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THERMO-HYDRAULIC PERFORMANCE ANALYSIS OF PARABOLIC CONCENTRATING SOLAR WATER HEATER

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ABSTRACT

This paper concerns the thermo-hydraulic performance analysis of a PCSWH (parabolic concentrating solar water heater) with placing the PTT (perforated twisted tape) in the absorber tube. The experiments are performed using water as testing fluid. In this analysis, the mass flow rate changes from 0.0326 kg/s to 0.0667 kg/s and Reynolds number ranges from 2100 to 4250 respectively. The analysis is based on the effect of porosity of the PTT and mass flow rate over the pressure drop and heat transfer enhancement during the flow into the absorber tube of the PCSWH. At last to guess the increment in pressure drop and enhancement of heat transfer the empirical correlations for friction factor and the Nusselt number have been formulated considering the turbulent effect caused by PTT inside the absorber tube. The major observations of this analysis are that PTT enhances the pressure drop and heat transfer and also both enhances with increasing porosity of the PTT.

Keywords: *Solar Water Heater, Perforated Twisted Tape, Thermo-Hydraulic Performance, Pressure Drop, Heat Transfer*

INTRODUCTION

Solar energy is a most important source of renewable energy as it is pollution free and no fuel consumption required. Only the collecting device required with modern improved technology. The demand for energy is increasing with the progress of society and civilization of the forthcoming years. A concentrating solar collector is the most eminent and efficient technique to collect the solar energy due to its higher concentration ratio. A parabolic concentrating solar water heater is used for power generation and industrial water heating purposes. Lately, many research works are performed to improve the performance. The perforated twisted tape is one of passive technique to augment the heat transfer in the absorber tube. This is used Hong and Bergles [1] performed the thermo-hydraulic study of a tube with and without twisted tape inserts. Their result viewed that friction factor and Nusselt number both enhances for the tube with twisted tape inserts. Huang et al. [2] used a transparent absorber instead of a metal absorber tube and they observed that the thermal performance enhances for using black working fluid. Heiti and Thodos [3] studied the performances of the PTC with and without coated receiver tube. Hamad [4] examined the impact of variable mass flow rate over the thermal performance. Mullick and Nanda [5] examined the heat loss analysis numerically and experimentally. Manglik and Bergles [6] studied swirl flow parameters and developed correlations for pressure loss and heat transfer of an isothermal tube. Twisted tape improved heat transfer and enhances pressure drop. Kothdiwala et al. [7] studied the influence of the change of angular inclination on the collector performance. Agarwal and Raja Rao [8] found that Nussenlt number enhances with twisted tape inserts and same effect for friction factor. Eskin [9] experimentally reported the temperature profile of the glass envelope and receiver surface along the length of the receiver tube. Chang et al. [10] examined the thermo-hydraulic performance by using broken twisted tape in a tube and developed correlations for the results of enhancement in heat transfer and pressure drop. Arasu and Sornakumar [11] evaluated the collector thermal efficiency as per ASHRAE 93 (1986) Standard). Fadar et al. [12] studied the heat energy stored in the tank. Padilla et al. [13] developed correlations for thermal loss and collector efficiency. Kumaresan [14] performed the experimental study (charging efficiency, overall efficiency) of a parabolic trough collector. Their results showed that the above efficiencies are reached a peak value at noon. Jafar and Sivaraman [15] conducted the thermo-hydraulic study of an absorber tube of the parabolic trough collector. They used twisted tape and their results showed that pressure drop and Nusselt number simultaneously

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augmented with low twist ratio. Ghomrassi et al. [16] numerically studied the influence of variation of receiver diameter on the thermal performance of a parabolic trough concentrator. Roy et al. [17] experimentally presents the effects of variable silver/water nano-fluid concentrations on the thermal performance of a flat solar plate collector. Bhakta et al. [18] studied the thermal performance of a CPCSWH for the two constant mass flow rates. Hussein et al. [19] found that nanofluid significantly augments the performance of direct absorption solar collector. Soudani et al. [20] examined the effects of mass flow rate, length of the absorber tube and glass cover on the thermal performance of the PTC. Yildirim and Ozdil [21] studied the performance of a solar air heater with the roughened absorber. Tokgoz et al. [22] numerically studied the heat transfer rate increment in a corrugated duct considering Al2O3/water nanofluid as heat transfer fluid. Bhakta et al. [23] experimentally investigated the performance parameters of a CPC fitted with nailed twisted tape in an absorber tube.

After survey of above stated literatures, it is clear that the majority of the authors have studied the thermal performance of the PCSWH with plain receiver tube. Only Jafar and Sivaraman [15] investigated the thermo-hydraulic performance of the PCSWH fitted with nail and simple twisted tapes in a receiver tube. No research work observed in the parabolic trough collector with placing the perforated twisted tape (PTT) in the receiver tube. So, at present the investigation has focused to examine the thermo-hydraulic performance of a PCSWH with the PTT insert in the absorber tube.

