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Thermal Performance Analysis of a Closed Loop Pulsating Heat Pipe without Insert and with Insert

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***Abstract:** In this paper, thermal performance of a Closed Loop Pulsating Heat Pipe (CLPHP) without insert and with insert inside the tube has been investigated. The effect of different parameters like working fluid, the filling ratio, inclination angle and the input heat load on the thermal performance has been analyzed thoroughly. In this study, CLPHP is made from long capillary copper tubes with inner diameter of 2.0 mm and outer diameter of 3.0 mm. The heat pipe is bent into eight 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. An insert made of copper wire with diameter 0.5mm is used throughout the tube of all three sections. Methanol and Ethanol are used as working fluids with different filling ratio varied from 40% to 60% in steps of 10%. The thermal resistance has been investigated with different inclination angles (viz. 0°, 30°, 45° and 60° from vertical) at various heat input from 10 to 100W in the steps of 10W. The result shows that, the thermal resistance decreases as heat input increases. CLPHP with insert structure shows better performance than the CHPHP without insert structure particularly at 45°inclination angle. CLPHP without insert structure shows better performance than the CHPHP with insert structure at 0^0inclinations. Methanol with 40% filling ratio and Ethanol with 60% filling ratio shows the best performance at 0° inclination angle for CLPHP without insert structure. CLPHP with insert structure shows better performance than the CLPHP without insert structure at high heat input particularly at 45°inclination angle.*

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

I. INTRODUCTION

The pulsating heat pipe (PHP), referred to as self-excited oscillating heat pipe (OHP), was first introduced by G. F. Smyrnov and G. A. Savchenkov (USSR patent 504065) in 1971 [1]. This PHP was the first wickless system able to operate against gravity and made use of his inventions in refrigeration systems. Although the fundamental aspect of a PHP is contained in the USSR patent 504065, the exploitation of the concept from an engineering point of view was done in the early 1990s by a Japanese scholar, H. Akachi [2] – [3]. PHP is a passive 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.

A typical PHP is made of a long continuous capillary tube bent into many U turns. The inner diameter of the pipe must be sufficiently small so that it can ensure capillary flow. The theoretical maximum inner diameter for capillary flow (based on balance of capillary and gravity forces) is given by [4]:

$$D_{max} = 2\sqrt{\frac{\sigma}{g(\rho_{liq}-\rho_{vap})}} \quad (1)$$

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 configuration. The PHPs can be broadly classified into three major categories like open loop, closed loop and closed loop with check valve [4].

Since its invention in early 1990, limited 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] – [7], closed loop PHP with check valve [2], [8]– [11] and closed loop PHP [2], [6], [7], [12] – [19]. It has been shown by 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 have shown to improve the performance, miniaturization of the device makes it difficult and expensive to install such valve(s). Therefore, a CLPHP without any check valve(s) is most favorable from many practical aspects. The most of the previous experimental studies mainly focused 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 in PHP, insert inside the tube of all three sections can be investigated. The purpose of present study is to reveal the insight physics of heat transfer mechanism, thermal performances of CLPHP through experimental investigation using wire insert inside tube of all section.

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II. EXPERIMENTAL SETUP

The schematic diagram of CLPHP without insert structure and with insert structure is illustrated in the Fig.1 and Fig.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). An insert made of copper wire with diameter 0.5mm is used throughout the tube of all three sections. 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 Fig.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.

