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Investigation on Thermal and Hydraulic Performances of Parabolic Trough Solar Collector

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ABSTRACT

Theoretical investigation on the thermal performance of a parabolic trough solar collector (PTSC) for a fixed water flow rate (0.04 kg/s) and theoretical investigation on heat transfer enhancement and pressure drop at the outlet of the absorber tube with the inserted twisted tape (TT) with twist ratio (Y) 3, 6, 10, 12 for the water flow rate 0.04-.11 kg/s were performed. The Reynolds number (Re) ranged from 3,100 to 9,600 and the swirl flow Reynolds number (Re_{sw}) is varied from 6,400 to12,300 respectively. The theoretical data of friction factor are validated with those published previously for the plain absorber tube. The values of Nusselt number (Nu) and friction factor (f) were observed much higher than those calculated from plain absorber tube one.

KEYWORDS: Parabolic trough solar collector, turbulent flow, twisted tape, swirl flow, heat transfer, pressure drop

I. INTRODUCTION

A twisted tape (TT) is an inactive heat transfer promoter in tube flow. Twisted tapes intense swirl flow of fluid flows through twisted tape insert tube. At present era, the parabolic trough solar collector is playing a vital role, as its efficiency much more than other conventional solar water heaters with respect to the same aperture area. Ceylan and Ergun [1] experimentally analyzed the temperature controlled parabolic trough collector and observed that the highest exergy efficiency obtained as 63% for 70oC. Eiamsa-ard et al. [2] studied the heat transfer augmentation in the tube inserted with straight and oblique delta-winglet TTs. Eiamsa-ard et al. [3], Cheng et al. [4, 5] reported that pressure drop and heat transfer both significantly enhances for the TT inserted tube and lower twist ratio performed far better. Manglik and Bergles [6] and Al-Fahed et al. [7] experimentally presented that the friction factor and heat transfer both increase for the lower twist ratio. Liu et al. [8] numerically studied the heat transfer and friction factor both increases for the center-cleared TT inserted tube. Kumar and Prasad [9] experimentally studied the influences of twist ratios on the thermal and hydraulic performances of solar water heater. They carried out the experiments with the twist ratio 3, 6, 10 and 12 respectively, and within the range of Re from 4000 to 21,000. They pointed out that performance enhances with using twisted tapes. Also, their result showed that performance significantly enhances with twist ratio Y=3 than that obtained with twist ratio 12. Seemawute and Eiamsa-ard [10] inserted peripherally-cut TT inside of tube and observed that heat transfer increases with decreasing twist ratio than that of plain tube one. Bhakta et al. [11] showed that the thermal efficiency arrives to peak at noon. Bhakta et al. [12] used three nailed TTs to measure the improvement in thermal efficiency. Bhakta et al. [13] studied the hydraulic performance of the PTSC by placing perforated TT inside the absorber tube.

From the above literature, most of the researcher experimentally studied the thermal performance only of the parabolic concentrating solar collector. Very few researchers studied the hydraulic performance of the PTSC inserting different geometries of TT and also, similar studies have been studied in the hydraulic system. Therefore, the present theoretical work has been focused to study the heat transfer augmentation by inserting the TT inside the absorber tube of the PTSC. The TT is specified by twist ratio (Y = H/Di) and TT inserted absorber tube is shown in Fig. 1.

