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Experimental study of inclination angle on an internally two-phase closed thermosyphon thermal behaviour

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ABSTRACT

This work studies the inclination angle effect on the two-phase closed thermosyphon (TPCT) with semicylindrical condenser internal fins. The finned thermosyphon thermal performance is studied at two different inclination angles 30^o and 60^o. Water is the working fluid for different filling ratios (FR) of 20, 50 and 80. The experiments are performed at different input power levels. The thermosyphon temperature is measured and both the heat transfer convection and condensation coefficients are calculated. In addition, the overall heat transfer coefficient is calculated and used as an indication of TPCT thermal performance. The lowest thermal resistance occurred at 50% FR at an inclination angle of 30^o. The results showed that, at 60^o inclination angle the average temperature of the thermosyphon is slightly lower than the 30^o. The thermal performance of the TPCT is superior at 80% FR for 60^0 inclination angle as it achieves the highest overall heat transfer coefficient at this condition. Based on the overall heat transfer coefficient values, The thermal performance of inclined TPCT is higher at inclination angle 60° compared to 30^o inclination angle.

1. Introduction

A thermosyphon is a device having a sealed tube inside which air is evacuated and a quantity of liquid is inserted. The tube is divided into three parts, the lower one is the evaporator while the upper one is nominated for the condenser and the third is the adiabatic one. The liquid in the evaporator is heated and vaporized vapor flows passing the adiabatic part to the condenser where it condenses, and condensate returns to the evaporator. Thermosyphons are superconductors because the temperature difference between the source and sink is minimal, and the distance between them is also relatively small, a large amount of heat can be transferred using these methods. Thermosyphon can transport very large quantities of heat with a small temperature difference depending on the latent heat. Thermosyphons and heat pipes have been used in a variety of engineering applications such as ventilation and air conditioning to recover waste heat energy and heating. Water heating systems, electronic cooling, nuclear reactors and heat exchangers. The TPCT is similar to some extent to the heat pipe. the TPCT is a wickless heat pipe. The main distinction between TPCT and the heat pipe is that the fluid in the heat pipe is returned to the evaporator in a different manner. while gravity operates in the thermosyphon, there is no restriction to the evaporator position in the heat pipe and it can operate in various orientations. The Thermosyphon evaporator must be at the lower part while in the heat pipe with wick no restriction for the

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evaporator position, it can be at the upper part.

Many researched have studied the different factors affecting the thermosyphon performance but to the best of the authors' knowledge, no researches have studied the inclination angle effect on internally finned thermosyphon. Kiatsiriroat et al, [1] studied the TPCT performance using different binary fluids TEG- Water and water-ethanol mixture. This study studied the various diameter effect, the mixture content and the working temperature. At a low heat source temperature, the ethanol-water mixture had a higher heat transfer rate than water and was comparable to pure ethanol., TEG in the mixture was discovered to increase the critical heat flux. PARK et al, [2] developed a TPCT with helical grooves on the inner surface of the thermosyphon FC-72 which is safe and more environmentally friendly than other traditional CFC refrigerants. The TPCT, mainly, consisted of three parts evaporator, adiabatic and condenser parts having lengths of 105,75 and 420mm their inner surfaces were helically grooved to enhance heat transfer while the adiabatic part was made of a ceramic tube to provide the thermosyphon with electric insulation between the evaporator and condenser parts. The average temperature of the evaporator portion, condenser and adiabatic portion at the steady state condition were determined and the heat transport rate was measured. Aniket, Ravindra [3] TPCT review focused on aspect ratio[AR], FR, heat load, mass flow rate and TPCT inclination, and also ultrasonic wave and resurfacing.

Aguiar et all, [4] Experimentally, studied TPCT with external circular fin. The condenser was cooled by air forced convection. It was found that using fins improves TPCT performance. Jouhara et al, [5]Experimentally investigated small thermosyphons made of copper. The thermosyphons were charged with four different working fluids water, FC-3283, FC-84, and FC-77. The choice of FC-3283, FC-84, and FC-77 is due to their wide range of thermophysical properties and being dielectric fluids. Water was tested for two different FRS one half filled and over filled but FC-3283, FC-84, and FC-77 were tested with the evaporator section overfilled only. The small diameter TPCT with different working fluids was compared with various available relations, for the water charged thermosyphon in the evaporator section the available expressions showed good predictions- thin film evaporation. Water was the best working fluid used for the power larger than 40 W but below 40W the other working fluids (Fluorinert liquids). liquidsFC-77 and FC-84 offer, nearly adequate, thermal performance.in addition to being dielectric which may be beneficial in some applications. Noie, [6] Experimentally investigated FR effect on TPCT performance, Input power and the length of the evaporator effect on the performance of the thermosyphon. The used working fluid was distilled water, the AR was held constant and the thermosyphon performance was investigated for filling ratios 30%, 60% and 90%. The AR was changed by changing the length of the evaporator (the heated part), the studied ARS were 7.45, 9.8, and 11.8 and the thermosyphon performance was studied at each AR for different FR. The applied power to the thermosyphon increased from 100W up to 900W. Noie et al,. [7] enhanced TPCT heat transfer by using Nanofluids of aqueous Al_2O_3 .Dube et al,.[8] theoretically and studied NCG effect on the loop thermosyphon heat exchanger performance, The optimum reservoir installing location to trap the non-condensable gases and minimize their adverse effect on the effectiveness.

