Analysis of Solar Flat Plate Collector Using Heat Transfer Enhancer Absorber Tube

S. Ramasamy [1], P. Balashanmugam[2], S. Muthukumar[3], N. Sivakumar[4]

[1,3,4]Assitant Professor, Department of Mechanical Engineering, Annamalai University, Tamilnadu
[2]Associate Professor, Department of Mechanical Engineering, Annamalai University, Tamilnadu

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Abstract - *This paper analyses the performance of an absorber tube with a heat transfer enhancer of a solar flat plate collector. The objective is to increase the heat transfer coefficient by increasing effective flow area between the absorbing fluid and the contact surface with increase in minimum pumping power. A novel design procedure is used for solar flat plate collector to reflect the experimental results. Two types of heat transfer enhancers that are rectangular and square are used herein. The heat transfer enhancer is frictionally engaged with the absorber tube and it is kept parallel to the absorbing fluid flow path. The performance factors are analyzed, and the results show that rectangular heat transfer enhancer gives higher efficiency when compared with square heat transfer enhancer with an increase in the convective heat transfer coefficient with minimum increase in pumping power for the heat transfer enhancer.*

Key Words: Solar flat plate collector, Absorber tube, Heat transfer enhancer, Thermal performance

1. INTRODUCTION

Flat plate collector plays a dynamic role using solar energy because of its reliability. The performance of the solar flat plate collector is based on several parameters including, absorber coating, tube geometry, insulating material, absorbing fluid and col lector design. The augmentation of heat transfer using passive technique plays a vital role for enhancing the performance of the system. The passive technique for modifying the absorber tube geometry involves using twisted tapes, conical ridges, coil spring wire, micro fin, longitudinal fin, helical tube, spiral tube, and curved tube. The absorbing fluid's modification also increases the convective heat transfer, and it involves Nano fluids and other organic and inorganic fluids. The performance of the collector is analyzed based on the flow type, thermal performance factor, and non-dimensional numbers. The thermal performance factor includes solar irradiation, atmospheric temperature, inlet temperature of the heat absorbing fluid, total head of the collector, col lector angles, wind speed, relative humidity, thermo-physical properties of the absorbing fluid, absorber coating and materials.

The combination of free and forced convection in straight tubes has been extensively studied in the past few decades. Several new findings and technology development have been achieved towards the mixed convection regions. The effect of natural and forced circulation of single-phase heat transfer fluid for different types of twisted tapes has been reported in [1-5]. The author has analyzed the performance of the different twisted tapes numerically and experimentally; the results show that twisted tapes increase the heat transfer. The performance of the collector using twisted tapes depends on the ratio of pitch to diameter and it decreases with increase in pressure drop and heat transfer rate. Two types of twisted tapes, helical and trailing edge, have been used and compared. At different twist angles from 3 to 7, helical twist tape provides better heat transfer compared to trailing edge twist tape. Three different configurations have been used in trailing edge twisted tape, namely, twist with rod, full length twist and spacer fitted at trailing edge for the length of 100, 200 and 300 mm for twist angles from 3 to 5º. The author has developed a new Nusselt number correlation for different twisted tapes. Higher heat transfer has been achieved using wire nail and V-cut twisted tape than plain twisted tape [6, 7].A simulation has been developed for a circular tube edge fold twisted tape [8]. The performance factors have been analyzed and it has been reported that higher heat transfer was achieved using circular tube edge fold twisted tape than plain tube. The twisted tapes increase the heat transfer rate because of the tangential and asymmetric velocity of the flowing fluid.