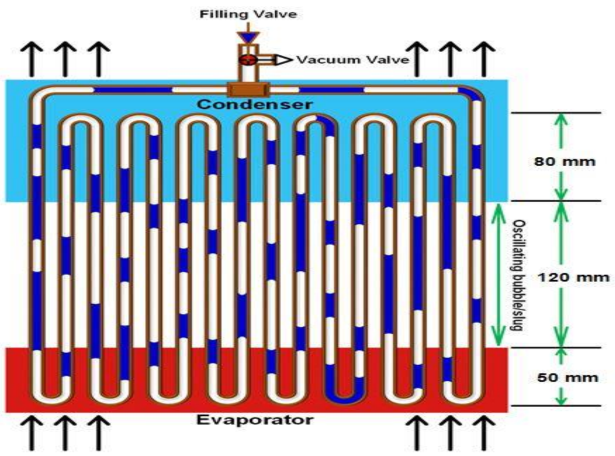

Fig. 1: CLPHP without insert structure

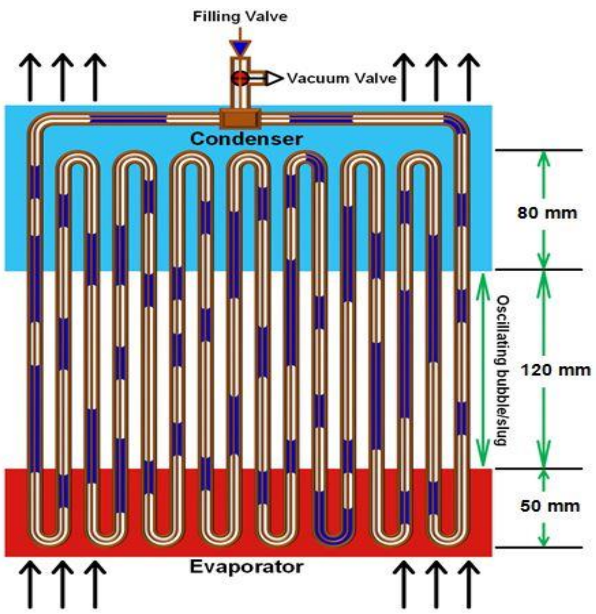

Fig. 2: CLPHP with insert structure

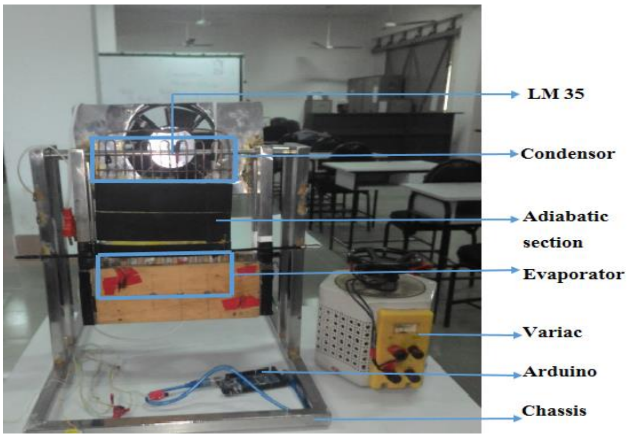

Fig. 3: Experimental setup

III. 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 methanol and ethanol.
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 ± 0.75% 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 [20]. The maximum uncertainty in the experimental results was found to be ± 2.26%.

IV. RESULTS AND DISCUSSION

Thermal performance in terms of thermal resistance has been investigated for ethanol and methanol with different filling ratios and inclination angles. The heat transfer characteristics with CLPHP insert structure have been studied and compared with CLPHP without insert in the tube. Thermal resistance (R) can be expressed as:

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

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.

A. Effect of Filling Ratio on Thermal Performance:

1) CLPHP without Insert Structure for Ethanol:

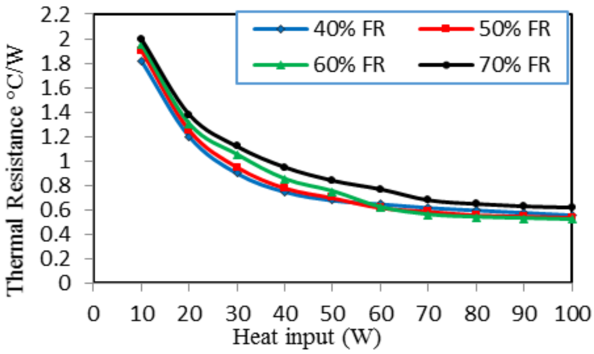

Fig. 4: Variation of thermal resistance with heat input for different filling ratio at 0º inclination angle

Fig.4 and Fig.5 shows the variation of thermal resistance with heat input for ethanol at various filling ratios with two different structures. From the figures it is observed that for ethanol the thermal resistance decreases with the increase in heat input up to 60% filling ratio. Ethanol with 60% filling ratio shows the lowest value of thermal resistance at 0^0 inclination angle without insert structure. Since the temperature difference between evaporator and condenser section is less at filling ratio of 60%, the magnitude of thermal resistance is less.