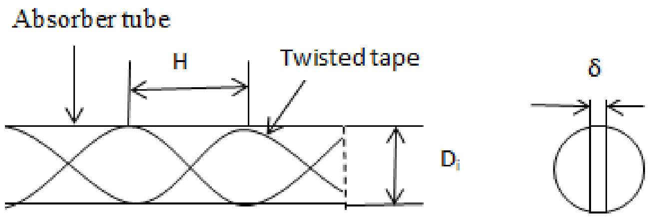

Fig. 1. Twisted tape and absorber tube geometry

II. Data Analysis and Collection

The calculation based on 1st April 2017 at IIT (ISM) Dhanbad (Latitude 23.875° and Longitude 86.444E). Dimension of the PTSC without TT inserted absorber tube is considered as: for trough length L=1.2 m, width W=0.8 m, reflectivity ρ=0.90; absorber tube's length, L=1.2 m, inner diameter, Di =0.016m, outer diameter, Do=0.020, thermal conductivity k=386W/m-K, absorptivity α=0.90, emissivity ε=0.90, intercept factor γ=0.95 and the same dimension is assumed for the plain absorber tube. For the plain absorber tube with and without TT inserts, Nusselt numbers, friction factors, and swirl parameters were calculated with varying mass flow rate and twist ratio (Y) of the TT. Whereas, for the useful heat gain by the PTC absorber tube mass flow rate is assumed as m=0.04 kg/s. Data were calculated for fully developed turbulent flow and wall temperature uniform throughout the length of the tube. The ranges of values of different operational parameters for plain tube were assumed as: Y= 3, 6, 10 and12; m=0.040-0.12 kg/s; Re =3,100-9,600; swirl flow Reynolds number Re_{sw}=4,600-12,300. The different data studied and calculated included: solar beam radiation, the useful heat gain ($Q_{u,\,th}$), friction factor (fp and fs) and Nusselt number (Nu and Nus) respectively. The thermo-physical properties of water and air were taken at 20°C. For water, density =998.2 kg/m3; Prandtl number Pr=7.02; dynamic viscosity =1004×10-6 Ns/m2; whereas for air, density =1.205kg/m3; dynamic viscosity=18.14×10-6 Ns/m2 and wind velocity Vw=0.5 m/s.

III. Mathematical Analysis

A. Heat gain analysis

The solar beam radiation (I_b) has estimated from [14] as expressed by Eq. 1,

$$I_b = I_{bn} \cos\theta_z \qquad (1)$$

And $$I_{bn} = A \exp[-B/\cos\theta_z]$$

$$\cos\theta_z = \sin\varnothing \sin\omega + \cos\varnothing \cos\delta_s \cos\omega$$

Where, A and B are two constants and calculated from [14]. The declination (δ_s) is calculated from [15] by using the Eq. 2 as expressed below,

$$\delta_s = 23.45\sin[(360/365)/(284+N)] \qquad (2)$$

Tilt factor (r_b) for the beam radiation is calculated from [15] by using the Eq. 3 as expressed below,

$$r_b = \frac{(1-\cos^2\delta \sin^2\omega)^{1/2}}{\sin\varnothing \ \sin\delta + \cos\varnothing \ \cos\delta \ \cos\omega} \qquad (3)$$

The heat flux (S_b) is determined from [15] by using the Eq. 4 as expressed below,

$$S_b = I_b r_b \rho\alpha\gamma + I_b r_b \alpha(D_o)/(W-D_o) \qquad (4)$$

The useful heat gain ($Q_{u,\,th}$) can be determined in terms of F_R, F' and U_l from [15], by using the Eq. 5 as expressed below,

$$Q_{u,th} = L(W-D_o)F_R[S - U_l(T_{fi}-T_a)/C] \qquad (5)$$

Where

$$F_R = (mC_p/\pi D_o L U_l)[1-\exp\{-(F'\pi L D_o U_l)/mC_p\}]$$

$$F' = (1/U_l)[(1/U_l) + (D_o/D_i h_i) + \{D_o \ln(D_o/D_i)/2k_r\}]$$

$$U_l = h_w + h_{p-a}$$

$$h_w = Nu_a k_a/D_a$$

$$Nu_a = 0.3\,Re_a^{\ 0.6}$$

for $1000 < Re_a < 50{,}000$

$$Re_a = V_w D_o/\nu_a$$

And $$h_{p-a} = \varepsilon\sigma(T_p + T_a)(T_p^{\ 2} + T_a^{\ 2})$$

The instantaneous efficiency can be evaluated by using the Eq. 6 as expressed below,

$$\eta_{ie} = Q_{u,th}/(I_b A_T) \qquad (6)$$

B. Heat transfer

Nusselt number (Nu_s) for the twisted tape inserted absorber tube is calculated using Hong and Bergles [16] equation which is written below as:

$$Nu_s = 5.172\left[1 + 0.005484\left\{Pr\left(\frac{Re}{Y}\right)^{1.78}\right\}^{0.7}\right]^{0.5} \qquad (7)$$