Circular tube with longitudinal fins has been analyzed experimentally [9]. Higher heat transfer and pressure drop occur using staggered arrangement compared to continuous fin. The above analysis states that there is an enhancement of heat transfer when using staggered arrangement on absorber tube for various profiles. Solar flat plate col-lector using different honeycomb structure with bottom arrangement has been experimentally investigated at different air gaps. 3mm air gap from the bottom for single honeycomb structure has given better results [10]. The uncertainty analysis has also been done for flat plate collector. The performance analysis of sheet and tube solar flat plate collector using rectangular duct and fin has been done by [11, 12]. The performance analysis using Nanofluids for micro fins and different types of twisted tapes has been reported in [13, 14]. The results of the experimental investigation show that, double twisted tape with micro fin gives higher heat transfer than other types of twisted tapes. The metal oxides of Nano particles have been used as heat absorbing fluid in solar flat plate collector. The Nanofluids give higher heat transfer than water at various volume fractions. The entropy generation, exergy destruction and pressure drop using Nanofluids for solar flat plate collector have been analyzed theoretically

[15]. The entropy generation is less for CuO than other Nanofluids and, it has also been compared with water. The effect of heat transfer enhancement devices in solar flat plate collector has been investigated experimentally [16]. Different types of heat transfer enhancement devices, twisted tape, coil spring wire, conical ridges, have been used. No significant difference has been reported regarding heat flux to the absorbing fluid. It has been reported that these heat transfer enhancement devices are ineffective in heat transfer enhancement. The different type of heat transfer enhancement devices are shown in figure 1.

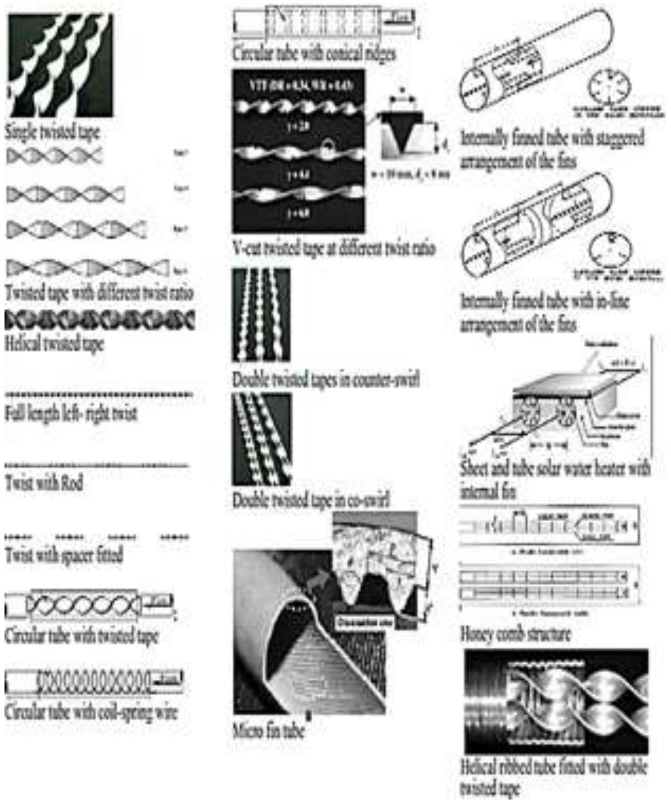

Fig - 1 Different type of heat transfer enhancement devices

The passive methods are based on the enhancement of shear produce turbulence and, it is ineffective in augmenting the heat transfer to the collector fluid. When the mass flow rate of the absorbing fluid is low and the temperature difference between the inner wall of the pipe and absorbing fluid significantly high, it increases the losses of the collector, and tangential and asymmetric velocities are ineffective. Buoyant forces coupled with axial flow create a three-dimensional complex motion when the conventional heat transfer method does not work.

The objective of the present work is to design the solar water heater with low heat transfer resistance between the absorbent and absorber tube in order to increase the convective heat transfer coefficient without affecting the flow of an absorbent. The heat transfer enhancer shows in figure 2 (b) is frictionally engaged with the absorber tube and it is and kept parallel to the absorbing fluid flow path.

2. ABSORBER TUBE MODIFICATION

The different flat plate collector parameters are presented in table 1.