2) CLPHP with Insert Structure for Ethanol:

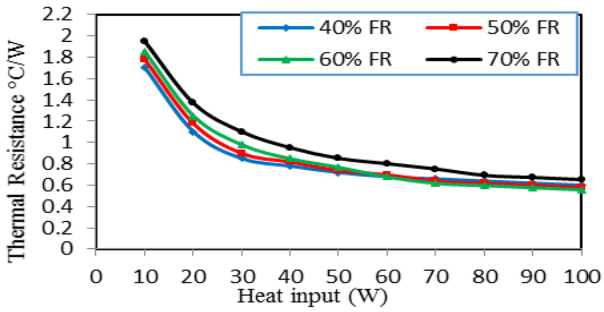

Fig. 5: Variation of thermal resistance with heat input for different filling ratio at 0º inclination angle

3) CLPHP without Insert Structure for Methanol:

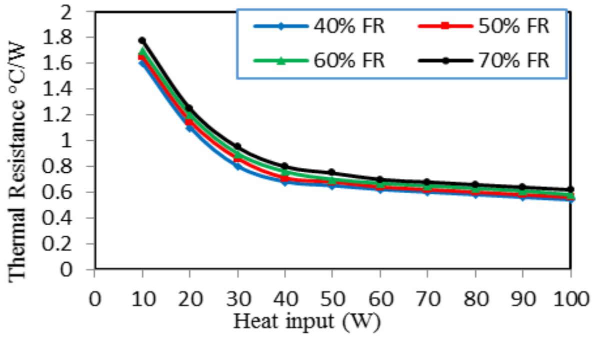

Fig. 6: Variation of thermal resistance with heat input for different filling ratio at 0º inclination angle

4) CLPHP with Insert Structure for Methanol:

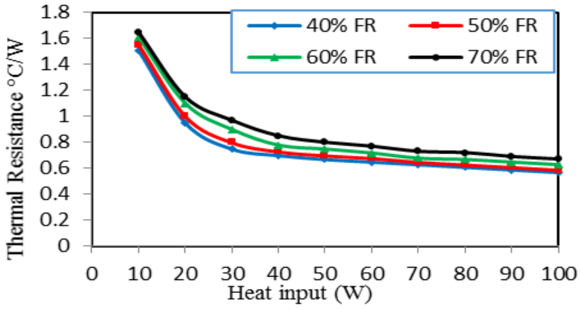

Fig. 7: Variation of thermal resistance with heat input for different filling ratio at 0º inclination angle

Fig. 6 and Fig. 7 show the variation of thermal resistance with heat input for methanol at various filling ratios with two different structures. It is observed that the thermal resistance increases with the increase in heat input for methanol at all filling ratios considered. Methanol with higher filling ratios, the bubble formation inside the tube is not adequate to pump the liquid slug from evaporator section to condenser section. As a result, temperature difference between the evaporator section and condenser section increase, so, the overall thermal resistance is increased. From the figures, it is observed that for methanol with 40% filling ratio shows the best performance for both structures.

B. Effect of Inclination Angle on Thermal Performance:

1) CLPHP without Insert Structure with Ethanol:

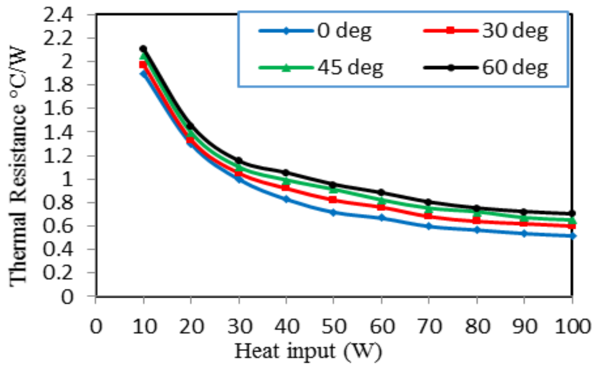

Fig. 8: Variation of thermal resistance with heat input at different inclination angle with 60% filling ratio

2) CLPHP with Insert Structure for ethanol:

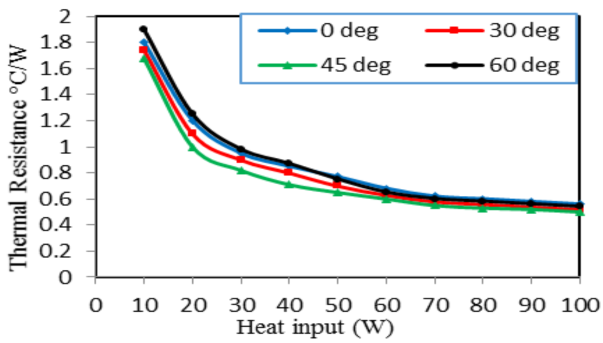

Fig. 9: Variation of thermal resistance with heat input at different inclination angle with 60% filling ratio

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3) CLPHP without Insert Structure for Methanol:

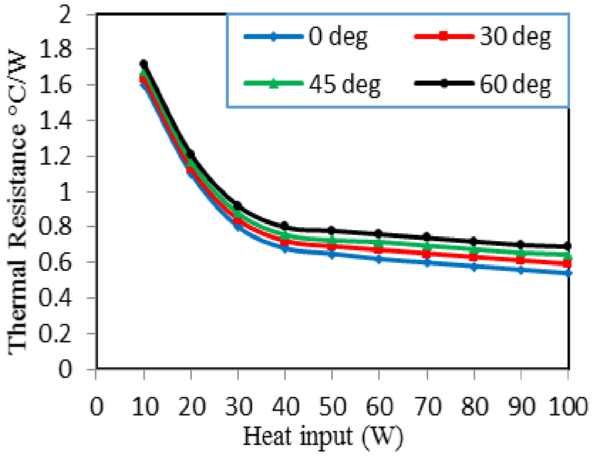

Fig. 10: Variation of thermal resistance with heat input at different inclination angle with 40% filling ratio

4) CLPHP with Insert Structure for Methanol:

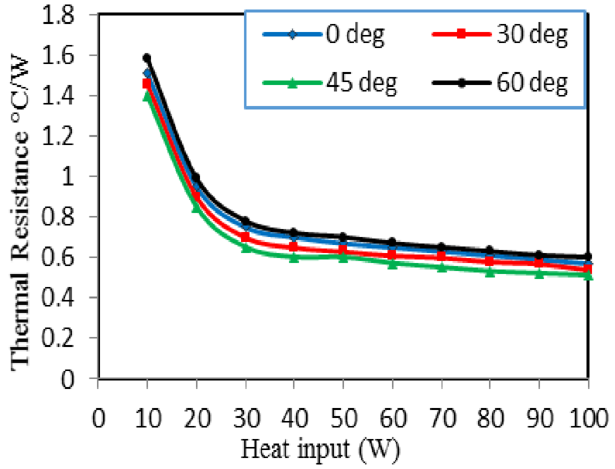

Fig. 11: Variation of thermal resistance with heat input at different inclination angle with 60% filling ratio

Inclination angle has a significant role on the thermal performance of CLPHP. The effect of inclination angle has been analyzed through Fig. 8 to Fig. 11. The result shows that the 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. Ethanol with 60% filling ratio and methanol with 40% filling ratio shows the best performance at 0° inclination angle. On the other hand CLPHP with insert structure shows that with increment of inclination angle the thermal resistance is decreases. The best performance for CLPHP with insert structure is observed at 45^0 inclination angle for both the working fluids.

C. Effect of Working Fluids:

1) Without Insert structure:

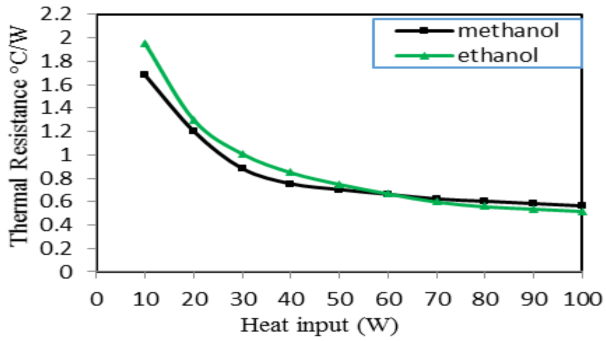

Fig.12: Variation of thermal resistance with heat input at 60% filling ratio and 0° inclination angle