The friction factor (f_p) for the plain absorber tube is determined by the equation of Blasius and Jain [17] written below as:

$$f_p = 0.3164/Re^{0.25}$$

$$\text{for } Re \le 10^5 \qquad (8)$$

Whereas, the friction factor in the twisted tape inserted absorber tube is calculated by using the equations of Date and Singham [18], Smithberg and Landies [19] which have been written as:

$$f_s = [4C/Re][Re/Y]^{.03}$$

$$\text{for } 100 \le Re/Y \qquad (9)$$

Where

$$C = 8.821\,Y - 2.1193\,Y^2 + 0.2108\,Y^3 - 0.0069\,Y^4$$

and $$f_s = 4\left[0.046 + 2.1/\sqrt{(Y-0.5)}\right]/Re^n \qquad (10)$$

Where, $n = 0.2[1 + 1.7/\sqrt{Y}]$ for $5\times10^3 < Re < 10^5$

and $1.81 < Y < \infty$

For the plain absorber tube, the Reynolds number is calculated in terms of average flow velocity V_o by the equation as follows:

$$Re = \rho V_o D_i/\mu \qquad (11)$$

Where $V_o = m/\rho A$

Whereas, the twisted tape inserted absorber tube, the swirl flow Reynolds number (Re_s) is calculated on the basis of swirl flow velocity V_s by the equation as follows:

$$Re_s = \rho V_s D_i/\mu \qquad (12)$$

Where $V_s = V_a[1 + (\pi/2Y)^2]^{1/2}$

$$V_a = m/\rho A_{ac}$$

$$A_{ac} = \pi(D_i^2/4) - \delta D_i$$

IV. Result and Discussion

Heat gain by the absorber tube

Fig. 2 presents the change in solar beam radiation (I_b) with respect to time (hour). It is clearly seen from the figure, the value of impinged solar beam radiation (I_b) is 414W/m^2 at 8.0 hour and it arrives at a maximum value 888 W/m^2 at 12:0 hour. Beyond this time, the value of impinged solar beam radiation (I_b) starts to decrease. Fig. 3 shows the variation of useful heat gain ($Q_{u, th}$) with time (hour) for a given water mass flow rate of 0.04 kg/s. It is clearly revealed in the fig. 3 that the useful heat gain ($Q_{u, th}$) of the PTSC increases with time up to noon and afternoon, it starts to decrease. The instantaneous efficiency (η_{ie}) of the PTSC is depicted in fig. 4. As the value of useful heat gain ($Q_{u, th}$) is significantly affected by the impinged solar beam radiation (I_b) therefore, the useful heat gain ($Q_{u, th}$) and instantaneous efficiency of the PTSC both vary with the variation of impinged solar beam radiation (I_b).

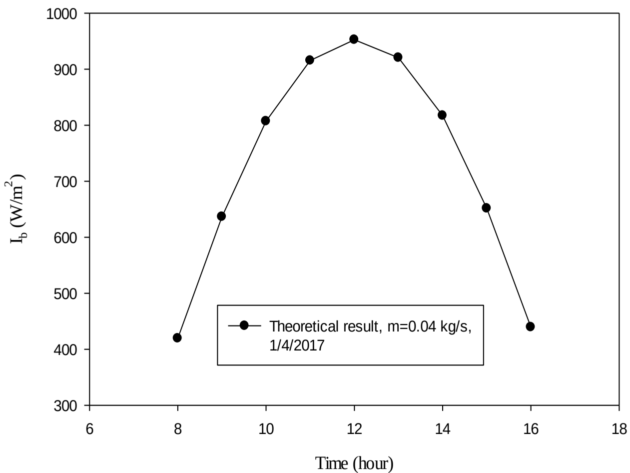

Fig. 2 Variation of Solar beam radiation (I_b) with time (hour).