EXPERIMENTAL SETUP DESCRIPTION AND METHOD OF EXPERIMENT

The photograph of PCSWH and photograph of the PTT have been shown in Figure 1 and Figure 2 respectively. The specifications of the PCSWH and PTT have been shown in Table 1. The PCSWH is equipped with a parabolic trough concentrator (PTC), a concentric glass-covered absorber tube, a pump and a storage tank. The PTC made of Acrylic mirror. The black nickel coated copper tube is used as absorber. The absorber tube is fitted along focal line of the PTC. The hydraulic hose pipes are used to connect between storage tank and absorber tube. Thus, a close loop formed and during the experimental work water circulates into this loop.

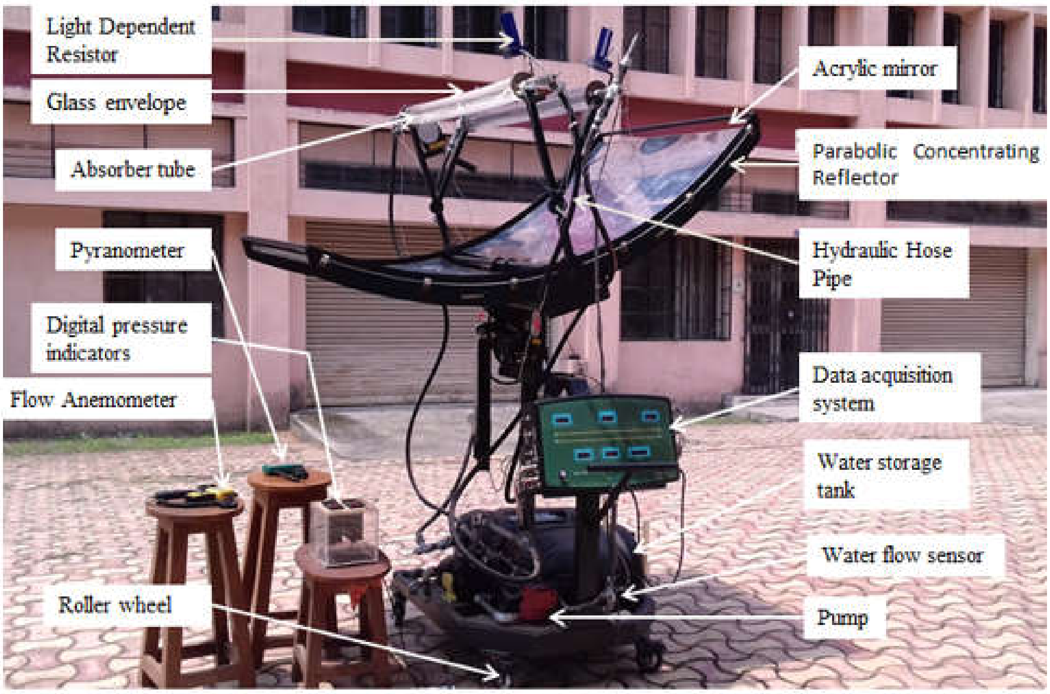

Figure1. Photograph of PCSWH

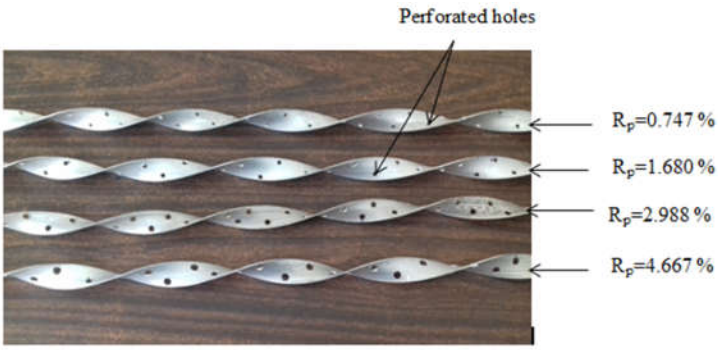

Figure 2. Photograph of PTT

Table 1. Specification of the geometrical characteristics of the PCSWH and PTT

Sl. No.	Nomenclature	Specifications
1	Concentrator aperture area (A_{ap})	2.03618 m^2
2	Inside heat transfer area of absorber tube (A_h)	0.08819 m^2
3	Absorber tube Length (L_p)	1.220 m
4	Absorber tube inner diameter (D_i)	0.0236 m
5	Absorber tube outer diameter (D_o)	0.0254 m
6	Outer diameter of glass cover (D_{co})	0.0710 m
7	Concentrator surface reflectivity	0.90
8	Cover trasmissivity	0.85
9	Absorber tube absorptivity	0.95
10	Perforated twisted tape's width (w)	0.020 m
11	Perforated twisted tape's thickness (t)	0.120×10^{-2} m
12	No of perforated hole on each tape	58
13	Perforated hole diameters (d_p)	0.002 m, 0.003 m, 0.004 m, 0.005 m
14	Porosity of tapes (Rp)	0.747%, 1.680%, 2.988%, 4.667%
15	Twist pitch ratio of tapes (Y)	4.5

A circulating pump pumps water to maintain water circulation continue into the receiver tube. To measure the water flow rate a water flow sensor is fitted at delivery of the pump. Two pressure transducers and two thermocouples, one of each at inlet and another of each at absorber tube's outlet are fitted to record the readings of pressures and temperatures at the corresponding places. Two LDR (a photo resistance) is fitted at the one end of the absorber tube to track the Sun during the experiment. During the experimental works, the solar intensity has by a Pyranometer (Solar Power Meter). The experimental works were carried out with and without inserting the PTT inside of the absorber tube. At the beginning of the experiments, first experiment was carried out for plain absorber and next experiments were carried out with placing PTT inside of the absorber tube in increasing order of porosity (0.747%, 1.680%, 2.988% and 4.667%).