Khazaee et al,[9] Studied the effect of input power, the coolant rate and the FR on TPCT geyser boiling. Naresh. Balaji. [10] Studied TPCT with internal rectangular fins; six internal rectangular fins were placed along the condenser portion. Fins were an integral part of the condenser; the thickness and the width of the fins were 1mm and 5mm respectively. Both acetone and water at three different FRS of 20, 50 and 80. It was found that the best performance occurs for 50% FR. TPCT thermal behavior improved by 17% as temperature reduction and by 35.48% as a reduction of thermal resistance at lower heat input. Naresh and,Balaji., [11]Studied TPCT with internal rectangular fins. R134a. TPCT with R134a was superior in comparison with the water charged thermosyphon. Emami et al,.[12] Studied FR, AR and the inclination angle on TPCT. The TPCT was tested for various inclination angles. The maximum TPCT thermal performance at 60° for all three ARS and several FRS.

Qian Xu et al, [13]Studied single and hybrid nanofluids in TPCT carbon tube. Goldoust et al. [14] Studied FR and evaporator section tilted angle on the thermal efficiency in a TPCT with the adiabatic and condenser sections in vertical positions. The thermosyphon was made of copper, distilled water at different FRS from 15% to 60%, Evaporator section (from the junction of an adiabatic section) is bent and compare with vertical positions. The optimum FR was found to be 45% while the best tilted angle of the evaporator section was found to be 600 from the horizontal axis at that angle the boiling heat transfer coefficient raised by about 15.2%. Kaya [15] Studied experimentally the performance of TPCT using working fluid containing CUO nanoparticles 1% and 2 %wt. The effects of cooling water flow rate, the type of the working fluid and the heat load were examined. The use of CUO/water nanofluid enhanced the TPCT performance.

Gedik [16] Experimentally used three different working fluids (ethylene glycol, water and ethanol.) for different operating conditions as the inclination angle, the cooling water flow rate and heat inputs. The TPCT temperature distribution and of the flowing water were measured. It was found that the efficiency of the thermosyphon varied between 30% and 95%, Results showed that the heat input and the inclination angle had a major effect on the performance of the thermosyphon and the best performance working fluid differed according to the heat input and the coolant flow rate, no working fluid was the best at all conditions. Abou-ziyan et al,[17] Studied TPCT at vibration and stationary condition.. Experiments were performed under different operating conditions of FR, length of the adiabatic part, input heat flux and vibration frequency. The vibration of the thermosyphon charged with R134a above the boiling limit enhanced by about 250% in comparison with the stationary state.

Based on the present exhaustive analysis of the literature, the effect of the inclination angle on the finned TPCT has not had enough interest from researchers. Therefore, the main objective of this research is to enhance the benefit of finned TPCT by studying its performance at different inclination angles. Also, this study is performed at different filling ratio.

2. Experimental setup

A TPCT with semi-circular internal fins is tested experimentally. The thermosyphon is made of copper. Working fluids used is (water). TPCT is tested at different FR, input powers, and inclination angles. A heating wire heat required for working fluid inside the evaporator. The cooling water was at room temperature. Thermocouples were used along the evaporator length to measure the evaporator, adiabatic, condenser, and coolant temperatures. The different parts forming this experiment are

- Thermosyphon and condenser jacket
- Evaporator heating system
- Condenser cooling system
- Charging and evacuating tools
- Measuring devices

