Experimental Investigation of Optimum Inclination Angle for Two Phase Closed Thermosyphon (TPCT)

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Abstract : The effect of inclination on the performance of a non-anodized TPCT is investigated experimentally. Experiments have been conducted with Aluminium TPCT using Acetone as a working fluid. TPCT is tested at different heat inputs and inclination angles (with respect to horizontal). Heat inputs are 50W, 100W, 150W, 200W, 250W and 300W. Inclination angles are 30°, 40°, 50°, 60°, 70°, 80° and 90°. Counter current flow limit and boiling limit are 496 W and 335 W respectively. To investigate the optimum inclination angle for TPCT evaporator resistance, condenser resistance and total thermal resistance are calculated. It is found that total thermal resistance decreases as inclination angle increases at heat input 50W, 100W and 150W. On the other hand, at heat input above 200W the effect of inclination angle is negligible.

***IndexTerms* - Two Phase Closed Thermosyphon, inclination angle, acetone, working fluid**

I. INTRODUCTION

Two phase closed thermosyphon is a wickless and gravity assisted heat pipe which is oriented vertically with a liquid pool at the bottom. The evaporator section is located below the condenser section so that the condensate is returned by gravity. TPCTs made of material having good thermal conductivity and light weight are getting popular in the area of aerospace, telecommunication and electronic cooling. In aerospace applications, development of the next generation advanced TPCT has become imperative due to the increasing demand for “light weight” TPCT. Aluminium TPCTs are being widely used in these areas over the past few decades [1].

There are different combinations of working fluid and a tube material. Acetone suits the Aluminium [2]. Many researchers have been performed with Acetone as working fluid and Aluminium as a tube material to improve the thermal performance of thermosyphons. A cost-effective anodizing technique is used to create porous structure on the inner wall of TPCT with 100% filling ratio. Experimental results show that the thermal resistance and heat transfer coefficient of the evaporator of the TPCT are reduced and improved respectively by 15% due to anodizing on the inner wall [1]. The thermal performance of thermosyphon using Al_2O_3/water as working fluid was studied and found that the efficiency of the thermosyphon was enhanced up to 14.7% as compared to pure water [3]. TPCTs with different cross section are used to improve the performance of TPCT. The thermal performance of flat thermosyphon with and without anodized inner wall investigated experimentally. Experiments were conducted at different inclination angles (0°, 45°, 90°) for anodized and non-anodized flat thermosyphons [4]. M. Rahimi et. al. studied the effect of evaporator and condenser resurfacing on overall performance of a closed two-phase thermosyphon. 75% fill ratio was used with water as a working fluid. Results shown the increase in the thermal performance by 15.27% and decrease in thermal resistance by 2.35 times as compared to the plain one [5].

Many researchers used nanofluids into the TPCTs and found considerable enhancement in the thermal performance of TPCT. The performance of open type thermosyphons was studied using CNT/water nanofluids [6]. An experiment was carried out to study the thermal performance of an open type thermosyphon with CuO/water nanofluid [7]. A TPCT was analyzed with pure water and various water based nanofluids by Khandekar et. al. [8]. A. B. Solomon et. al. [9] studied and compared the heat transfer of a TPCT with a thin, porous copper coating with an uncoated TPCT. Heat transfer coefficient of an evaporator is enhanced up to 44%.

A superhydrophilic evaporator and slippery lubricant-infused porous surface condenser is used to investigate the effect of filling ratio on the heat transfer performance of a novel two-phase closed thermosyphon. It is found that different evaporation mechanism takes place depending on filling ratio and has a strong impact on the overall heat transfer performance. At the filling ration 25% and also filling ratios of 40% and 70% at low heat flux, film evaporation plays a vital role. Filling ratio of 40% shows the best heat transfer performance [10]. An experimental investigation has been conducted to study the heat transfer performance of a stainless steel TPCT. Water, ethanol and acetone were used as a working fluid. Three filling conditions were used such as under-filled, overfilled and optimally filled [11]. The effect of evaporator wettability and filling ratio on heat transfer performance of a thermosyphon is studied by Zhi Xu et. al. [12]. S. H. Noie et. al. investigated experimentally the effect of the inclination angle on the thermal performance of a TPCT with different filling ratios under normal operating conditions. The distilled water was used as working fluid [13].