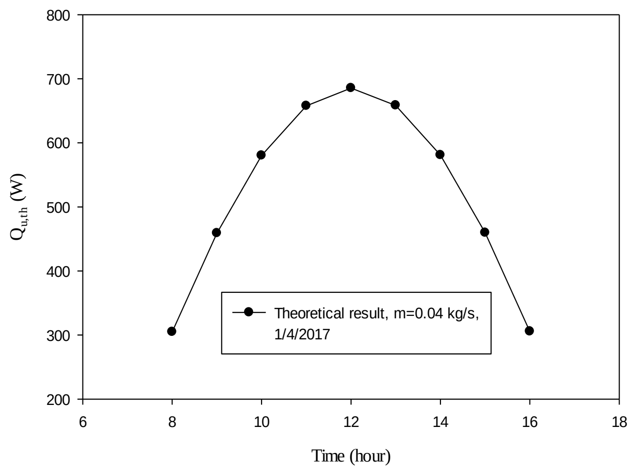

Fig. 3 Variation of the useful heat gain ($Q_{u, th}$) with time (hour).

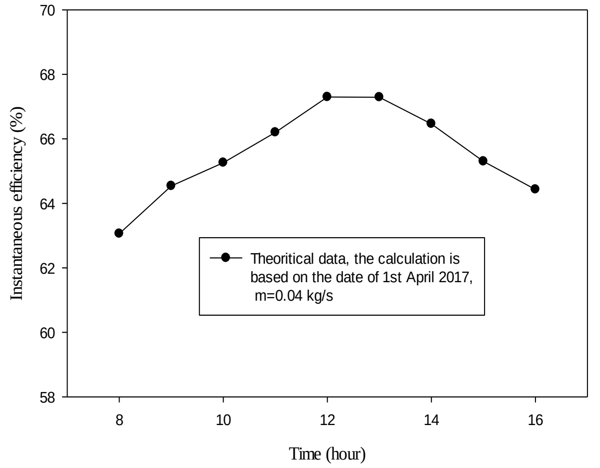

Fig. 4 Change of instantaneous efficiency (%) with time (hour).

Influence of Y over Nusselt number (Nus)

Plots of Nusselt number (Nu_s) vs. Reynolds number are depicted in Figs. 5 and 6 respectively. The change of Nusselt number (Nu_s) increases with Reynolds number for both cases with and without TT inserts in the absorber tube. From Fig. 5, it is clearly seen that the value of Nusselt number (Nu_s) enhances with an increase in Reynolds number and also increases with a lower twist ratio (Y). As the at higher Reynolds (Re) number, the flow is fully developed and turbulent, and TT creates swirl flow and the swirl flow highly affected by the TT with a lower twist ratio (Y). The combined effect enhances the value of heat transfer coefficient and thus, the same effect on Nusselt number (Nu_s) result.

Fig. 6 presents the change of Nusselt number (Nu_s) against Reynolds number (Re) for Y=3 and this variation is validated with the plain absorber tube data and the validation have made between the present theoretical result and experimental result [10] for Y=3. From fig. 6 it is clear that theoretical Nusselt number data are greater than that experimental data for the same Reynolds number (Re) range.

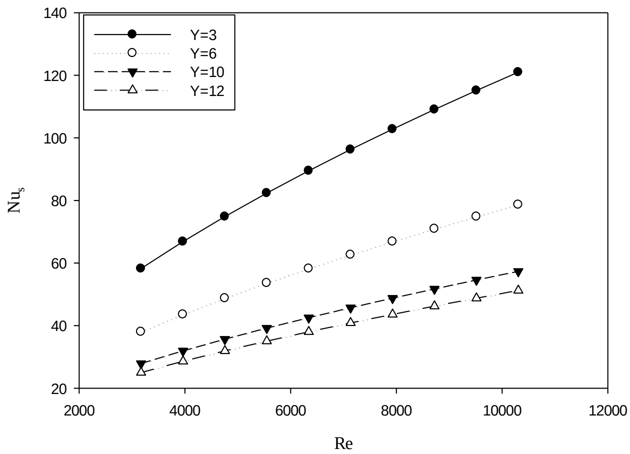

Fig. 5. Change of Nu_s with Re for twist ratio Y=3, 6, 10 and 12.