Table-1 Flat plate collector parameters

Collector Parameter	Standards
Type	Flat plate collector, 2 m^2, Single glass
absorbent fluid	water
Absorber plate area	1.6 m^2
Sun temperature	5600 K
Glass thickness	4 mm
Diameter of absorber tube	I.D = 12.5 mm, thickness of 1 mm
Lower and upper header	I.D = 22.3 mm, thickness of 1.5 mm
Insulation thickness	Glass wool, t = 50 mm
Number of riser tube	9
Side wall insulation	Thickness of 5 mm, wood
Absorber plate	Thickness of 4 mm, copper
Rectangular	N = 4, L = 1500 mm per tube
Square	N = 4, L = 1500 mm per tube

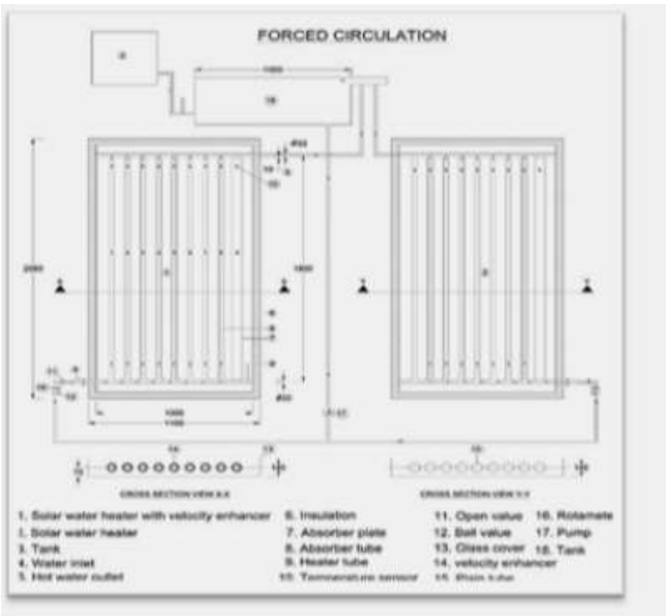

Fig - 2 (a) Solar flat plate water heater with and without heat transfer enhancers

The water flows naturally inside the tube. In fig. 2 (a) the cross section view of x-x shows heat transfer enhancer and cross section y-y shows plain absorber tube. The design parameters are shown in table.1. Fig. 2 (a) shows solar water heater with rod and tube heat transfer enhancers. The radiation falls on solar flat plate collector and it heats up the absorber plate, thereby transferring the heat energy to the absorber tube. The water flowing through the tubes will absorb the heat energy and it is heated up. Solar water heaters are grouped in to two major categories, active and passive solar water heating system. The active solar water heating systems have higher efficiency than passive solar water heating systems and it has a pump to circulate the water. Active solar water heating system is more complex and it is mainly used for industrial applications. Passive solar water heating system does not required a pump to circulate the water and it is heated up by buoyancy due to temperature difference between two regimes.

2.1 Heat transfer enhancer

Fig- 2 (b) Cross section of absorber tube A) plain tube, B) rectangular heat transfer enhancer, C) square heat transfer enhancer

Both, the rectangular as well as the square heat transfer enhancers are placed at a 90° angle to each other in an axial flow direction for the entire length of the absorber tube, as shown in fig. 2 (b). The dimensions of the heat transfer enhancers are shown in table 1. The difference in geometry of the rectangular and square heat transfer enhancers are wetter perimeter and the total mass of the heat transfer enhancers are same. The contact surface area is higher for rectangular heat transfer enhancer compared to square heat transfer enhancer and plain tube. The hydraulic diameter for heat transfer enhancer is less compared to plain tube. The heat transfer enhancer is frictionally engaged with the absorber tube and it is kept parallel to the absorbing fluid flow path.

3. Data reduction

The data reduction is used to reduce the complexity of the analysis. Table 1 shows some assumed parameters of the collector. Besides the inlet temperature of the absorbing fluid, thermal conductivity of the insulation material, atmospheric temperature and intensity of radiation are assumed. A novel design procedure used herein, to reflect the experimental results of flat plate collector.