Fig. 1 indicates the different parts of the test rig

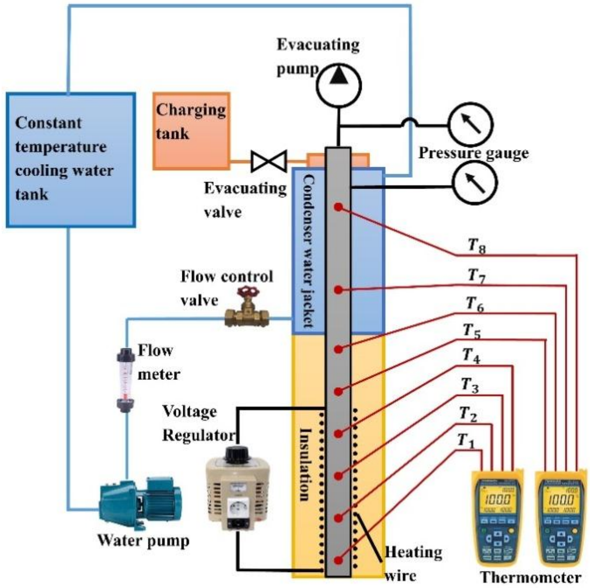

Fig. 1. test reg schematic.

3. Experimental procedure and calculation methodology

3.1. Pre-experiment Preparation.

A thermosyphon leakage test is performed before starting the thermal performance experiment. Air is supplied to the thermosyphon by an air compressor through the charging valve then the valves are closed and the thermosyphon valves are completely closed after that pressure up to 7 bar is stored inside the thermosyphon tube. The air is left inside the thermosyphon for 72 hours to make sure that no leakage occurs out of the thermosyphon. the pressure inside the tube is held constant and this makes sure that no leakage occurred. After that, the air is evacuated from the tube. Another leakage test is performed for the water jacket leakage of the flowing water by flowing water in the water jacket and noticing the water leakage by the naked eye. Leakage openings are closed by epoxy. The thermocouple connections and the power meter are examined before starting the tests. The coolant rate is set to the desired value and remained constant during the experiments.

3.2. Experiment Procedures

Heat is supplied to the finned TPCT by the heating wire and the temperature is measured at different positions where the thermocouples are installed. Coolant flows through the condenser jacket. the heat transferred to (water.) the working fluid causes the vapor to be formed, the vapor flows up to the condenser section passing through the adiabatic section. The coolant removes heat from the vapor and causes it to condense. the TPCT is set to different inclination angles 30^0, 60^0. the working fluid is also studied at 20, 50 and 80 FR.

3.3. Data reduction

The electric power is calculated from

$$= V \times I \qquad [W] \qquad (1)$$

P input power, V voltage difference, I electrical current.

The heat rate transferred to the cooling water is obtained by 1:

$$= \dot{m}_c\, C_p (T_{cwo} - T_{cwin}) \qquad [W] \qquad (2)$$

The average temperature at the evaporator section is calculated using

$$_{vge} = \frac{T_1 + T_2 + T_3 + T_4}{4} \qquad [^oC] \qquad (3)$$

Where T_1, T_2, T_3, T_4 the thermocouples which are fixed on the evaporator tube surface.

The average temperature at the adiabatic section

$$_{d} = \frac{T_5 + T_6}{2} \qquad [^oC] \qquad (4)$$

The average temperature at the condenser section Where T_5, T_6 the thermocouples which are fixed on the adiabatic section on thermosyphon tube.

$$_{vgc} = \frac{T_7 + T_8}{2} \qquad [^oC] \qquad (5)$$

Where T_7, T_8 the thermocouples which are fixed on the condenser section of the thermosyphon tube.

$$_{h} = \frac{\Delta T_{avg}}{\dot{Q}} \qquad [^oC/W] \qquad (6)$$

ΔT_{avg} is the average TPCT temperature difference between the TPCT evaporator and the condenser.

The heat transfer coefficient of the evaporator and condenser are calculated from

$$= \frac{\dot{Q}_c}{A_c \quad (T_{ad} - T_{avgc})} \qquad [W/m^2K] \qquad (7)$$

$$h_e = \frac{\dot{Q}_e}{A_e \quad (T_{avge} - T_{ad})} \qquad [W/m^2K] \qquad (8)$$

Where: T_{avge} is the average evaporator section wall temperature, and $\dot{Q}_e$ is the input heat power.

The overall heat transfer coefficient is calculated from

$$_t = \frac{1}{\frac{1}{h_e} + \frac{1}{h_c}} \qquad [W/m^2K] \qquad (9)$$

3.4. Measuring devices

The temperature at the wall of the thermosyphon is measured by eight T-type thermocouples fixed on the surface of the thermosyphon at the certain position showed in Fig. 2. The thermocouple temperature is measured using (TENMARS 747 DU) device. A voltage regulator is used to control the power input to the evaporator heating coil. The electrical current is measured by a digital clamp meter while the voltage is measured by a multimeter device. The water flow rate is measured by using an inline rotameter that measures the water flow rate.