The experiments were performed during the month of December, 2017 in front of Mechanical Engineering Department of IIT(ISM) Dhanbad, India.

DATA REDUCTION

Absorber tube's inside flow area with PTT is calculated with the help of Equation 1 as follows,

$$A_f = \frac{\pi D_i^2}{4} - wt \tag{1}$$

The useful heat gain is determined with the help of Equation 2 as follows,

$$Q_u = mc_p(T_o - T_i) \tag{2}$$

Nusselt number is the non-dimensional parameter used for calculating the heat transfer between a flowing fluid and a solid body. It is determined using Equation 3 as follows,

$$Nu = \frac{h_f D_h}{k_f} \tag{3}$$

The heat transfer coefficient is determined with the help of Equation 4 as follows,

$$h_f = \frac{mc_p(T_o - T_i)}{A_h(T_p - T_b)} \tag{4}$$

The Reynolds number (Re) is determined with taking the help of Equation 5 as follows,

$$Re = \frac{\rho_f u_f D_h}{\mu_f} \tag{5}$$

The equivalent hydraulic diameter (D_h) at the entrance of the receiver tube having PTT insert is calculated with taking help of Equation 6 as follows,

$$D_h = \frac{\pi D_i^2 - 4wt}{\pi D_i + 2(w+t)} \tag{6}$$

The friction factor in term of pressure drop is calculated with the help of Equation 7 as follows,

$$f = 2\frac{\Delta p D_h}{L_p \rho_f u_f^2} \tag{7}$$

UNCERTAINTY ANALYSIS

The method invented by Kline and McClintock [24] has applied to evaluate the uncertainties in these experimental measurements. The uncertainty is calculated to be 1.699% for solar intensity, ± 6.024 % for pressure drop, ± 6.052 % for Reynolds number, ± 5.152 % for heat transfer coefficient, ± 6.936 % for the Nusselt number (Nu) and ± 7.100 % for friction factor (f) respectively. The instruments' accuracies and attachments' accuracies and have considered for uncertainty analysis have shown in Table 2.

Table 2. Instruments' accuracy

Sl. No.	Instruments	Accuracy
1	Water Flow Sensor	± 10 %
2	Pyranometer	± 0.499 % or ± 10 W/m^2
3	Thermocouple	± 0.4 %
4	Pressure Transducer	± 0.25 %

RESULTS AND DISCUSSION

Figure 3 shows the plot of solar intensity against time on different dates. In Figure 3, it is also most transparent that the values of solar intensity enhance with the faster rates since 9:0 h to till noon and at noon its value reaches to a peak. After noon, solar intensity decreases.

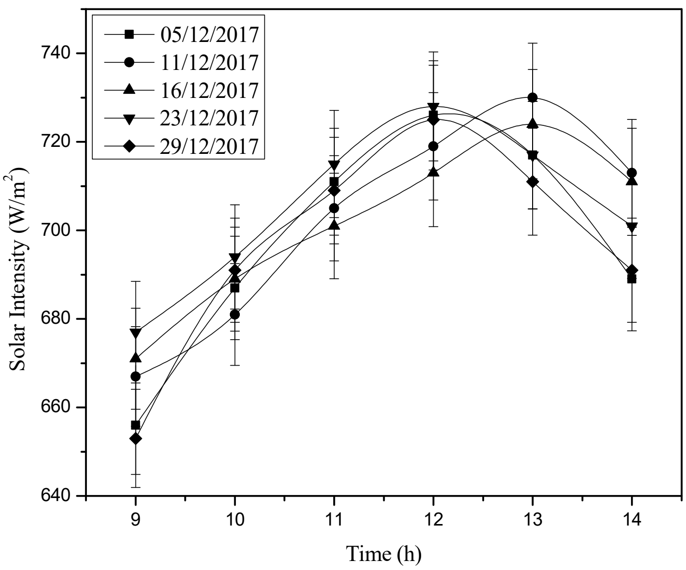

Figure 3. Solar intensity vs. time (h)

INFLUENCE OF REYNOLDS NUMBER AND POROSITY OF PTT ON HEAT TRANSFER COEFFICIENT

Figure 4 presents the change of heat transfer coefficient with respect to Reynolds number (Re) for the absorber tube with and without PTT inserts. From Figure 4, it can be cleared that heat transfer coefficient always enhances with Reynolds number for the absorber tube with and without PTT inserts. Also enhances for the PTT fitted absorber tube with increasing porosity. Moreover, the additional water flow disturbance and secondary flow caused by holes on the tapes. This effect prolongs water flow duration and increases heat transfer rate from absorber tube's inner surface to circulating water. The average value of heat transfer coefficient obtained using perforated twisted tape with porosity 4.667 %, is 44.855% higher than that of the plain absorber tube. The heat transfer coefficients obtained using PTT with porosities 0.747 %, 1.680 % and 2.988 % respectively, 27.812%, 34.247% and 39.093% higher than that obtained from a plain absorber tube result.