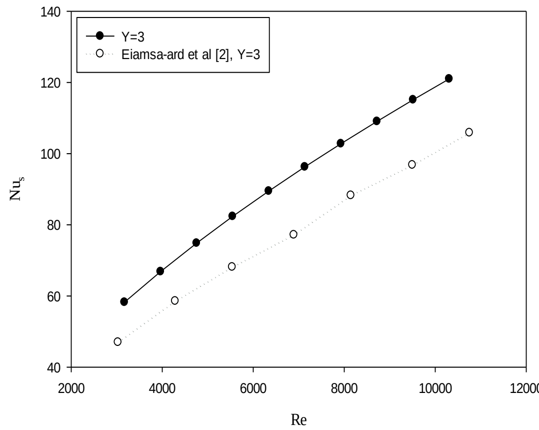

Fig. 6. Change of Nu_s with Re for Y=3 and comparision this result with other experimental result.

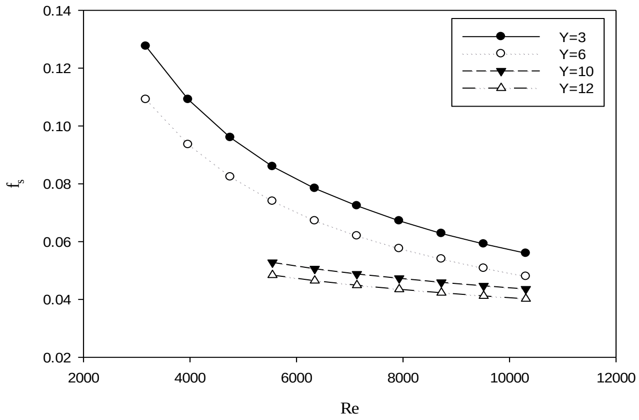

Fig. 8. Change of f_s with Re for Y=3, 6, 10 and 12.

Fig. 7 presents the friction factor (f_p) vs. Reynolds number (Re) for the plain absorber tube and also, the present theoretical result has been validated with the experimental result [10]. From fig. 7 it is clear that the theoretical friction factor (f_p) data are greater than that experimental data for the same Reynolds number range. Fig. 8 presents the change of friction factor (f_s) with Reynolds number (Re) for Y=3, 6, 10 and12 respectively. From this figure, it most clear that friction factor (f_s) reduces with an increase in Reynolds number (Re) value. Also, the value of friction factor (f_s) obtained from the absorber tube with TT inserts comparatively better than that the plain absorber tube data. Moreover, the theoretical friction factor (f_s) calculated for the absorber tube with Y=3 perform much better, due swirling effect highly intensifies and frictional resistance enhances at Y=3. Fig. 9 indicates the effect of the twist ratios (Y=3, 6. 10 and 12) on friction factors (f_p and f_s) with Reynolds numbers (Re and Re_{sw}). For a particular value of Swirl flow Reynolds number (Re_{sw}= 7,500), the friction factor (f_s) have calculated as: 0.0836, 0.0672, 0.0507, 0.0464 (approx.) for the twist ratios (Y) of 3, 6, 10 and 12 respectively, while, for plain absorber tube it is 0.0335 at the same.

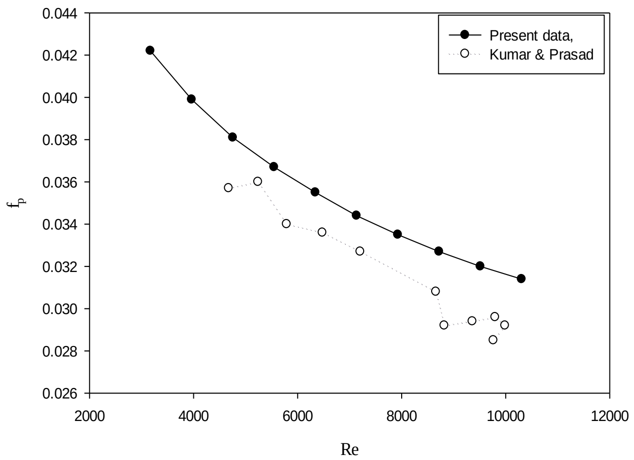

Fig. 7. Variation of f_p with Re for plain absorber tube.