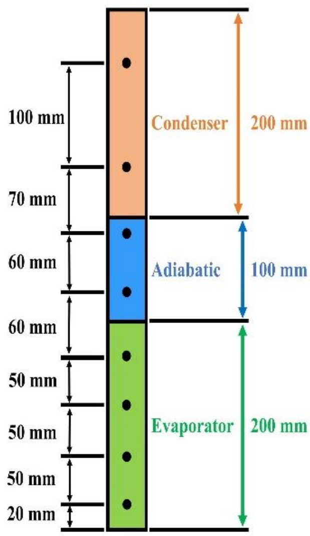

Fig. 2. Positions of thermocouples along the length of the thermosyphon.

3.5. Measurement uncertainty

The uncertainty analysis assesses the degree of correctness of measured values in experimental measurements. The measured temperature is ±0.1 accurate but the input power accuracy should be calculated. The accuracy of the input power is affected by the accuracy of both input voltage and current. The power uncertainty is calculated using Equation (10).

$$, = \pm\left[\left(\frac{\partial P}{\partial I}\sigma_I\right)^2 + \left(\frac{\partial P}{\partial V}\sigma_V\right)^2\right]^{1/2} \qquad (10)$$

where: σ_I is the electrical current uncertainty, and σ_V the voltage uncertainty. Table 1 indicates the uncertainty results.

Table 1: The uncertainty analysis results

Quantity	Uncertainty	Unit
Current	±0.01	A
Temperature	±0.1	℃
Voltage	±0.1	V
Power	±0.29	%

4. Experimental results and discussions

The thermal performance of the two-phase closed thermosyphon (TPCT), in which a semi-cylindrical shape fins are internally installed in the longitudinal direction with water flow, is investigated for various inclination angles, filling ratios (FR), and input power. Two inclination angles are studied 30^o and 60^o. The FR changes from 20%, 50%, and 80%. The input power varies from 100W to 250W. the input power is applied to the heating coil that allow the heat energy to be conducted through the TPCT external wall. After that, the heat can be transferred through wall to the flowing water. The pool water temperature rises up to the saturation temperature. Water at this point would boil and vapor will be generated. The water vapor flows up while losing heat energy to the cooling water and this get water to be condensed and then returns to the evaporator. The TPCT temperature is measured since the power is applied to the heat source. Measurements are recorded when the temperature is kept constant at each point (temperature variation does not exceed 0.1°C). The thermosyphon temperature is recorded at eight points for the three FRs mentioned.

4.1. 30^o TPCT Inclination angle effect

In this case, the thermosyphon is set inclined 30^o with the horizontal. The inclination angle is measured using the protractor. First, the working fluid FR is set to 20%. The TPCT performance is studied at different input power levels. Then the FR is changed to 50% and 80%. Figs. 3 – 5 illustrate the temperature variation at 30^o inclination angle varying with the input power levels for 20%, 50%, and 80% FR, respectively.

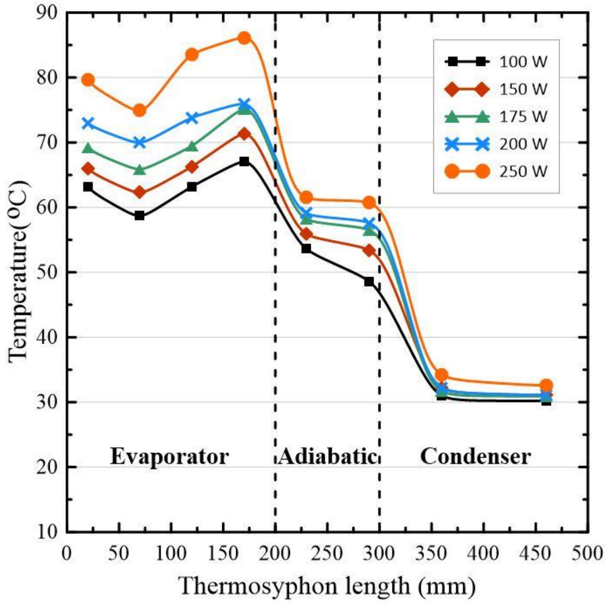

Fig. 3. Temperature variation along the thermosyphon length for 20% filling ratio at 30^o inclination angle.