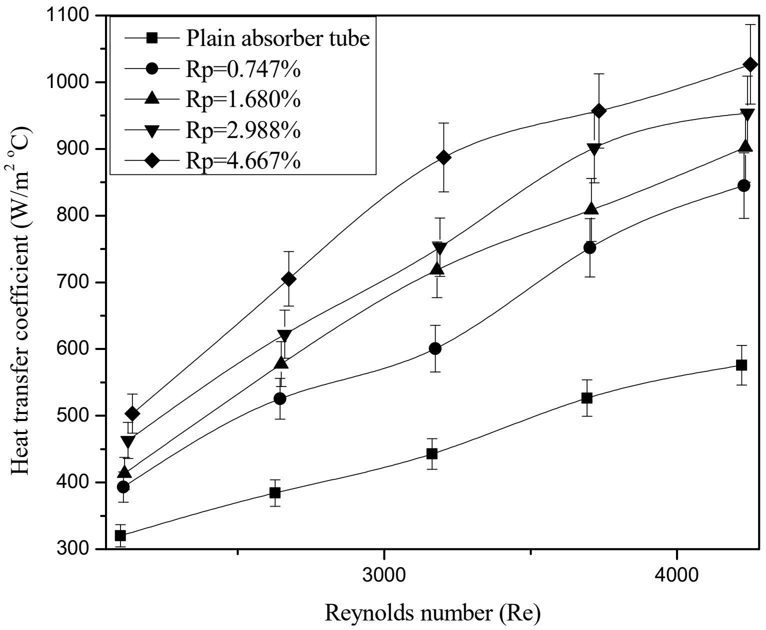

Figure 4. Variation of heat transfer coefficient against Reynolds number (Re) and porosity

INFLUENCE OF REYNOLDS NUMBER AND POROSITY OF PTT ON NUSSELT NUMBER

Figure 5 demonstrated the results of heat transfer in term of Nusselt number in the absorber tube equipped with PTT inserts at various porosities (0.747 %, 1.680 %, 2.988 % and 4.667 %). The results show that Nusselt number enhances for the PTT inserts absorber tube with Rp=4.667%. The high heat transfer rate at Rp=4.667 % is attributed to a higher turbulent intensity and stronger swirl flow imparted to the flow. Thus, a stronger disturbance of a thermal boundary layer is created along the inner surface of the absorber tube, resulting the formation in a very thinner thermal boundary layer. The thinner thermal boundary layer is most favourable for heat transfer from inner surface to water. In addition to the above, the twisted tape and hole prolongs water flow duration which is main cause

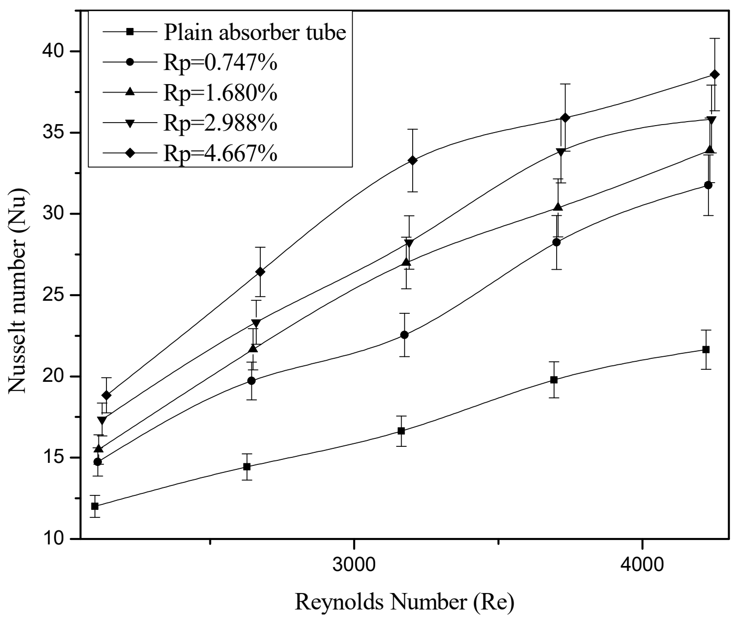

Figure 5. Variation of Nusselt number against Reynolds number and porosity

of increase in overall heat transfer. The average value of Nusselt number (Nu) obtained using PTT with porosity 4.667 %, is 44.783% higher than the same of a plain absorber tube. Nusselt numbers obtained using PTT with porosities 0.747 %, 1.680 % and 2.988 % respectively, are 27.785%, 34.209% and 39.039% higher than that for a plain absorber tube.