3.1 Theoretical Design Model

Flat plate collector is assumed to be steady state. Density, viscosity, thermal conductivity and kinematic viscosity of the flowing fluid are calculated at mean temperature:

The overall heat transfer coefficient for heat transfer enhancer is calculated for obtaining the same outlet temperature by varying the hydraulic diameter. The overall heat transfer coefficient is higher for heat transfer enhancer compared to plain tube. From the difference in overall heat transfer coefficient, new outlet temperature for heat transfer enhancer tube is calculated.

4. Result and discussion

4.1 Validation of the theoretical model using inlet temperature of absorbing fluid

Figure 3 shows the efficiency of the collector at different flow rates from 45 to 225 kg/hr. The flat plate collector achieves maximum efficiency when the inlet temperature of the absorbing fluid is low. The outlet temperature of the absorbing fluid decreases when the mass flow rate of the collector is increased. It increases the useful heat gain and this causes lower losses since the average collector temperature is lower.

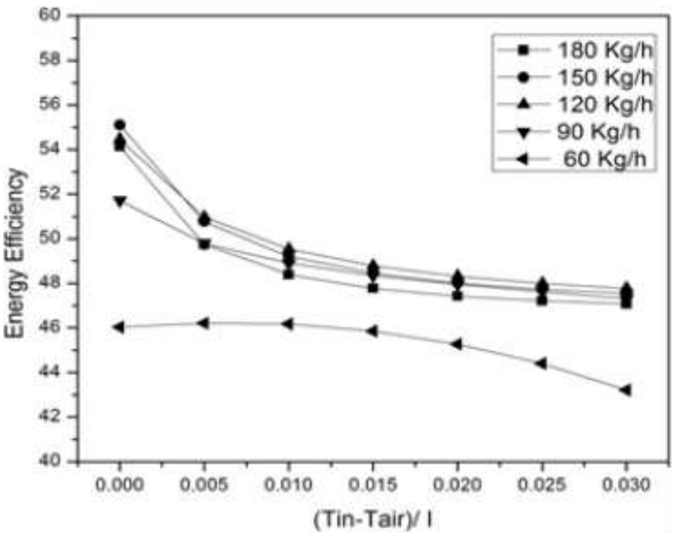

Fig-3 Validation of the theoretical design with different experimental results

The theoretical model was developed to explicitly prove the experimental results. The energy efficiency was calculated using the theoretical model, and it was compared with experimental results reported by different authors as shown in figure 3. At different mass flow rates and different atmospheric conditions, the energy efficiency results reported by various authors coincided with the theoretical model. The experimental investigation carried out for plain tube solar flat plate water heater at two different mass flow rates of 36 and 360 kg/hr has resulted in a maximum collector efficiency of 51% and 40 % respectively [20]. The efficiency of the plain tube solar flat plate collector is 54% at a mass flow rate of 36 kg/hr based on theoretical analysis. The theoretical de-sign data for the plain tube solar flat plate collector is within +1% of experimental data measured data by Jee Joe Michael and Iniyan, 2015 at a mass flow rate of 36 kg/hr.

4.2 Entropy generation and energy destruction of the flat plate collector

The entropy generation and energy destruction with increasing mass flow rate is shown in figure 4 and for different inlet temperature of the absorbing fluid named as a and b. Entropy generation increases with increasing mass flow rate. Rate of heat flux increases with increase in mass flow rate. Heat absorbing fluid absorbs more heat and it increase the efficiency of the collector. Higher temperature leads to reduction in the thermal conductivity and specific heat of the heat absorbing fluid.