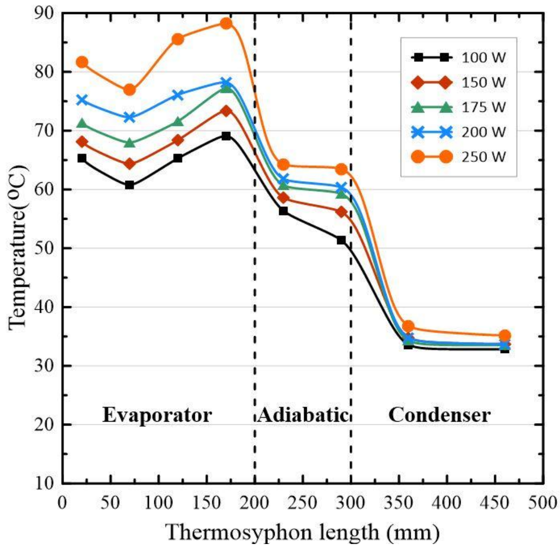

Fig. 4. Temperature variation along the thermosyphon length for 50% filling ratio at 30^o inclination angle.

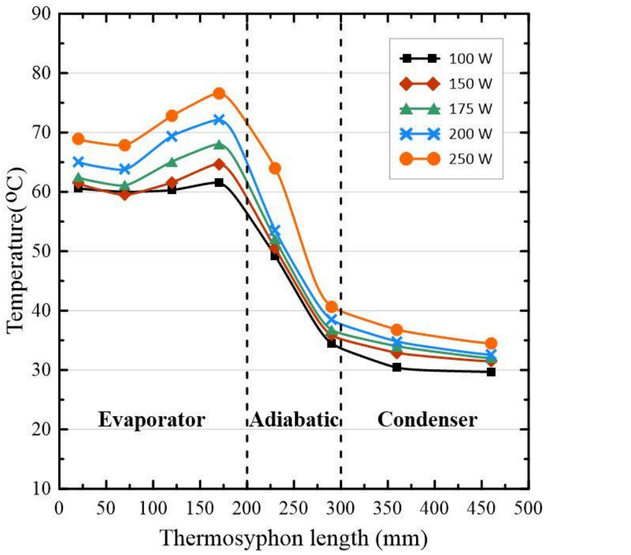

Fig. 5. Temperature variation along the thermosyphon length for 80% filling ratio at 30^{o} inclination angle.

It is clearly noticed from figures that, the input power has a high effect on the thermosyphones temperatures. As the input power increases, the thempreature of the thermosyphone increases. The temperature values vary along each section of thermosyphone. In the evaporator section, the temperature of T_1 and T_2 are alwayes lower than the other points T_3 and T_4 and this due to the flowing water neer the lower side of the evaporator section. For the adiabatic and the condenser sections, the temperature is almost constatnt along each section exept at the higher FR, the temperature drop is noticed in the adiabatic section. Figs. 6 – 8 illistrate the Average temperature of the thermosyphon at the evaporator, adiabatic and condenser sections at 30^{o} inclination angle. the average temperature of the thermosyphon decreases along its sections. The evaporator section has the highest temperature then the adiabatic section and the condenser section has the lowest average temperature.

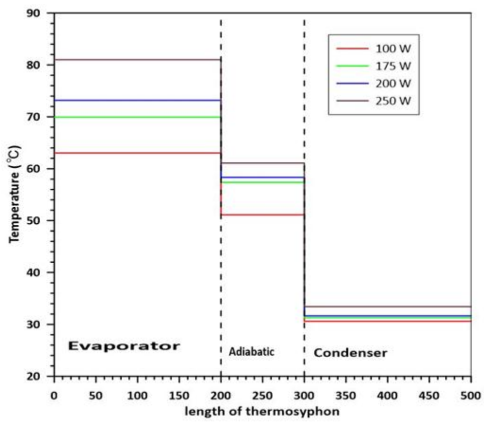

Fig. 6. Average temperature of TPCT for 20% filling ratio at 30^{o} inclination angle.

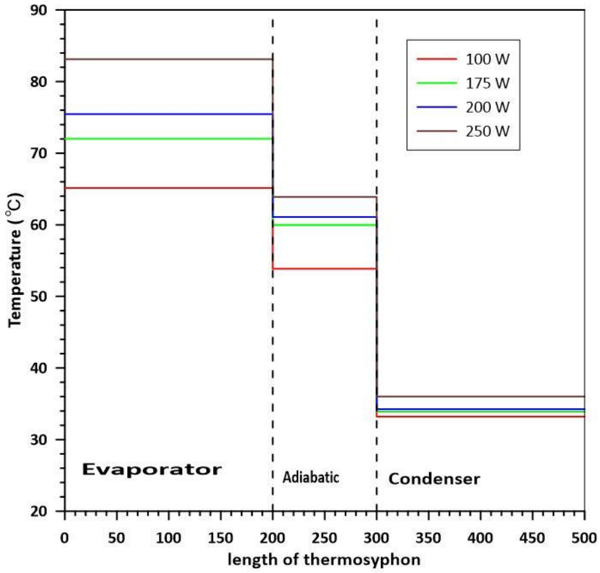

Fig. 7. Average temperature of TPCT for 50% filling ratio at 30o inclination angle.