Some studies shows the numerical simulations of the two-phase closed thermosyphon for performance optimization. S. Fertahi et. al. built a comprehensive CFD modelling to reproduce the liquid condensation in a closed thermosyphon and the pool boiling in the evaporator section. The CFD model was validated using experimental results [14]. Limin Ma et. al. established a transient simulation model for a TPCT using SINDA/FLUINT with R234fa as working fluid [15].

Based on the available literature, an experiment has been conducted to determine the optimum inclination angle for a two-phase closed thermosyphon using acetone as working fluid. In the present investigation, the experiments have been conducted for filling ratio of 60%. This filling ratio was chosen in order to avoid dry-out phenomena in the experiments.

II. EXPERIMENTAL STUDY

Experimental setup and details

The experimental setup consists of a TPCT, 4 resistance heaters (each of 100W) connected in parallel, RTD (PT100), temperature indicator, heat input unit and condenser and evaporator block. TPCT is made of Aluminium. The total length of the TPCT is 350 mm. The evaporator and condenser section is of 100 mm and condenser section is of 150 mm. The inner diameter and thickness of the TPCT is of 17.05 mm and 1 mm respectively. Acetone is used as a working fluid as it is compatible with Aluminium. The heat input unit consists of resistance heater, ammeter, voltmeter, variable transformer. It is used to heat the evaporator of TPCT in a controlled manner. RTDs (PT100) are used to measure the temperature at different heights of the TPCT and inlet outlet temperatures of the cooling water. An adiabatic section is insulated by using glass wool to avoid heat loss.

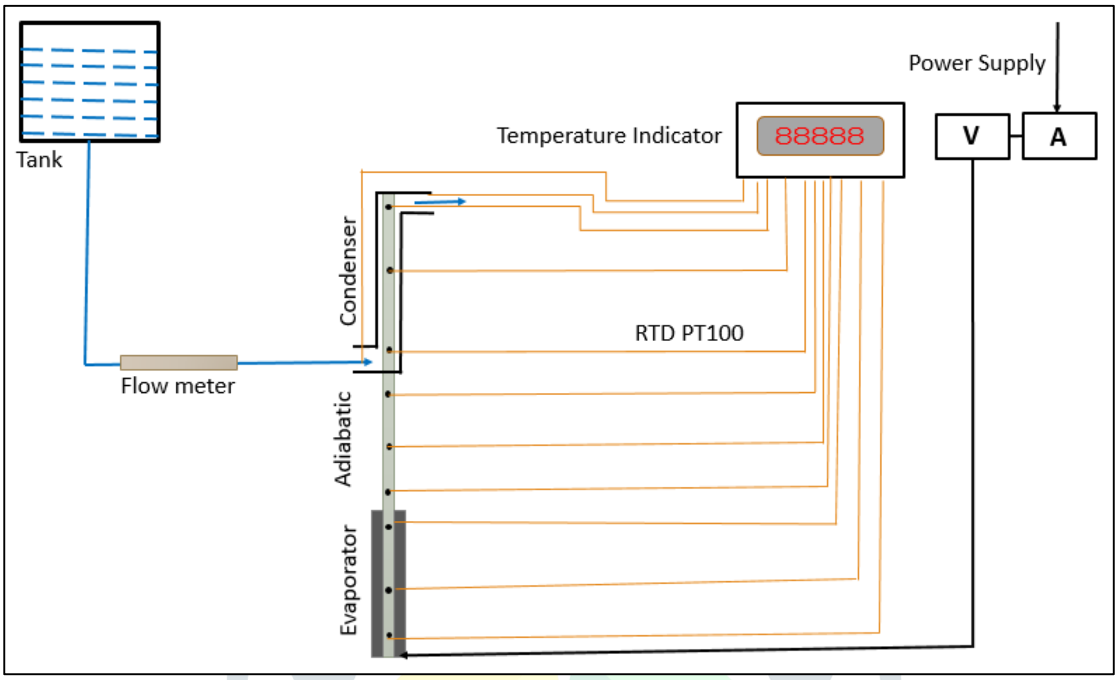


Figure 1 Schematic of Experimental Setup

The flow rate of the cooling water is maintained at 30 LPH. It is chosen to have a temperature difference of 1°C to 7°C. The accuracy of the PT100 RTD is ±0.1°C. To investigate the performance of TPCT different experiments were conducted. Heat input ranges from 50W to 300W with an increment of 50W for inclination angles of 90° to 30° (w. r. t. horizontal) with an increment of 10°.