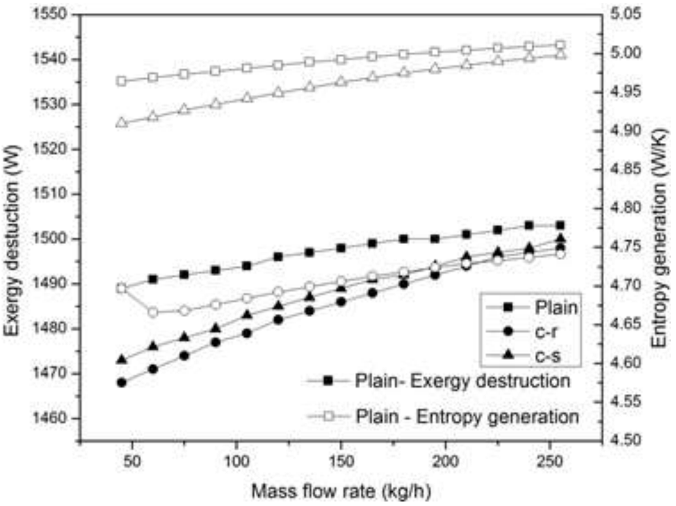

Fig-4 (a) Effect of mass flow rate on exergy destruction and entropy generation at Tin= Ta

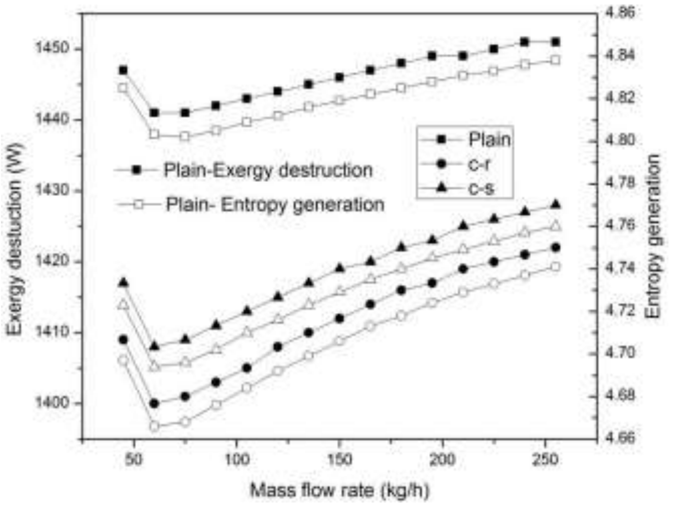

Fig- 4 (b) Effect of mass flow rate on exergy destruction and entropy generation at Tin= Ta+20

Figure 4 (b) shows the entropy generation and exergy destruction with increasing mass flow rate when the inlet temperature of the absorbing fluid greater than atmospheric temperature. When inlet temperature of the heat absorbing fluid increases, the specific heat gets reduced. The rectangular heat transfer enhancer has the lowest entropy generation and exergy destruction as compared to plain tube and square heat transfer enhancer. When increasing mass flow rate, the specific heat of the absorbing fluid comes about greater in magnitude. The heat transfer enhancer reduces the viscous boundary layer and entropy generation but as a whole, entropy generation which includes heat and fluid friction increases.