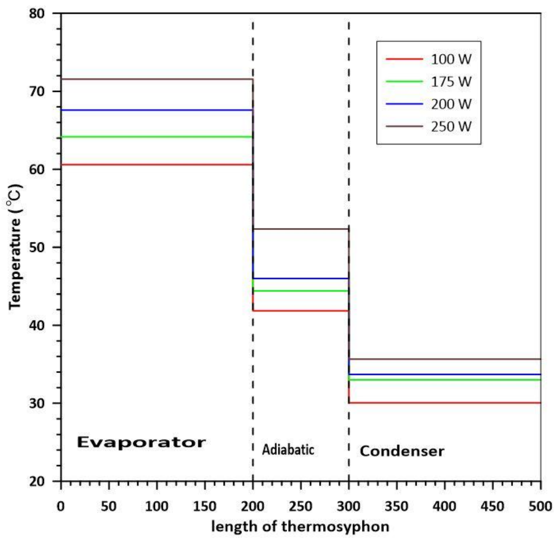

Fig. 8. Average temperature of TPCT for 80% filling ratio at 30o inclination angle.

Figs. 9 and 10 indicate the evaporation and condensation heat transfer coefficient at a 30^{o} inclination angle for different input power levels and different FR. The results at the 30^{o} inclination showed that the evaporation heat transfer coefficient is higher than the condensation heat transfer coefficient. The highest evaporation heat transfer coefficient occurred at 50% FR, however the highest condensation heat transfer coefficient occurred at the 80% FR. Fig. 11 illistrate the overall heat transfer coefficient at a 30° inclination angle varying with FR and input power. It is clearly noticed that the highest overall heat transfer coefficient occurred at 80% FR. This means that the best performance of the semi-circular internally fined TPCT occurred at a filling ratio of 80%.

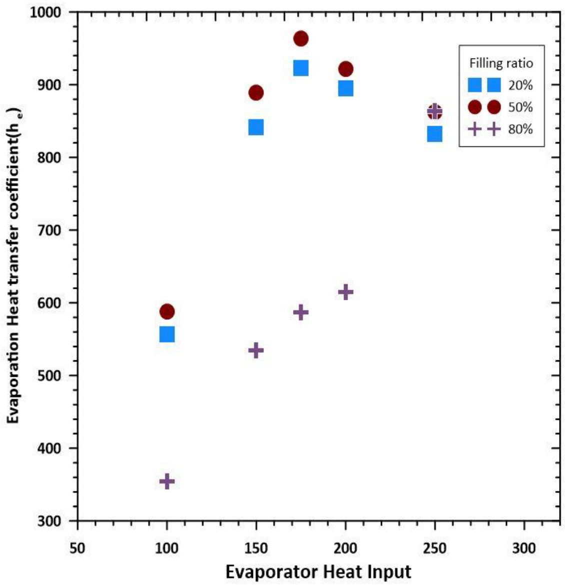

Fig. 9. Evaporation heat transfer coefficient for different evaporator input heat power levels at variable water filling ratio at 30o angle of inclination.

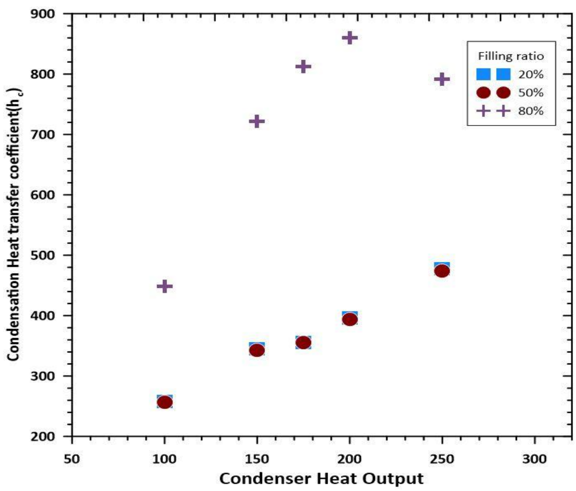

Fig. 10. Condensation heat transfer coefficient for different evaporator input heat power levels at variable water filling ratio at 30° angle of inclination.