Operational limits of TPCT

The TPCT is having different constraints such as entrainment or counter current flow (CCFL) and boiling limitations (BL). The most important are counter current flow, dryout and boiling limitations. The dry out limit is calculated to find out the minimum volume of acetone in the TPCT. The boiling limitations and counter current flow for the non-anodized TPCT is calculated using Eqs. 1 and 3 respectively.

$$Q_{max} = A_{rad} 0.16 \left[1 - exp\left\{\left(\frac{-d}{l_e}\right)\left(\frac{\rho_l}{\rho_v}\right)^{0.13}\right\}\right]\left(h_{fg}\rho_v^{0.5}[g\sigma(\rho_l - \rho_v)]^{1/4}\right) \qquad (1)$$

Where,

$$A_{rad} = \pi d l_e \qquad (2)$$

This correlation is proposed by Faghri [2].

A correlation proposed by Imura et. al. is used to calculate the boiling limit of the heat pipe.

$$Q_{max} = A_{axi} \frac{\left(\frac{\rho_l}{\rho_v}\right)^{0.14} tanh^2\, Bo^{1/4}}{\left[1+\left(\frac{\rho_l}{\rho_v}\right)^{1/4}\right]^2}\left(h_{fg}\rho_v^{0.5}[g\sigma(\rho_l - \rho_v)]^{1/4}\right) \qquad (3)$$

Where,

$$A_{axi} = \frac{\pi d^2}{4} \qquad (4)$$

And

$$Bo = d[g(\rho_l - \rho_v)/\sigma]^{1/2} \qquad (5)$$

The following figure 2 shows the maximum allowable heat input that can be supplied to operate TPCT without boiling limitations and counter current flow limitations.

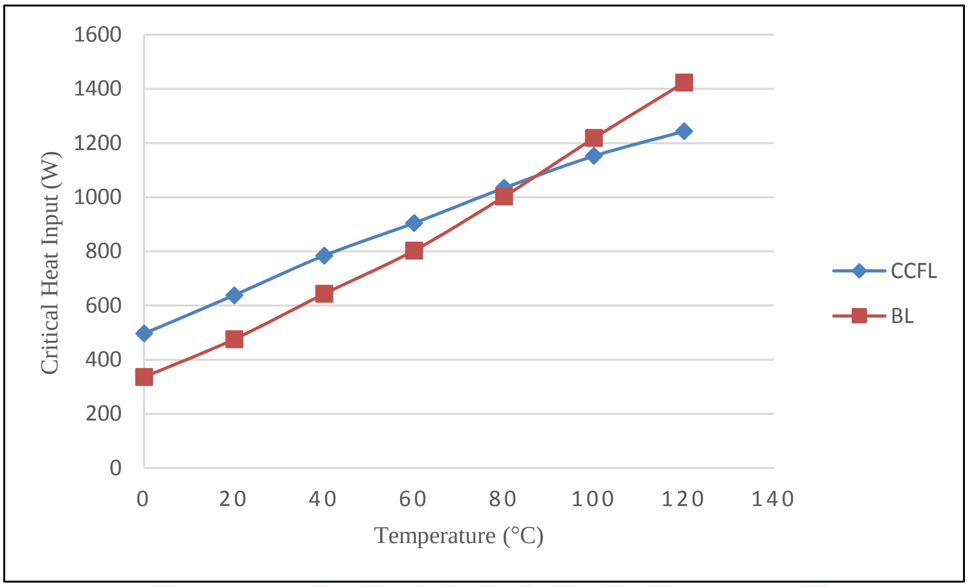


Figure 2 Operational limits of TPCT

III. RESULTS AND DISCUSSION

To investigate the optimum inclination angle for the TPCT, heat transferred by the TPCT, thermal resistance at condenser (Rc) and evaporator (Re) sections and the total thermal resistance is calculated. The heat transfer coefficients at evaporator (he) and condenser (hc) section are also calculated. Heat balance equation is used to calculate heat transferred by the TPCT.