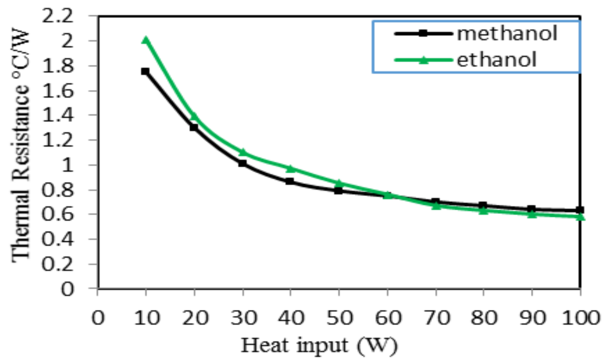

Fig.13: Variation of thermal resistance with heat input at 60% filling ratio and 45° inclination angle

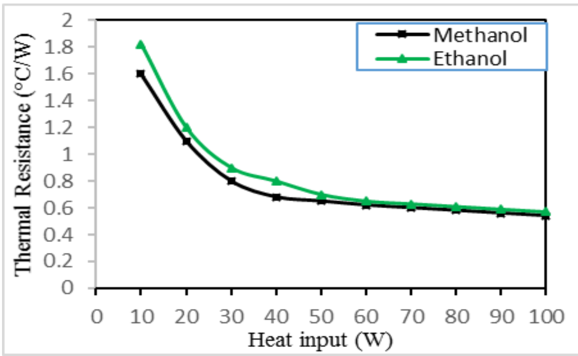

Fig. 14: Variation of thermal resistance with heat input at 40% filling ratio and 0 ° inclination angles

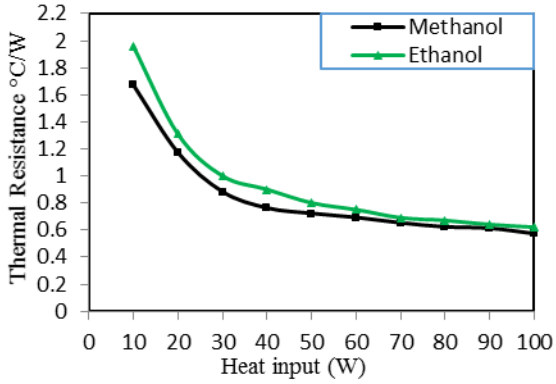

Fig. 15: Variation of thermal resistance with heat input at 40% filling ratio and 45 ° inclination angles

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2) With Insert Structure:

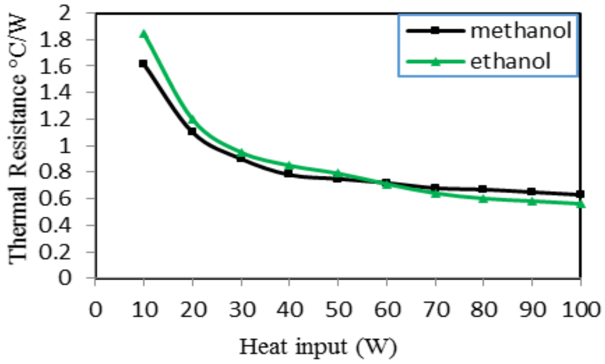

Fig. 16: Variation of thermal resistance with heat input at 60% filling ratio and 0 ° inclination angles

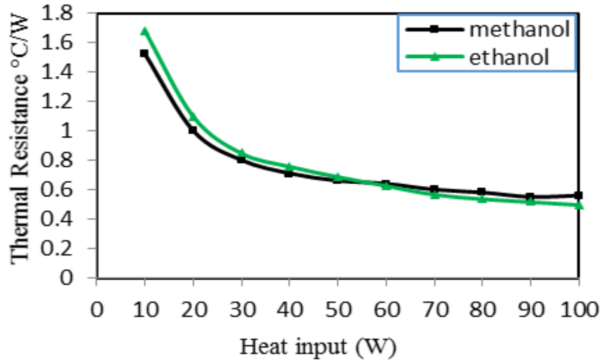

Fig. 17: Variation of thermal resistance with heat input at 60% filling ratio and 45 ° inclination angles

The thermo physical properties of the working fluid coupled with the geometry of the device have profound implications on thermal performance of CLPHP.