4.3 Effect of Inlet temperature of the absorbing fluid on thermal performance

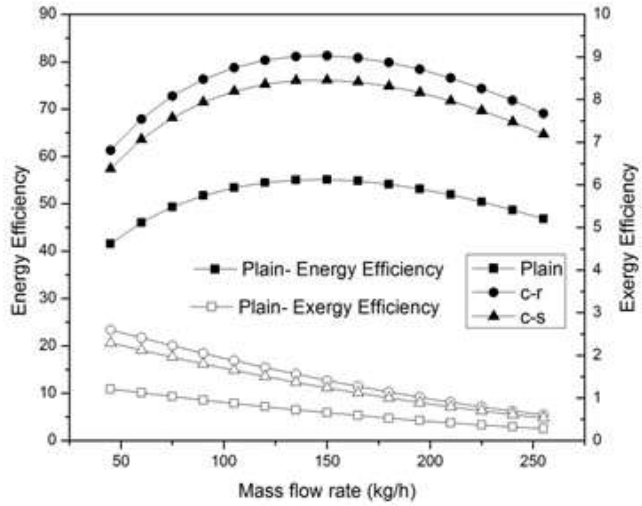

Fig-5 (a) Effect of mass flow rate on energy and exergy efficiencies at Tin = Ta

Figure 5 shows the efficiency of the collector when increasing the mass flow rate; a and b shows the variation of inlet temperature of the absorbing fluid. The collector achieves maximum efficiency when the inlet temperature of the water is low. A comparative analysis was done between the two different heat transfer enhancers with plain tube. Rectangular and square were used herein as heat transfer enhancers and that are frictionally engaged with inner side of the absorber tube wall. The purpose of the heat transfer enhancer is to increase the surface area with axial flow to the heat absorbing fluid. The rectangular configuration heat transfer enhancer has higher efficiency than the tube and plain tube configurations in all operating conditions because of area of contact surface. The convective heat transfer coefficient is higher for the heat transfer enhancers than plain tube. Due to higher thermal conductivity, Copper was used as heat transfer enhancer material.

When inlet temperature of the absorbing fluid is greater than atmospheric temperature, it leads to reduction in the efficiency of the collector as shown in fig 5 (a) and 5 (b) because of wall heat flux. The heat transfer enhancer devices used herein are effective in heat transfer enhancement. The velocity is enhanced by means of increasing the shear production, which is the product of Reynolds stress and mean velocity.

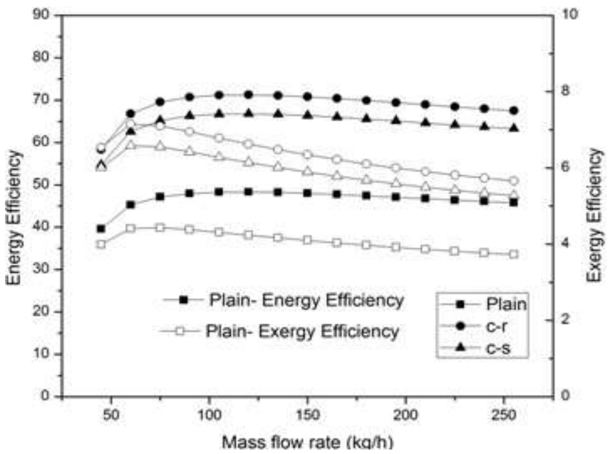

Fig- 5 (b) Effect of mass flow rate on energy and exergy efficiencies at Tin = Ta+20

The heat transfer enhancement in the heat transfer enhancer indicates that under specific conditions as given above, increased shear production influences the wall heat transfer. In the present investigation, the incident heat flux and the conduction heat transfer in the pipe are uniform because of constant radiation. Under practical condition, the radiation is not uniform, and the conduction heat transfer will be varied.

4.4 Effect of heat transfer enhancer on non-dimensional number of the collector

Figure 6 shows the effect of Nusselt number with increasing mass flow rate of the absorbing fluid. Nusselt number is a function of Reynolds number and Prandtl number. As observed in fig. 6, the Nusselt number increases with increase in mass flow rate. Increasing the inlet temperature of the absorbing fluid does not affect the Nusselt number, the rate of heat transfer will be constant. Specific heat is reduced when increasing inlet temperature of the heat absorbing fluid, and it leads to reduction in the efficiency of the collector. The heat transfer enhancers are having higher Reynolds number than plain tube. Nusselt number for the plain tube collector are verified with experimental data reported in [5], and the values are in good agreement with the present theoretical value.