$$Q_{out} = \dot{m}_w c_{p,w}(T_{out} - T_{in}) \qquad (6)$$

The thermal resistance at the condenser and evaporator section is calculated by using Eqs. (7) and (8)

$$R_c = \frac{\Delta T_c}{\dot{Q}_{out}} \qquad (7)$$

$$R_e = \frac{\Delta T_e}{\dot{Q}_{in}} \qquad (8)$$

Where, $\Delta T_c = T_v - T_c$ and $\Delta T_e = T_e - T_v$

The total resistance of the TPCT is calculated by using following equation,

$$R_T = \frac{\Delta T}{\dot{Q}_{out}} \qquad (9)$$

Where, $\Delta T = T_e - T_c$

Heat transfer coefficient at evaporator and condenser end is calculated by using following Eqs. (10) and (11),

$$h_e = \frac{q_e}{T_{e,i} - T_{sat}} \qquad (10)$$

Where, $q_e = \frac{Q_{in}}{\pi d l_e}$

$$h_c = \frac{q_e}{T_{sat} - T_{c,i}} \qquad (11)$$

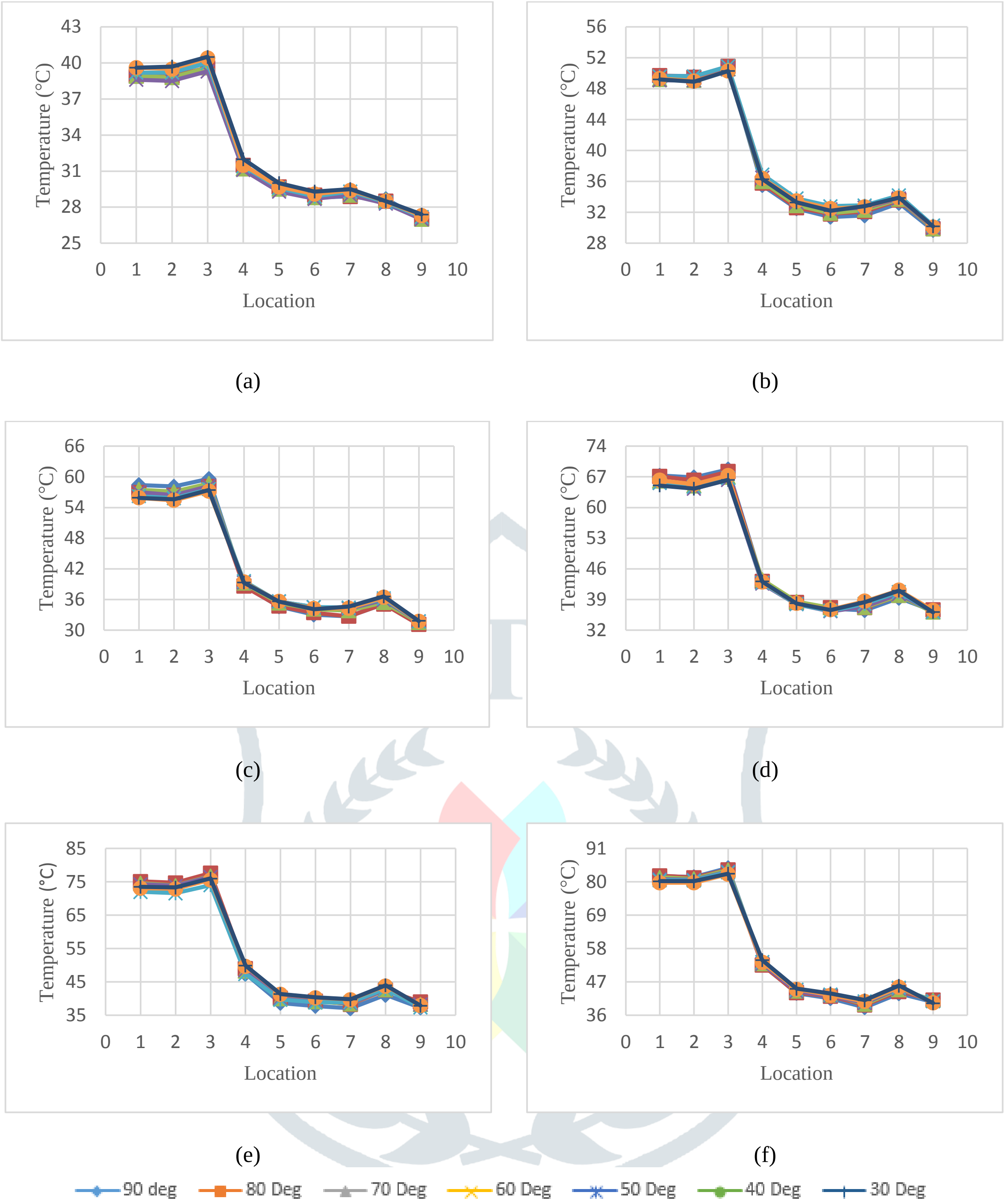
Where, $q_c = \frac{Q_{out}}{\pi d l_c}$