INFLUENCE OF REYNOLDS NUMBER AND POROSITY OF PTT ON PRESSURE DROP

Figure 6 demonstrated the change of pressure drop with respect to Reynolds number and porosity of PTT. From this figure it is clear that pressure drop increases with Reynolds number and increasing porosity of tapes. Also, at Rp=4.667 %, pressure drop by PTT is much higher than those obtained by plain absorber tube and other PTT inserted absorber tube with porosities of Rp=2.988 %, Rp=1.680 % and Rp=0.747 % respectively. At same operating conditions, PTTs offer higher flow frictional resistances and drop pressures in the test section than plain absorber tube one. It is owing to the fact that the additional water flow disturbance and secondary flow caused by holes on the tapes. This effect increases the interaction between pressure and inertia forces, resulting in a pressure drop. Thus, the pressure drop increases with Reynolds number and increasing porosity of tapes. In the present investigation, the mean value of friction factor has found to be increased by 39.595%, 42.217%, 44.501% and 46.876% for the porosity of Rp=0.747%, Rp=1.680%, Rp=2.988% and Rp=4.667% respectively, under the similar flow conditions.

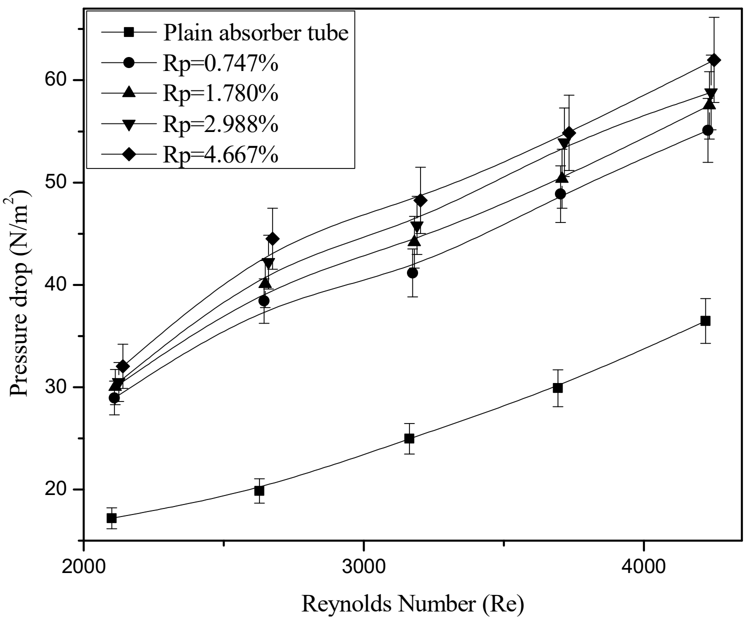

Figure 6. Variation of pressure drop (Δp) vs. Reynolds number (Re) and porosity

INFLUENCE OF REYNOLDS NUMBER AND POROSITY OF PTT ON FRICTION FATOR

Figure 7 demonstrated the change of friction factor with respect to Reynolds number (Re) and porosity of PTT. The value of friction factor increases with respect to Reynolds number and increasing porosity of tapes. At Rp=4.667 %, friction factor generated by PTT is much higher than those obtained by plain tube and PTT inserted absorber tube with porosities of Rp=2.988 %, Rp=1.680 % and Rp=0.747 % respectively. At same operating conditions, PTTs offer higher flow frictional resistance than plain absorber tube one. It is owing to the fact that the additional water flow disturbance caused by holes on tapes. This effect increases the interaction between pressure and inertia forces around the velocity boundary layer, resulting an increase in pressure drop and friction factor (f). In this investigation, the average value of friction factor (f) is observed to be increased by 44.960 % for Rp=4.667%, 42.371% for Rp=2.988%, 40.163% for Rp=1.680% and 37.476% for Rp=0.747% than that of plain absorber tube one.

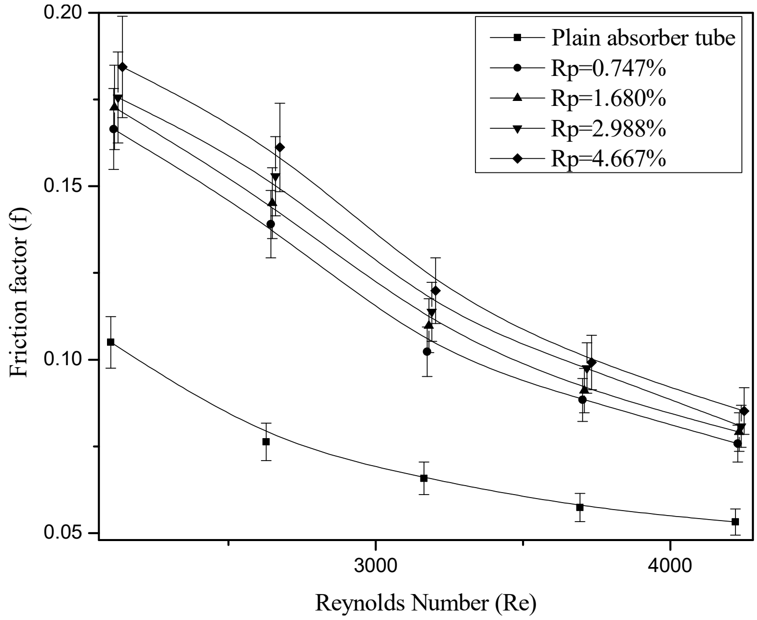

Figure 7. Variation of friction factor (f) against Reynolds number (Re) and porosity