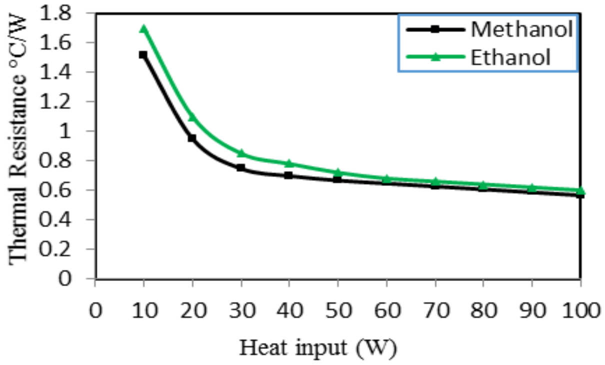

Fig. 18: Variation of thermal resistance with heat input at 40% filling ratio and 0 ° inclination angles

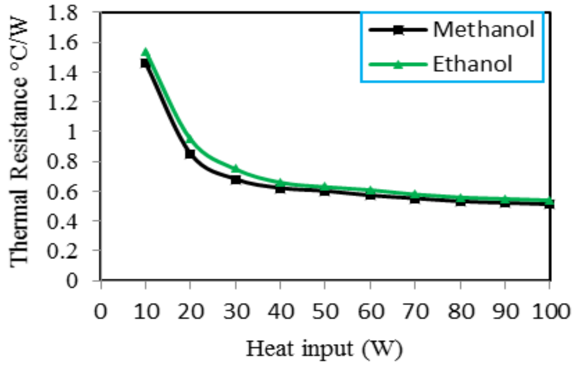

Fig. 19: Variation of thermal resistance with heat input at 40% filling ratio and 45 ° inclination angles

Fig. 12 to Fig. 19 represent the variation of thermal resistance with heat input for two working fluids. The fig.s indicate that the thermal resistance decreases with the increase of heat input for both the working fluids. It is observed that ethanol exhibits lower value of thermal resistance compared to methanol for both the structure at high heat input with 60% filling ratio. The reason behind the statement can be explained as there will be enough bubble formation inside the capillary tube to pumps the liquid slug from evaporator section to condenser section and reduce the temperature difference. It is seen that methanol shows lower value of thermal resistance with 40% filling ratio compared to ethanol for both the structures. Methanol has a low boiling point and a very high latent heat of evaporation as compared to ethanol. It is also seen that for lower heat input (≤ 60W) CLPHP with methanol shows better thermal performance for both structures and at higher heat input (≥ 60W) CLPHP with ethanol shows the best thermal performance at 60% filling ratio compared to methanol.

D. Comparison of Structure:

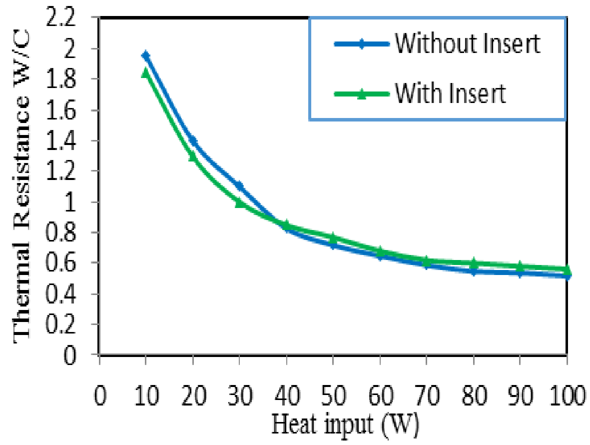

Fig. 20: Variation of thermal resistance with heat input for different structures with ethanol at 60% filling ratio and 0° inclination angle

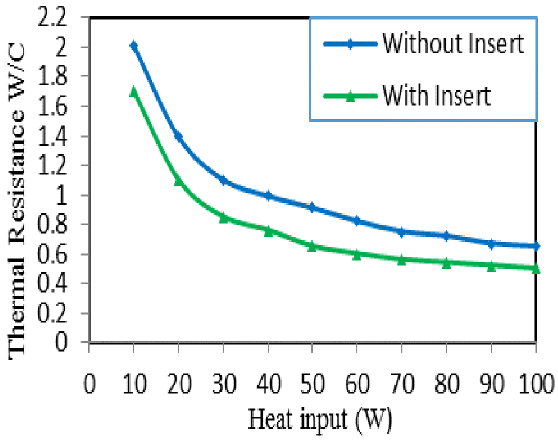

Fig. 21: Variation of thermal resistance with heat input for different structures with ethanol at 60% filling ratio and 45° inclination angle