The inner wall temperatures of the evaporator and condenser are obtained from Eqs. (12) and (13) respectively.

$$T_{e,i} = T_e + \frac{q r_o}{k} \ln\left(\frac{r_i}{r_o}\right) \qquad (12)$$

$$T_{c,i} = T_c + \frac{q r_o}{k} \ln\left(\frac{r_o}{r_i}\right) \qquad (13)$$

A vapor temperature of the working fluid is the average temperature of the adiabatic section.



(a) (b)

(c) (d)

(e) (f)

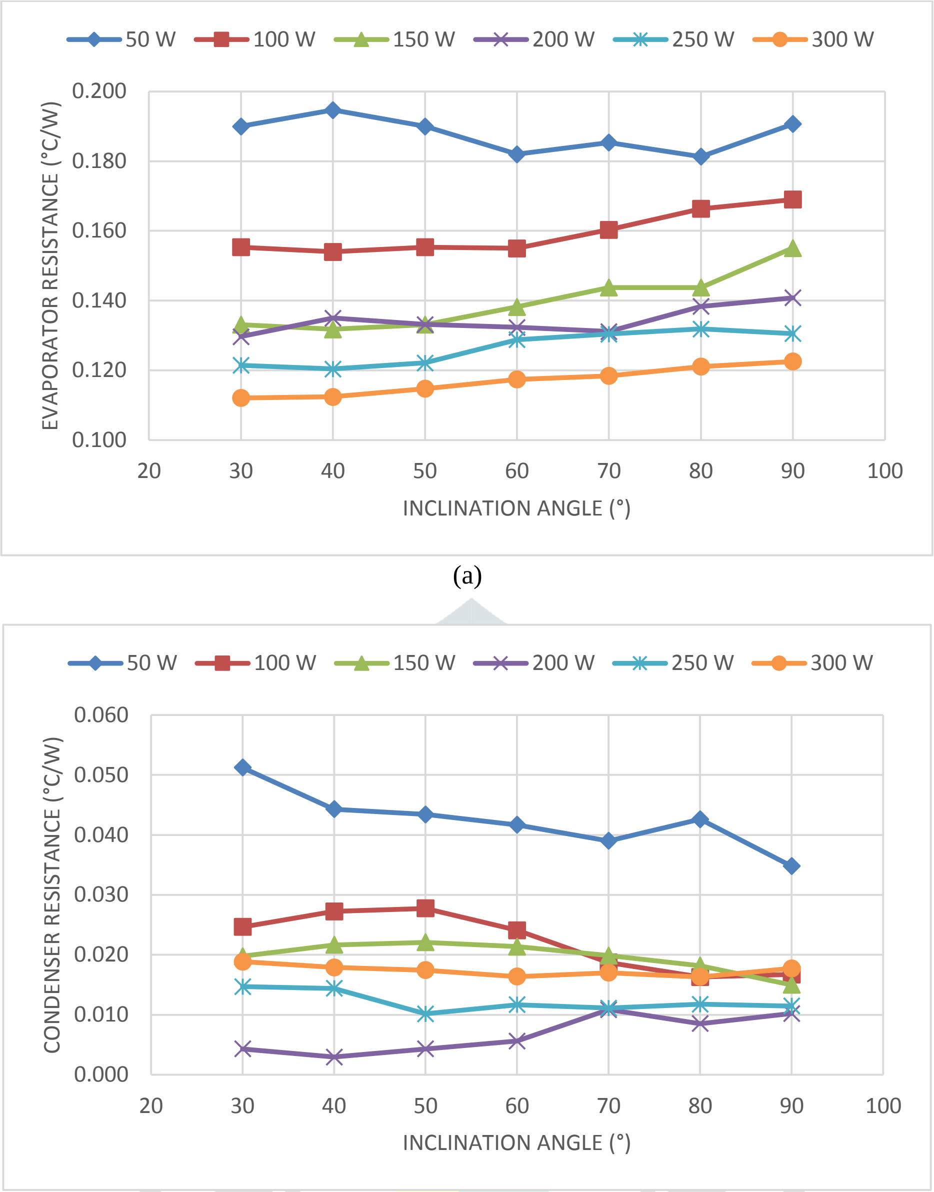
Figure 3 Wall temperatures at various locations of TPCT at various heat inputs