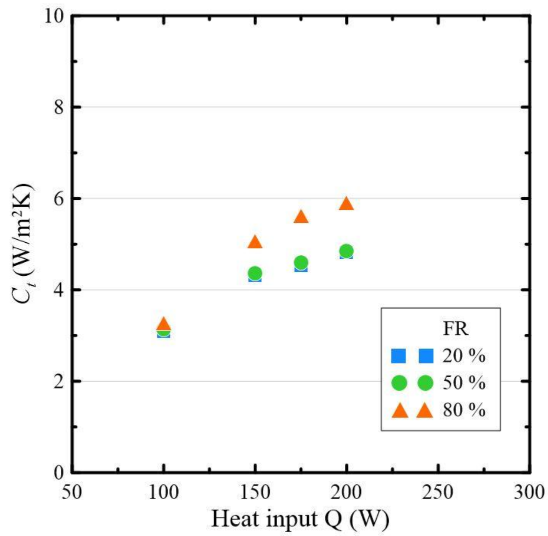

Fig. 11. Overall heat transfer coefficient at different input power for variable filling ratio at 30o inclinations

4.2. 60^0 TPCT Inclination angle effect

In this case, the thermosyphon is set inclined 60° measured from the horizontal axis. The TPCT performance is studied at different input power levels while the FR value changes as 20%, 50%, and 80%. Figs. 12 – 14 illustrate the temperature variation at 60° inclinations along the TPCT length. By comparing these figures with those in the 30° inclination angle case, it is clearly noticed that the temperature is slightly decrease when the inclination angle increase.

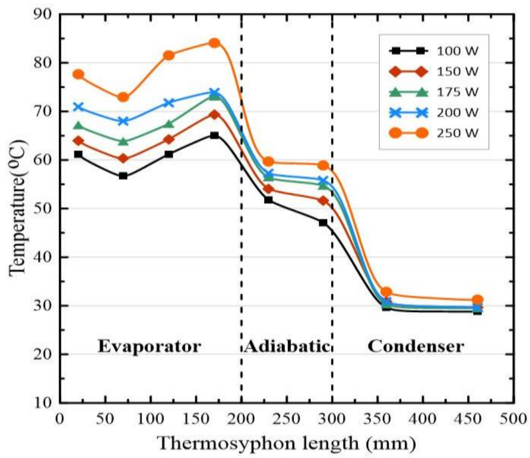

Fig. 12. Temperature variation along the thermosyphon length for 20% filling ratio at 60o inclination angle.

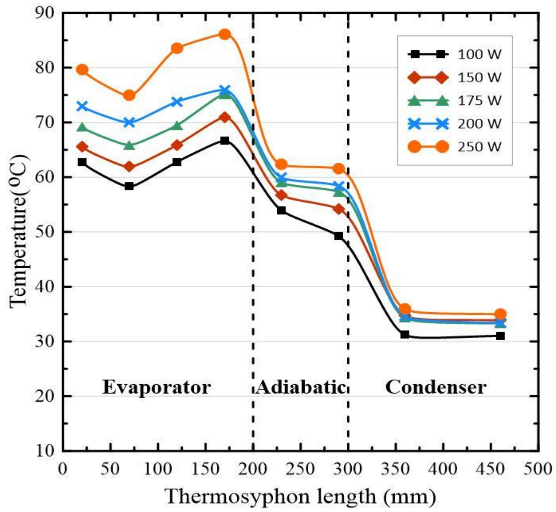

Fig.13. Temperature variation along the thermosyphon length for 50% filling ratio at 60o inclination angle.

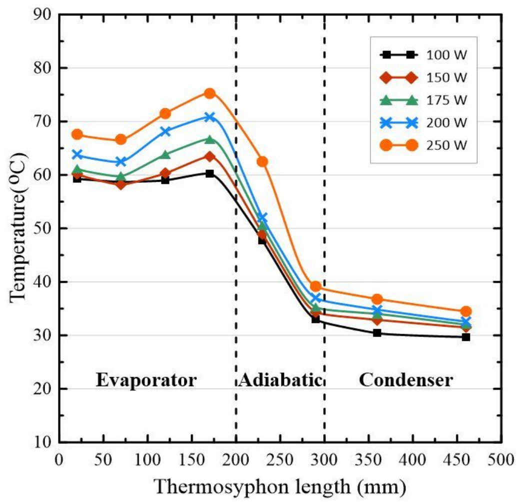

Fig. 14. Temperature variation along the thermosyphon length for 80% filling ratio at 60^{o} inclination angle.

Figs. 15 – 17 show the evaporation, condensation, and overall heat transfer coefficient at a 60o inclination angle for different input power levels and different FR, respectively. The results at the 60^{o} inclination showed that the highest evaporation heat transfer coefficient occurred at the FR of 50%, but the highest condensation heat transfer coefficient occurred at the 20 % FR. The highest overall heat transfer coefficient occurred at an 50% FR. The performance of TPCT with semi-circular internal fins is superior at the filling ratio of 80%. By comparing the TPCT performance for the two inclination angles, the overall heat transfer coefficient values is higher in case of 60^{o} inclination angle. Therefore, the best performance of TPCT occurs at the higher inclination angle (60^{o}).