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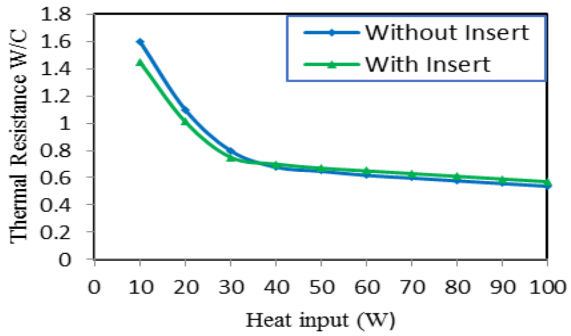

Fig. 22: Variation of thermal resistance with heat input for different structures with methanol at 40% filling ratio and 0° inclination angle

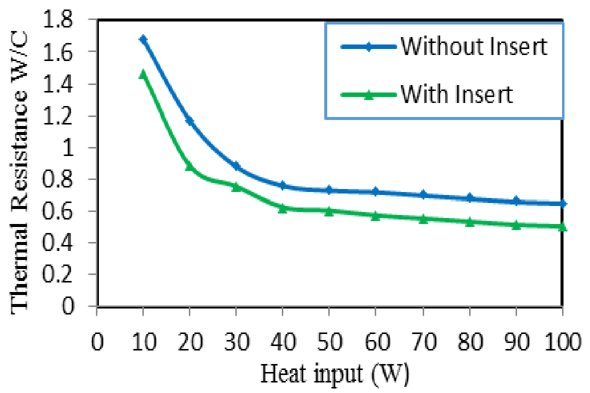

Fig. 23: Variation of thermal resistance with heat input for different structures with methanol at 40% filling ratio and 45° inclination angle

The CLPHP with insert has a great influence on thermal performance over the CLPHP without insert, particularly with the inclination angle. Fig. 20 to Fig. 23 show the variation of thermal resistance with heat input for different structures. It is seen that CLPHP without insert structure shows the better thermal performance than CLPHP with insert structures at 0º inclination angle. At 0º inclination angle surface tension force dominates over the gravitational force. But at 0º inclination angle, wire inserted structure shows the poor performance. Because at 0º inclination angle the inserted wire remains more or less at the center of the tube which creates additional shear resistance to flow. With the increase of inclination angle, thermal resistance is decreased particularly at 45° orientation and it offered the best performance. Due to the incorporation of wire insert inside the tube, hydraulic diameter of the tube is decreased.

As a result this reduced diameter will create sufficient capillary pressure to carry the liquid slug towards the condenser section. Moreover with the increment of inclination angle, the wire gradually gets attached with the tube wall due to the effect of gravity. When vapor plug gets collapsed at the condenser section, it returns to the evaporator section through the inserted wire due to the wick action.

V. CONCLUSION

It is observed that for ethanol, the thermal resistance decreases with the increase in heat input up to 60% filling ratio. On the other hand, the thermal resistance increases with the increase in heat input for methanol at all filling ratios considered. CLPHP without insert structure shows poor thermal performance with the increase of inclination angle whereas CLPHP with insert structure exhibits better thermal performance with the increase of inclination angle. The best performance is found at 45 inclination angle.

It is also seen that for lower heat input (≤ 60W) CLPHP with methanol shows better thermal performance for both structures at all filling ratios considered whereas at higher heat input (≥ 60W) CLPHP with ethanol shows the best performance at 60% filling ratio compared to methanol.

The experimental investigation shows that, CLPHP without insert structure exhibits lower value of thermal resistance for both the working fluid at 0º inclination angle whereas CLPHP with insert structure exhibits the lower value of thermal resistance for both working fluids at 45º inclination angle. At 0º inclination angle, Ethanol with 60% filling ratio and methanol with 40% filling ratio shows lower value of temperature difference leading to lower value of thermal resistance for both the structures considered.

At 0º inclination angle, CLPHP without insert structure, the thermal resistances observed are 0.52 °C/W for ethanol at 60% filling ratio and 0.54 °C/W for methanol at 40% filling ratio. While in case of CLPHP with insert structure the thermal resistances observed are 0.50 °C/W for ethanol at and 0.51 °C/W for methanol at 45º inclination angle in above mentioned filling ratios.

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