INFLUENCE OF MASS FLOW RATE AND POROSITY OF PTT ON INSTANTANEOUS EFFICIENCY

Figure 8 presents the change of instantaneous efficiency (η_i) with water flow rate and porosity of tapes. For all the cases, instantaneous efficiency (η_i) enhances mass flow rate. Instantaneous efficiency (η_i) for

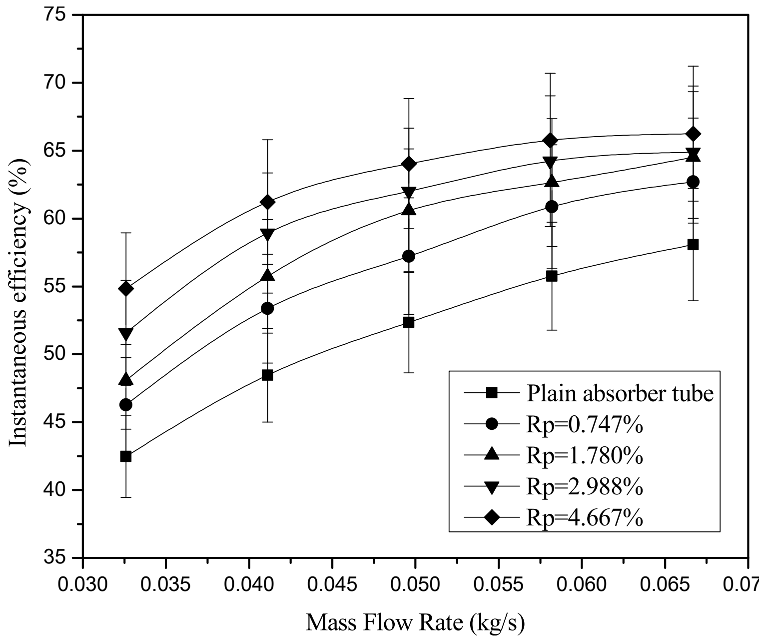

Figure 8. Variation of instantaneous efficiency (η_i) against mass flow rate and porosity

PTT inserts absorber tube with Rp=4.667 % is observed much better than the results calculated for others PTT inserts tube with Rp=2.988 %, Rp=1.680 %, Rp=0.747 % and also than the result of a plain absorber tube. It is owing to the matter that heat transfer rate increases due to higher turbulent intensity and stronger swirl flow generated for the PTT inserts absorber tube with Rp=4.667 %. In addition to the above, the twisted tape and perforated hole prolongs water flow duration which is main cause of increase in overall heat transfer. The resultant effect increases the useful heat gain result of PCSWH. In this investigation, the mean value of instantaneous efficiency is found to be increased by 17.616 % for PTT at Rp=4.667 %, 14.751 % for PTT at Rp=2.988 %, 11.809 % for PTT at Rp=1.680 %, 8.305 % for PTT at Rp=0.747 % than the same result obtained for a plain absorber tube, under similar flow rate.

INFLUENCE OF MASS FLOW RATE AND POROSITY OF PTT ON TEMPERATURE RISE PARAMETER

Figure 9 presents the change of Temperature Rise Parameter (TRP) with respect to mass flow rate (m) and Rp of PTT. For all the cases, Temperature Rise Parameter (TRP) enhances with an increase in mass flow rate. Temperature Rise Parameter (TRP) for PTT inserts absorber tube with Rp=4.667 % is observed much better than the results calculated for others PTT inserts absorber tube with Rp=2.988 %, Rp=1.680 %, Rp=0.747 % and also than the result of a plain absorber tube. It is owing to the matter that heat transfer rate increases due to higher turbulent intensity and stronger swirl flow generated by the PTT inside of the absorber tube with Rp=4.667%. In addition to the above, the twisted tape and hole/pore prolongs water flow duration which is main reason of increase in overall heat transfer and rise in temperature. The resultant effect increases the value of useful heat gain. In this investigation, the mean value of TRP has found to be enhanced by 18.543 % for PTT at Rp=4.667 %, 15.357 % for PTT at Rp=2.988 %, 11.971 % for PTT at Rp=1.680 % and 8.364 % for PTT at Rp=0.747 % than the result observed in case of a plain absorber tube, under similar operating condition.

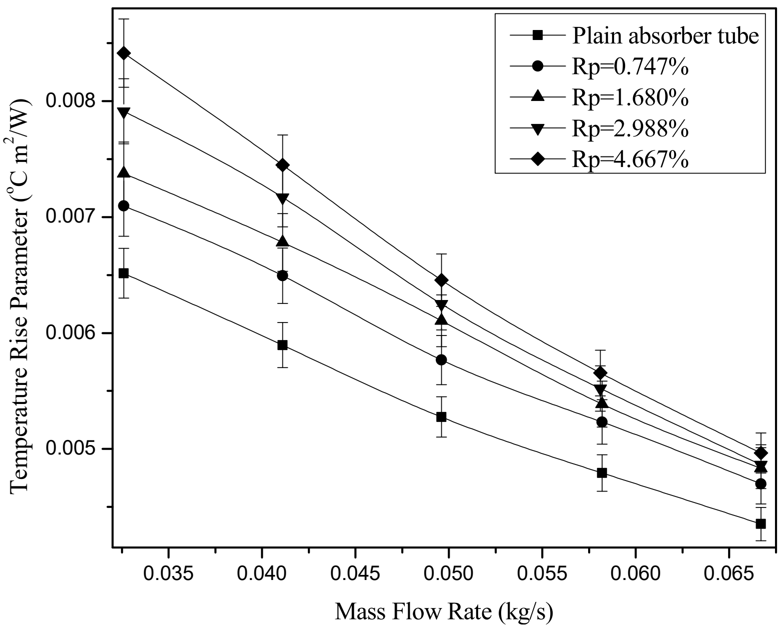

Figure 9. Variation of temperature rise parameter vs. mass flow rate and porosity