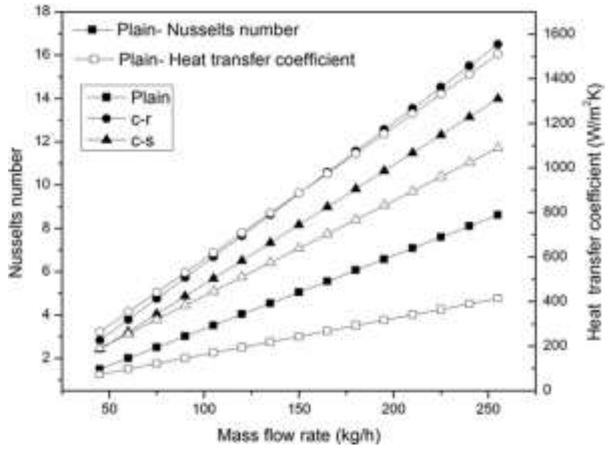

Fig. 6 Increasing Nusselt number and heat transfer coefficient with respect to mass flow rate

The Nusselt number steadily increases with increasing mass flow rate of the heat absorbing fluid. When mass flow rate of the absorbing fluid increases, inertia force also increases, and it reduces the viscous boundary layer. The heat transfer enhancers are frictionally engaged with the inner side of the tube wall, and it increases the Reynolds number minimally compared to plain tube. Stably stratified layer of light and warm absorbing fluid is maintained near the heat transfer enhancer in the top which absorbs the heat. The warmer fluid near the bottom of pipe induces the convective motion of the absorbing fluid, and it increases the velocity of the absorbing fluid. A thin boundary layer forms near the surface of the wall, and it is stationary with respect to the surface. Free stream velocity will be reached at leading edges of an extended surface and it increases the inertia force. The heat transfer enhancer reduces the viscous boundary layer than plain tube. Plain tube collector has the lowest Nusselt number, and it is also the determining factor for heat transfer of the collector. Rectangular heat transfer enhancer has higher Nusselt number than the square and plain tube. Increasing the contact surface area increases the Nusselt number because of free convection. Free convection is dominating under the specified condition mentioned above. At lower Reynolds number, free convection is stronger.

4.5 Effect of heat transfer enhancer on head losses, pressure drop and pumping power of the collector

Increasing the mass flow rate, increases the total head loss, and it reduces the buoyance force. Figure 7 clearly shows that head loss is high for rectangular heat transfer enhancer. There is no variation in buoyancy head loss up to 125 kg/hr for both the heat transfer enhancers; there after the difference in head loss is low. Head loss for the square heat transfer enhancer falls between the plain tube and rectangular heat transfer enhancer. Buoyance force removes the energy from fluid higher than shear force. The turbulence is damped against the buoyancy force and the heat transfer is entirely due to laminar flow in flat plate collector.