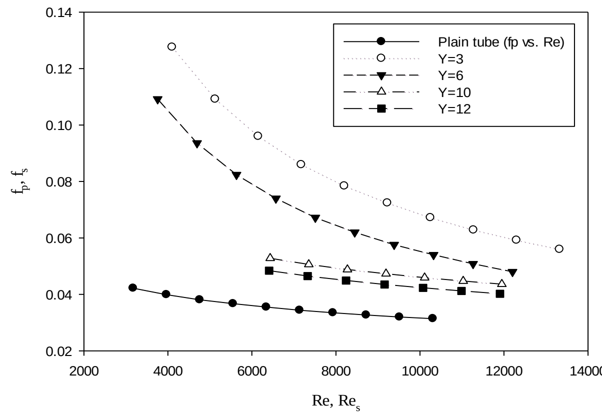

Fig. 9. Change of f_p, f_s with Re, Re_s.

V. Conclusions

Below the conclusions are summarized from the present theoretical investigation:

(i) The impinged solar beam radiation (I_b), useful heat gain ($Q_{u,th}$) and instantaneous efficiency (η_{ie}) these all enhance with time (hour) up to noon. The useful heat gain increases at a faster rate from 8.00 hour and 9.00 hour; after that, it increases at a slower rate up to noon and then it starts to decrease.

(ii) The absorber tube with twisted tape inserts causes the higher value of Nusselt number (Nus) due to swirling flow created by the TT. It has been found that decreasing values of the twist ratio (Y) lead to increasing values of Nusselt number (Nus). Therefore, lower the twist ratio (Y) higher the Nusselt number (Nu_s).

(iii) The increase in friction can be presented by swirl flow induced by TT. It has been seen that decreasing values of the twist ratio (Y) lead to increasing values of friction factor (fp and fs). The swirling effect is significantly enhanced by lowering the twist pitch.

Nomenclature

A plain duct flow cross-sectional area, m^2
A_{ac} axial flow cross-sectional area, m^2
A_T collector aperture, m^2
C_p constant pressure specific heat, J/kgK
D_i internal diameter of the plain tube, m
D_o external diameter of the plain tube, m

D_h hydraulic diameter of the tube, $(4A_{ac}/P)$, m
f_p fully developed friction factor for plain tube
f_s friction factor for twisted tape inserted
h_{ci} convective heat transfer coefficient inside the absorber tube
H pitch for 180° rotation of twisted-tape, m
h_{r-a} axially local heat transfer coefficient, W/(m^2 K)
k fluid thermal conductivity, W/(mK)
L axial length, length of the tube, m
L_T collector length, m
m water mass flow rate, kg/s
Nu_s Nusselt number for twisted tape inserted
PTSC parabolic trough solar collector
Re_{sw} Reynolds number based on swirl velocity, dimensionless
Re Reynolds number based on plain duct diameter, dimensionless
T temperature, K
T_a ambient temperature, K
T_{fi} water inlet temperature, K
T_{fo} water outlet temperature, K
TT twisted tape
Tw wall to fluid bulk temperature difference, K
Va mean axial velocity, m/s
V_o mean velocity based on plain duct diameter, m/s
V_s actual swirl velocity at duct wall, m/s
V_w wind velocity, m/s
W_T collector width, m
Y twist ratio, dimensionless.
Greek symbols
δ thickness of the twisted tape, m
δ_s declination of collector, (degree)
ρ fluid density, kg/ m^3
μ fluid dynamic viscosity, kg/ (s m)
g thermal performance factor