INFLUENCE OF MASS FLOW RATE OF WATER AND POROSITY OF PTT ON WATER INLET AND OUTLET TEMPERATURES

Figure 10 presents the variations of water inlet and outlet temperatures with variable water flow rate and Rp of PTT. For all the cases, the water outlet temperature reduces with an increase in water flow rate. Water outlet temperature for PTT inserted absorber tube with Rp=4.667 % is observed much better than the results calculated for others PTT inserted absorber tube with Rp=2.988 %, Rp=1.680 %, Rp=0.747 % and the result observed in case of a plain absorber tube. It is owing to the matter that heat transfer rate increases due to higher turbulent intensity and stronger swirl flow generated by the PTT inside of the absorber tube with Rp=4.667%. In addition to the above, the twisted tape and perforated hole prolongs water flow duration which is main reason of increase in water outlet temperature.

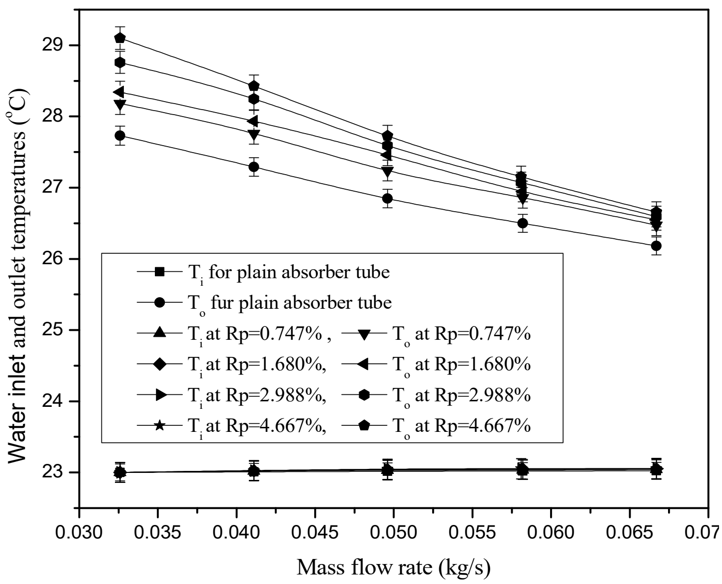

Figure 10. Variations of water inlet and water outlet temperatures with mass flow rate and porosity

EMPIRIAL ORRELATION DEVELOPMENT FOR NUSSELT NUMBER

Based on present experimental data (4×5=20 runs), the correlations Nusselt number (Nu) has been formulated as expressed in Equation 8 as follows,

$$Nu = 0.0039Re^{1.0005}Rp^{0.1392}Pr^{\mathbf{0.380}} \tag{8}$$

From Equation 8 it is very transparent that Re, Rp and Pr, all directly influence the Nusselt number (Nu). A correlation coefficient of 0.970 indicates the predicted result of Nusselt number holds very good agreement with experimental result of Nusselt number as shown in Figure 11.

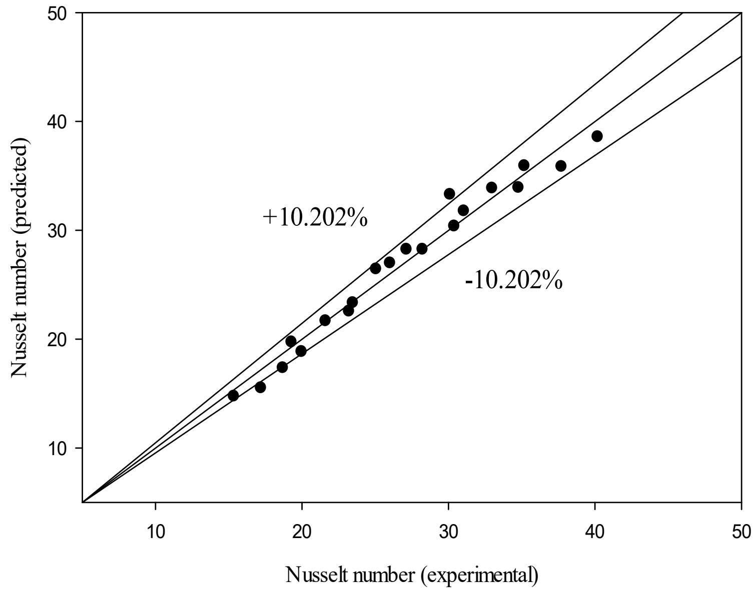

Figure 11. Parity plot of predicted and experimental values of Nusselt number

EMPIRIAL ORELATIO DEVELOPMENT FOR FRICTION FATOR

Based on present experimental data, the friction factor (f) correlated with Re and porosity (Rp) as expressed in Equation 9 as follows,