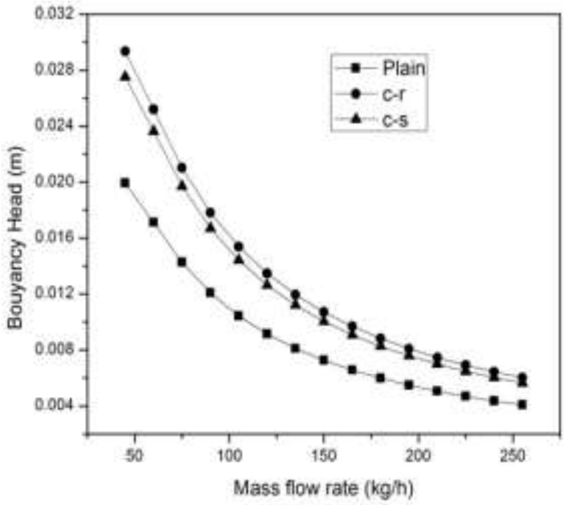

Fig- 7 Variation of buoyancy head loss due to mass flow rate

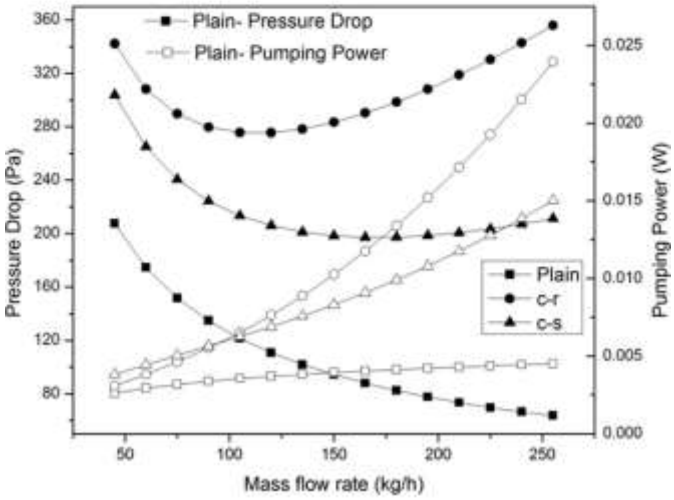

Fig-8 (a) Effect of mass flow rate on pressure drop and pumping power of the collector

Fig. 8(a) shows the variation of pressure drop and pumping power with increasing mass flow rate. Inlet temperature of the absorbing fluid is equal to atmospheric temperature in the graph shown in fig. 8 (a). Pumping power is directly proportional to the mass flow rate. The plain tube required less pumping power and pressure drop to circulate the absorbing fluid compared to rectangular and square heat transfer enhancers. Due to higher buoyance force, the rectangular heat transfer enhancer removes the energy from fluid higher than shear force. This theoretical model data for pumping power is verified with the data reported [15]. The result shows good agreement with marginal deviation of +1.05 and +1.15 for pumping power and pressure drop respectively. Rectangular heat transfer enhancer has 1.30 times higher pressure drop compared to plain tube and for square heat transfer enhancer it is 1.15 times higher. Fig. 8 (b) shows that the pumping power get reduced when inlet temperature of the absorbing fluid is greater than atmospheric temperature. The density of the absorbing fluid is low when increasing the temperature

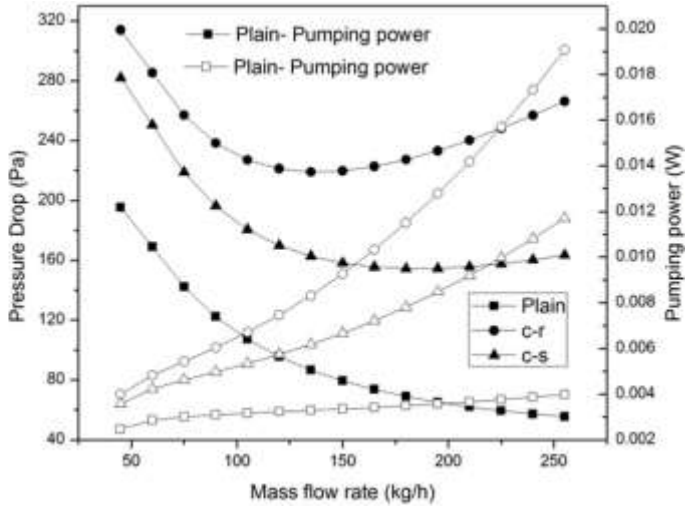

Figure -8 (b) Effect of mass flow rate on pressure drop and pumping power of the collector at Tin = Ta+20

5. Conclusion

The absorber tube modification by enhancing the surface are of the pipe is analysed theoretically. Inlet temperature of the absorbing fluid is found to highly dominate the system performance. Lower inlet temperature of absorbing fluid gives higher efficiency. The heat transfer enhancers give higher efficiency than plain tube. The heat transfer enhancers reduce the thermal and viscous boundary layer. The rectangular heat transfer enhancer gives 18-20 % higher efficiency than plain tube at different mass flow rates. Square heat transfer enhancer gives about 3 to 5% less efficiency than rectangular heat transfer enhancer. The pumping power for both heat transfer enhancers remains same for the mass flow rate range of 45 to 120 kg/hr. Rectangular heat transfer enhancer is suitable for the absorber tube modification

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