exhibits higher thermal resistance. For both the structures, Acetone with 70% filling ratio and Water with 50% filling ratio shows the best performance at 0º inclination angle.

3.3. Effect of Working Fluids

(a) With Fin Structure:

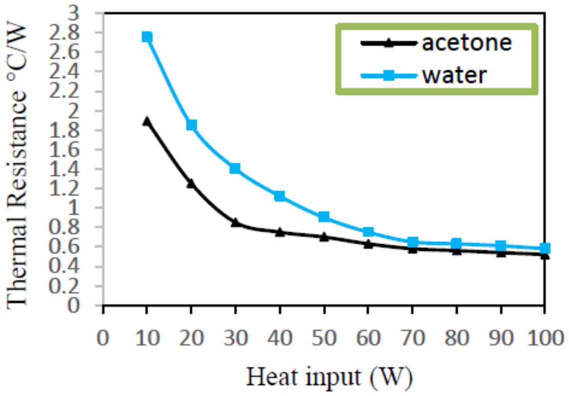

Figure 8. Variation of thermal resistance with heat input at 70% filling ratio and 0º inclination angle

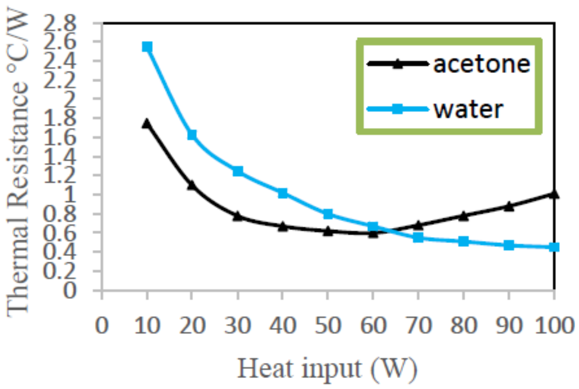

Figure 9. Variation of thermal resistance with heat input at 50% filling ratio and 0º inclination angle

(b) Without Fin structure:

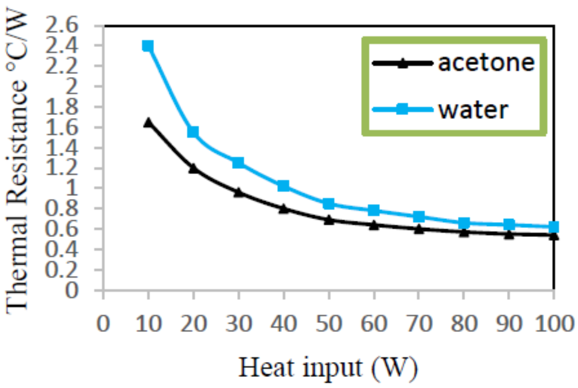

Figure 10. Variation of thermal resistance with heat input at 70% filling ratio and 0º inclination angle

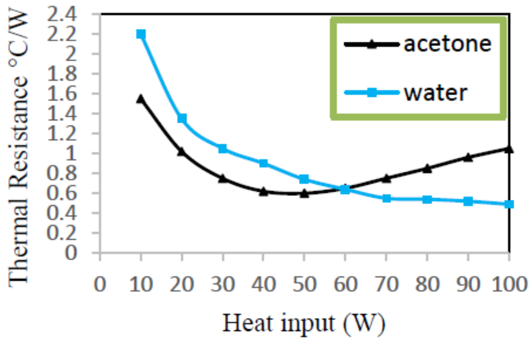

Figure 11. Variation of thermal resistance with heat input at 50% filling ratio and 0º inclination angle

The thermo physical properties of the working fluid coupled with the geometry of the device have profound implications on thermal performance of the device. Figure 8 to Figure 11 represents the variation of thermal resistance with heat input for different working fluids. The figures indicate that the thermal resistance decreases with the increase of heat input for both the working fluids. It is observed that Acetone exhibits lower value of thermal resistance compared to Water for both the structure with 70% filling ratio. The reason behind the statement can be explained as formation of enough bubble inside the capillary tube pumps the liquid slug from evaporator section to condenser section and reduce the temperature difference. It is seen that water shows lower value of thermal resistance with 50% filling ratio at high heat input compared to Acetone for both the structures. Water has a very high surface tension, a very low $(dP/dT)_{sat}$,a very high latent and specific heat and reasonably higher dynamic viscosity as compared to Acetone. Acetone shows the worst performance in the form of evaporator dry-out for both the structure with 40% and 50% filling ratio at all orientation considered.