$$f = 918.9528 Re^{-1.1221} Rp^{0.0740} \tag{9}$$

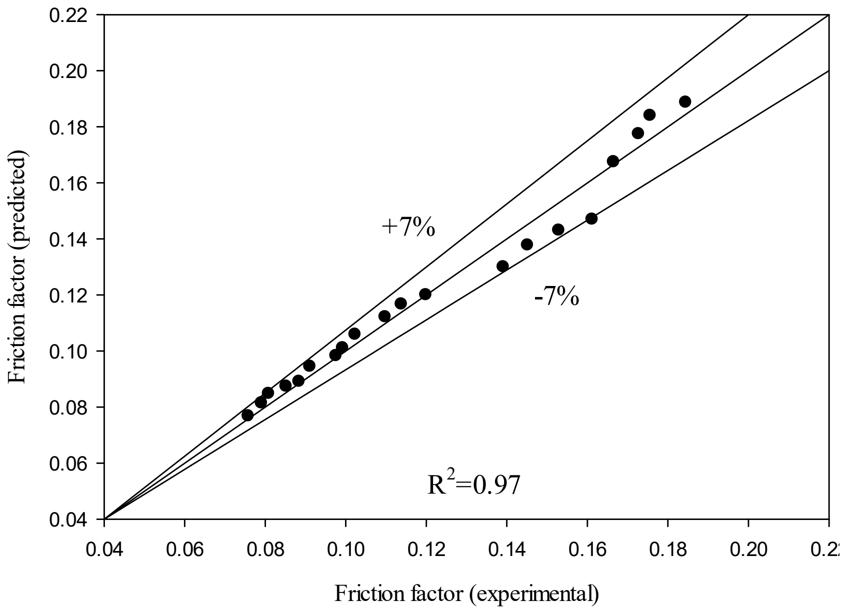

Figure 12. Parity plot of predicted and experimental values of friction factor

From Equation 9 it is very transparent that Rp directly influences and Re inversely influences the friction factor (f) result. The correlation coefficient of 0.970 indicates the predicted result of friction factor holds very good agreement with experimental result of Nusselt number as shown in Figure 12.

CONCLUSION

The conclusions have been drawn from the above results and discussions as follows:

The Nusselt number, friction factor and heat transfer coefficient increase with increasing porosity of the tapes. The Nusselt number and heat transfer coefficient both enhances with Reynolds number (Re). Whereas, friction factor (f) reduces with increasing Reynolds number (Re). As the frictional resistance decreases with an increase in Reynolds number (Re).

The instantaneous efficiency (η_i) enhances with increasing mass flow rate. Whereas, water outlet temperature and TRP, both reduces with an increase in Reynolds number (Re). Instantaneous efficiency, water outlet temperature and temperature rise parameter, all are increases with increasing porosity of tapes.

To predict the enhancement in heat transfer and pressure drop considering the effect of PTT, correlations are developed for Nusselt number and friction factor. The predicted values of Nusselt number and friction factor are observed to be within ± 10.202 % and ± 7.0 % with experimental data.

NOMENCLATURE

A_{ap}	Aperture of concentrator, m^2
A_h	Absorber tube's inside surface area, m^2
A_f	Absorber tube's flow area, m^2
A_p	Total perforated holes area, m^2
c_p	Specific heat, J/kg K
D_i	Absorber tube's inside diameter, m
D_o	Absorber tube's outside diameter, m
D_h	Hydraulic diameter, m
D_p	Diameter of perforated holes, m
f	Friction factor, nd
h_f	Heat transfer coefficient, $\mathrm{W/m^2\ K}$
I_b	Intensity of solar radiation, $\mathrm{W/m^2}$
k_f	Thermal conductivity of water, W/m K
L_{ptt}	PTT length, m
L_p	Absorber tube's length, m
m	Mass flow rate, kg/s
Nu	Nusselt Number, nd
P	PTT twist pitch, m
Q	Useful heat gain, W
Re	Reynolds Number, nd
Rp	Porosity$\left(= \mathrm{A_p}/\left(\mathrm{L_{ptt}} \times \mathrm{w}\right)\right)$, nd
u_f	Water velocity, m/s
t	PTT thickness, m
T_i	Inlet temperature, °C
T_o	Outlet temperature, °C
T_p	Surface temperature of absorber tube, °C
T_b	Bulk mean temperature, °C
TRP	Temperature rise parameter, $\mathrm{m^2}$ °C/W
w	Width of PTT, m

Greek symbols

ρ_f	Density, kg/m^3
η_i	Instantaneous efficiency, nd
μ_f	Dynamic viscosity, Ns/m^2
Δp	Pressure drop, N/m^2

Subscripts

f	Refers to fluid

Abbreviations

$PCSWH$	Parabolic concentrating solar water heater
PTT	Perforated twisted tape
PTC	Parabolic trough concentrator

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