VI. References

1. Ceylan, I. and Ergun, A. 2013. Thermodynamics analysis of a new design of temperature controlled parabolic trough collector. International Conversion and Management 74, 505–510.
2. Eiamsa-ard, S., Wongcharee, K., Eiamsa-ard, P. and Thianpong, C. 2010. Heat transfer enhancement in a tube using delta-winglet twisted tape inserts. Applied Thermal Engineering 30, 310–318.
3. Eiamsa-ard, S, Thianpong, C, and Promvong, P. 2006. Experimental investigation of heat transfer and flow friction in a circular tube fitted with regularly spaced twisted tape elements. International Communications in Heat and Mass Transfer 33, 1225–1233.
4. Chang, S. W, Yang, T. L and Liou, J. S. 2007. Heat transfer and pressure drop in tube with broken twisted tape insert, Experimental Thermal and Fluid Science 32 (2007) 489–501.
5. Chang, S. W, Jan Y. J., and Liou, J. S. 2007. Turbulent heat transfer and pressure drop in tube fitted with serrated twisted tape, International Journal of Thermal Sciences 46, 506–518.
6. Manglik, R. M. and Bergles, A. E. 1993. Heat Transfer and Pressure Drop Correlations for Twisted-Tape Inserts in Isothermal Tubes: Part I – Laminar Flows, Journal of Heat Transfer 115, 881–889.
7. Al-Fahed, S., Chamra, L. M. and Chakroun, W. 1999. Pressure drop and heat transfer comparison for both microfin tube and twisted-tape inserts in laminar flow, Experimental Thermal and Fluid Science 18, 323–333.
8. Guo, J., Fan, A., Zhang, X. and Liu, W. 2011. A numerical study on heat transfer and friction factor characteristics of laminar flow in a circular tube fitted with center-cleared twisted tape. International Journal of Thermal Sciences 50, 1263–1270.
9. Kumar, A. and Prasad, B.N. 2000. Investigation of twisted tape inserted solar water heaters heat transfer, friction factor and thermal performance results, Renewable Energy 19 (2000) 379–398.
10. Seemawute, P. and Eiamsa-ard, S. 2010. Thermo-hydraulics of turbulent flow through a round tube by a peripherally-cut twisted tape with an alternate axis, International Communications in Heat and Mass Transfer 37, 652–659.
11. Bhakta, A. K., Kumar, B. and Singh, S. N. 2016. Investigation on Thermal Performance of a Cylindrical Parabolic concentrating Solar Water Heater, Indian Journal of Science and Technology 9 (48) 1–6.
12. Bhakta, A. K., Panday, N. K. and Singh, S. N. 2018. Performance Study of a Cylindrical Parabolic concentrating Solar Water Heater with Nail Type Twisted Tape inserts in the absorber Tube, Energies 11 (1) 1–15.
13. Bhakta, A. K. and Singh, S. N. 2020. Thermo-hydraulic Performance Analysis of Parabolic concentrating Solar Water Heater. Journal of Thermal Engineering 6 (5) 802–815.
14. Iqbal, M. 1983. An Introduction to Solar Radiation, Academic Press, Canada.
15. Garg, H. P. and Prakash, J. 2005. Solar Energy Fundamentals and Applications, New Delhi, www. Tata McGraw-Hill.Com.
16. Hong, S. W. and Bergles, A. E. 1976. Augmentation of laminar flow heat transfer in tubes by means of twisted tape inserts, Journal of Heat Transfer, Trans. ASME, 98: 251.
17. Jain, A. K. 1976. Accurate explicit equation for friction factor, J. of Hyd. Div., ASCE: 674–677.
18. Date A. S. and Simgham, J. R.1972. Numerical prediction of friction and heat transfer characteristics of fully developed laminar flow in

tubes containing twisted tapes. ASME, Paper12-HT–17.

19. Smithberg E, and Landies, F. 1964. Friction and forced convection heat transfer characteristics in tubes with twisted tape swirl generators. Journal of Heat Transfer, Transactions of ASME, 86: 39–49 Series C.