3.4. Comparison of Structure

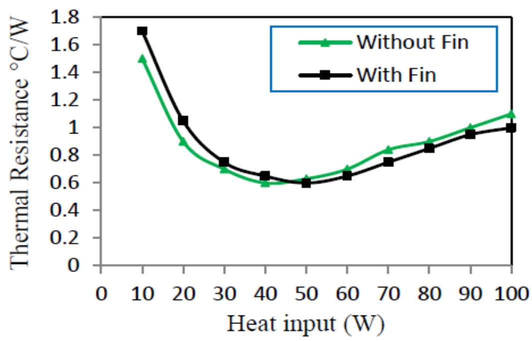

Figure 12. Variation of thermal resistance with heat input for different structures with acetone at 40% filling ratio and 0° inclination angle

The CLPHP with fin has a great influence on thermal performance over the CLPHP without fin, especially at high heat input. Figure 12 to Figure 14 shows the variation of thermal resistance with heat input for different structures. It is seen that CLPHP with fin structure shows the better thermal performance than CLPHP without fin structures. Both the structures exhibit evaporator dry out for Acetone with filling ratios of 40% and 50%. One significant observation is found that, for Acetone with fin structure, at lower filling ratios evaporator dry out occurs at higher heat input in comparison to structure without fin.

Due to incorporation of fin at the condenser section, enhanced heat transfer takes place and vapor bubble gets collapsed quickly. Liquid slug from condenser section moves rapidly to the evaporator to compensate for the liquid loss through vaporization. As a result the dry out situation occur a bit higher heat input. It is also seen that for lower heat input (≤ 60W) CLPHP without fin structure shows lower thermal resistance and at higher heat input (≥ 60W) CLPHP with fin structure shows the best performance for both working fluids. CLPHP with fin structure releases heat at the condenser section faster than CLPHP without fin structure. Consequently the temperature difference between the evaporator and condenser section drops quickly resulting the lower value of thermal resistance

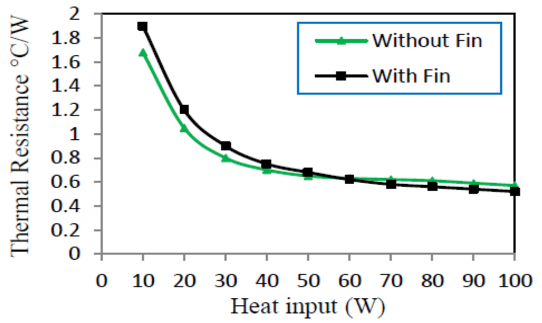

Figure 13. Variation of thermal resistance with heat input for different structures with acetone at 70% filling ratio and 0° inclination angle

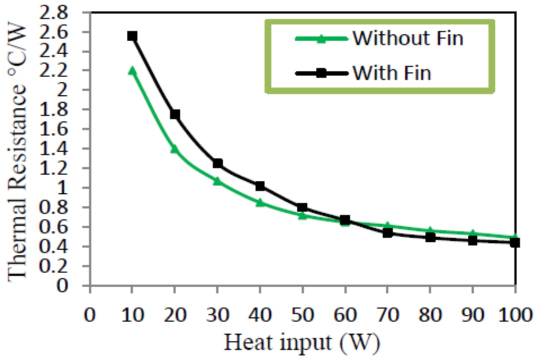

Figure 14. Variation of thermal resistance with heat input for different structures with acetone at 50% filling ratio and 0° inclination angle

3.5. Effect of Temperature Difference between Evaporator Section and Condenser Section with Heat Input

(a) CLPHP without Fin Structure for Acetone:

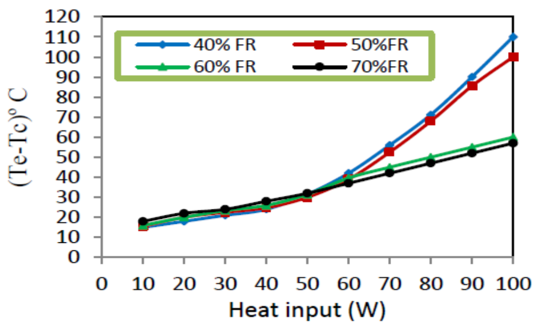

Figure 15. Variation of temperature difference between evaporator and condenser section with heat input for different working fluids at 0º inclination

(b) CLPHP with Fin Structure for Acetone:

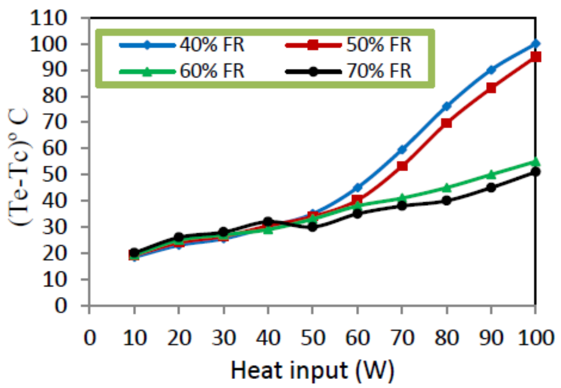

Figure 16. Variation of temperature difference between evaporator and condenser section with heat input for different working fluids at 0º inclination

(c) CLPHP without Fin Structure for Water:

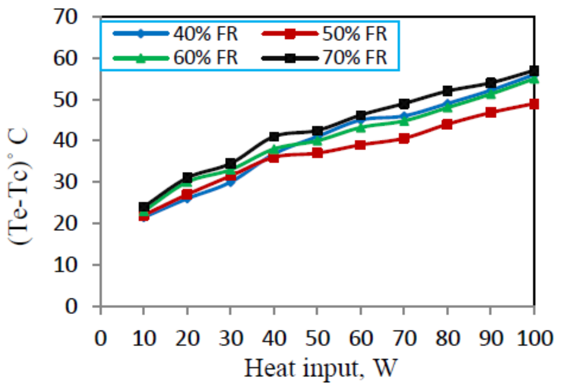

Figure 17. Variation of temperature difference between evaporator and condenser section with heat input for different working fluids at 0º inclination

(d) CLPHP with Fin Structure for Water:

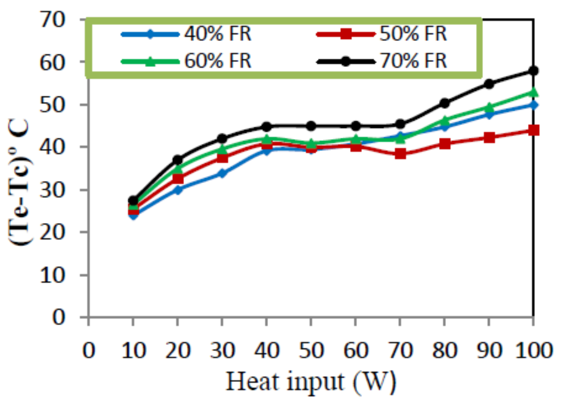

Figure 18. Variation of temperature difference between evaporator and condenser section with heat input for different working fluids at 0º inclination

Figure 15 to Figure 18 shows the variation of temperature difference between evaporator and condenser section with heat input. It is seen that the temperature difference between the evaporator and condenser section is less for Acetone with 70% filling ratio and for water with 50% filling ratio. The result is evident for both the structures at an inclination angle of 0°. CLPHP with fin structure shows the better performance than the structure without fin for both the working fluids with above mentioned filling ratio. Due to incorporation of fin at the condenser section heat transfer enhancement take place from both the section at high heat input. The temperature difference between evaporator and condenser section is found 52°C for Acetone with fin structure and 57°C without fin structure. On the other hand water with fin structure temperature difference is found 44°C and 49°C without fin structure.

4. Conclusion

The experimental investigation shows that heat input up to 60W, CLPHP without fin structure exhibits lower value of thermal resistance while heat input over 60W, CLPHP with fin structure exhibits the lower value of thermal resistance for both working fluids. At 0° inclination angle, Acetone with 70% filling ratio and water with 50% filling ratio shows lower value of temperature difference leading to lower value of thermal resistance for both the structures considered.

The temperature difference between evaporator and condenser section is found 52°C for Acetone with fin structure and 57°C without fin structure. On the other hand water with fin structure temperature difference is found 44°C and 49°C without fin structure. In 0° inclination angle, CLPHP without fin structure, the thermal resistances observed are 0.57°C/W and 0.49 °C/W for acetone and water respectively, while in case of CLPHP with fin structure the thermal resistances observed are 0.53°C/W and 0.44°C/W for acetone and water respectively. The result also shows that with the increase of inclination thermal resistance increases for both the working fluids and structures. Hence, the optimum filling ratio for acetone is 70% and water is 50% with an optimum inclination angle is found at 0º for both the structures.

Evaporator dry out is observed only for Acetone with 40% and 50% filling ratios for both the structures. CLPHP with fin structure experiences evaporator dry out at higher heat input than CLPHP without fin structure. CLPHP with fin structure shows the better thermal performance than CLPHP without fin structures at high heat input.

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