(a) 50W (b) 100W (c) 150W (d) 200W (e) 250W (f) 300W

Figure 3 shows the wall temperature at various locations of TPCT for different heat inputs ranging from 50W to 300W at different inclination angles (30° to 90° w. r. t. horizontal). Locations 1 to 3 belongs to evaporator section, 4 to 6 belongs to adiabatic section and 7 to 9 belongs to condenser section. It shows same trend at different heat inputs for all the inclination angles. It can be seen that there is a negligible difference between the temperatures at location 1 and 2 and the temperature at location 3 is greater than that of the location 2. This is because of the filling ratio 60%. Location 2 is at 50% length of evaporator section. Working fluid is filled up to 60% length of the evaporator section. At adiabatic section, temperature at location 5 is greater than that of the location 5 and 6, because location 5 is very near to the evaporator section.

Figure 4 shows the thermal resistance at evaporator and condenser sections of the TPCT at various inclination angles for different heat inputs. It doesn't give a clear idea of what is happening in the TPCT. To get a clear idea about the same look at figure 5. Figure 5 shows the total thermal resistance of TPCT at different heat inputs for various inclination angles. Total thermal resistance is the effect of evaporator resistance and condenser resistance.

Figure 5 shows two different trends of total resistance. One is for heat inputs 50 W, 100 W and 150 W and other is for heat inputs 200 W, 250 W and 300 W. In first trend total resistance is decreasing as inclination angle (w. r. t. horizontal) increases. On the other hand, in second trend there is negligible change in the total resistance w. r. t. inclination angle.



(a)

(b)

Figure 4 Thermal resistance at the (a) evaporator and (b) condenser sections of the TPCT

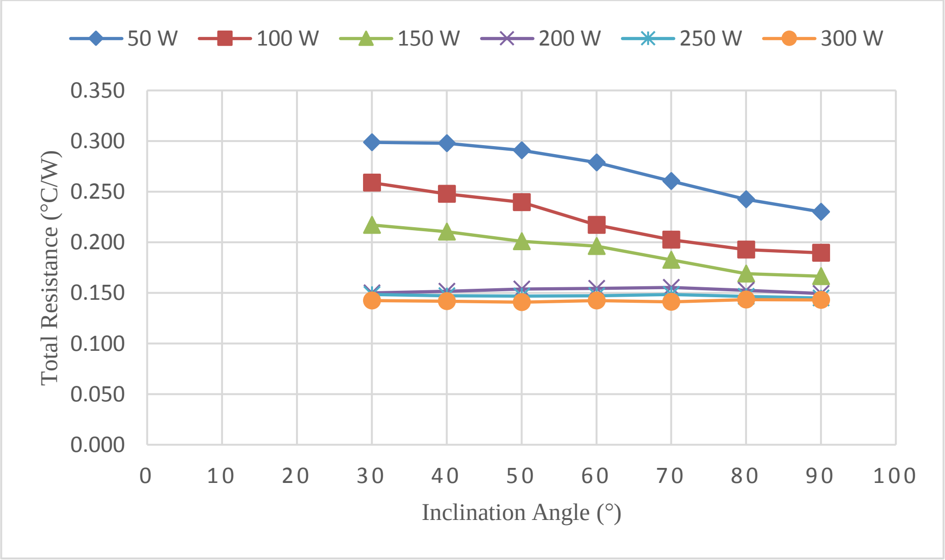


Figure 5 Total thermal resistance of the TPCT

IV. CONCLUSION

The prerequisite for TPCT testing i.e. counter current flow limit and boiling limit is fulfilled by the selected filling ratio. The counter current flow limit and boiling limit are observed to be 496 W and 335 W respectively which are greater than the highest heat input selected for the testing i.e. 300 W. Wall temperature shows the same trend at all heat inputs for all inclination angles.

The difference between evaporator and condenser at heat inputs ranging from 50W to 300W is 11°C to 41°C. As per the above discussion about total thermal resistance, it can be concluded that there is an effect of inclination angle at low heat inputs. On the other hand, as heat input increases above 200W the effect of inclination angle is negligible i.e. the change in the total thermal resistance w. r. t. inclination angle is negligible. The TPCT works best in vertical orientation i.e. evaporator section kept below the condenser section.

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