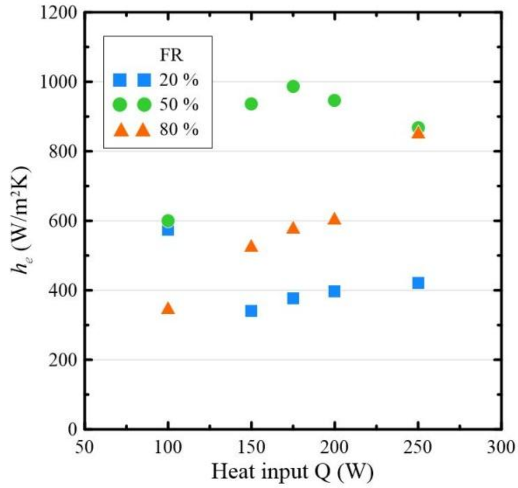

Fig. 15. Evaporation heat transfer coefficient for different evaporator input heat power levels at variable water filling ratio at 60o angle of inclination.

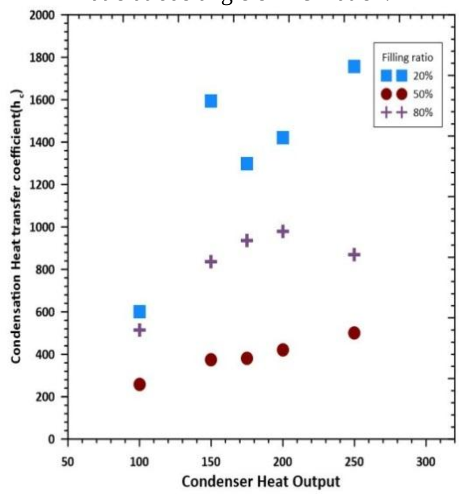

Fig. 16. Condensation heat transfer coefficient for different evaporator input heat power levels at variable water filling ratio at 60o angle of inclination.

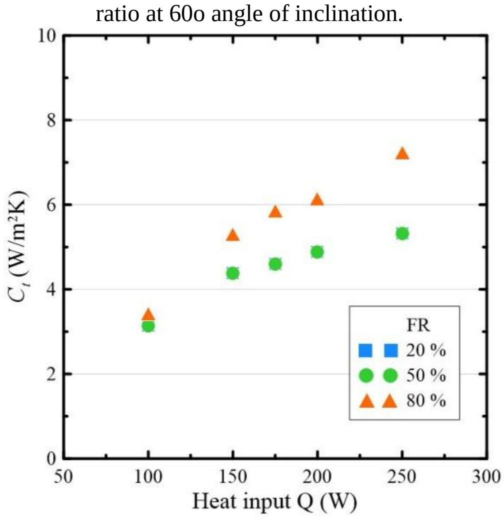

Fig. 17. Overall heat transfer coefficient at different input power for variable filling ratio at 60o inclinations

In order to clarify the different between the current study and other in literatures, a comparison was performed between the current finned TPCT and the non-finned cases from literatures. As presented in literature review, there is some researches studied the effect of inclination angles on the non-finned thermosyphon. It was found that the inclination angle had a major effect on the performance of the thermosyphon [12, 16]. According to Emami et al. [12], The maximum TPCT thermal performance at 60° for all three ARS and several FRS. In the present work, the inclination angle also had an effect on the internally finned TPCT performance. Based in the overall heat transfer values. in Figs. 11, and 17 the best performance of TPCT occurs at the 60^{o} inclination angle.

5. Conclusion

In this study, the thermal performance of the two-phase closed thermosyphon (TPCT), in which a semi-cylindrical shape fins are internally installed in water flow direction, is investigated for various inclination angles, filling ratios (FR), and input power. Two inclination angles are studied 30o and 60o. The studied FRs are 20%, 50%, and 80%. The input power varies from 100W to 250W. Following are the conclusions of this research:

1. As the input power increase, the temperature of TPCT wall increase in all TPCT sections.
2. The TPCT average temperature decreases along its sections. The evaporator section has the highest temperature then the adiabatic section and the condenser section has the lowest average temperature.
3. The evaporation heat transfer coefficient is higher than the condensation heat transfer coefficient.
4. The thermal performance of the TPCT is superior at 80% FR for 60^{0} inclination angle as it achieves the highest overall heat transfer coefficient at this condition.

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