THEORETICAL INVESTIGATION ON HEAT TRANSFER AND FRICTION FACTOR CHARACTERISTICS OF CYLINDRICAL PARABOLIC CONCENTRATING COLLECTOR WITH TWISTED TAPES

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ABSTRACT
The present work deals with the theoretical study on heat transfer characteristics and the performance of a cylindrical parabolic solar water heater with twisted tape inserted inside the absorber tube. The absorber tube equipped with twisted tape with six different twist ratios 5, 6, 7, 8, 9 and 10. The theoretical work is conducted in a turbulent flow regime and considering water as a working fluid flowed through the absorber tube, the Reynolds number varied from 5410 to 31033 within the range of study. The theoretical results showed that Nusselt number and friction factor increase with smaller twist ratio for a given mass flow rate. Over the range investigated, beam radiation, useful heat gain and efficiency were found high at noon and reach maximum in winter Season.

Key words: Efficiency; heat transfer enhancement; parabolic trough; solar water heater; twisted tape.

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1. INTRODUCTION
Solar energy is free of cost, stable and without polluting source of energy. Cylindrical parabolic concentrating solar collector is a system in which radiation energy is focused on the focal axis of the parabola and the absorber tube located at the focal axis through which fluid to be heated flows. Solar
parabolic trough collectors are the best and cheapest technique for collecting solar thermal energy. Most of the applications are in Power generation, Swimming pool heating, Industrial processes and some domestic uses is a popular concept in India and abroad.

In recent time there has been renewed interest in non conventional solar water systems because of its application for achieving maximum collector performance out of different non conventional solar energy collectors, power generation, Swimming pool heating, Industrial processes, are some of the important application of solar energy.

Huang et al. [1] developed and analyzed a new analytical model for optical performance and a modified integration algorithm which were applied to simulate the performance of a parabolic trough solar collector with vacuum tube receiver. Fadat et al. [2] investigated the solar adsorption cooling machine where the rector was heated by a parabolic trough collector and was coupled with heat pipe (HP). Reddy and Kumar [3] have investigated and analyzed solar parabolic trough collector field power generation, and they used different type of working fluids like oil and water. Kumarasan et al. [4] have presented out a study to investigate the performance of a solar parabolic trough collector integrated with a storage unit. Padilla et al. [5] used a detailed one dimensional numerical heat transfer analysis over parabolic trough collector.

Yousefi et al. [6] have studied the effects of a surfactant to Al$_2$O$_3$/Water nanofluids on the thermal efficiency of a using flat plate solar collector. They found that the nanofluid with a weight fraction of 0.2% provides a higher thermal efficiency than that of the weight fraction of 0.4%. They also concluded that adding surfactant increases the efficiency up to 15%.

Eiamsa-ard et al. [7] experimentally investigated the heat transfer enhancement in the tube fitted with oblique delta-winglet twisted tape and straight delta-winglet twisted tape at different twist ratios. The results showed that Nusselt number and friction factor in the tube fitted with the delta-winglet twisted tape increase with decreasing twisted ratio. The O-DWT is more effective than the S-DWT.

Paisarn Naphon et al. [8] have investigated heat transfer characteristics and the performances of the flat plate solar water heater were studied numerically. The results obtained from the model are compared with the experimental data obtained from previous works.

Bhuiya et al. [9, 10] experimentally studied the performance of heat transfer for turbulent flow through a tube with double and triple helical tape inserts.

Faik A. Hamad et al. [11] Have studies experimentally the parabolic trough collector consists of a reflector and absorber. The reflector 1m in length and 1m in width and the diameter of the absorber is 0.0125 m. The researcher found that the collector performance depends mainly on water mass flow rate, and there was no significant change when the mass flow rate becomes more than ten kilograms per hour. Kumar and Prasad [12] experimentally investigated the performance of twisted tape inserted solar water heater. They carried out the experiment with twist ratio of twisted tape are: Y=3, 6, 10 and 12 respectively and within the range of Re from 4000 to 21,000. They pointed out that heat transfer rate and friction factor enhances with using twisted tapes. Also, their result shows that heat transfer rate increases with twist ratio Y=3 than that obtained with twist ratio 12.

Hsieh et al. [13] have conducted experimental studies for heat transfer and pressure drop of laminar flow in horizontal tubes with/ without longitudinal inserts. They reorted that enhancement of heat transfer as compared to a conventional bare tube at the same Reynolds number to be a factor of 16 at Re ≤ 4000, while a friction factor rise of only 4.5.

Saha and Dutta [14] have observed that, for regularly spaced twisted-tape elements, thermo hydraulic performance of twisted tape s with multiple twists in the tape module is not much different from that with single twist in the tape module. Twisted tapes with gradually decreasing pitch perform worse than their uniform-pitch counterparts. Saha et al. [15, 16] have introduced regularly spaced twisted tape elements which are better than full length twisted tapes under certain circumstances.
However, a research of technical literature review indicates that only a limited amount of work has been done in cylindrical parabolic concentrating solar collector with twisted tape inserted in the absorber tube. The present work is motivated.

- To study on steady and transient Performances of the Cylindrical Parabolic Concentrating Solar collector with and without twisted tape inserted inside the absorber tube.
- To study the instantaneous efficiency of Cylindrical Parabolic Concentrating Solar collector;
- To study the variation of the Nusselt number with a Reynolds number for different twist ratios;
- To study the variation of friction factor with a Reynolds number for different twist ratios;
- To study the useful heat gain, overall heat loss coefficient.

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>Aap</td>
<td>Aperture area [m²]</td>
</tr>
<tr>
<td>Ac,r,int</td>
<td>Cross sectional area of absorber tube [m²]</td>
</tr>
<tr>
<td>Ar,ext</td>
<td>External surface area of receiver [m²]</td>
</tr>
<tr>
<td>Ar,int</td>
<td>Internal surface area of receiver [m²]</td>
</tr>
<tr>
<td>Cp</td>
<td>Specific heat of water [j/kg °C]</td>
</tr>
<tr>
<td>C</td>
<td>Concentration ratio [dimensionless]</td>
</tr>
<tr>
<td>Dr,ext</td>
<td>External diameter of receiver [m]</td>
</tr>
<tr>
<td>Dr,int</td>
<td>Internal diameter of receiver [m]</td>
</tr>
<tr>
<td>F</td>
<td>Collector efficiency factor [dimensionless]</td>
</tr>
<tr>
<td>FR</td>
<td>Heat removal factor of collector [dimensionless]</td>
</tr>
<tr>
<td>H_ab</td>
<td>Absorbed beam radiation [W/m²]</td>
</tr>
<tr>
<td>h_c,i</td>
<td>Convective heat transfer coefficient [W/m² °C]</td>
</tr>
<tr>
<td>hr,r-a</td>
<td>Radiative heat transfer coefficient [W/m² °C]</td>
</tr>
<tr>
<td>h_w</td>
<td>Convective heat transfer coefficient between receiver and ambient [W/m² °C]</td>
</tr>
<tr>
<td>K_a</td>
<td>Conductivity of air [W/m²]</td>
</tr>
<tr>
<td>K_r</td>
<td>Conductivity of water [W/m²]</td>
</tr>
<tr>
<td>L</td>
<td>Collector length [m]</td>
</tr>
<tr>
<td>M</td>
<td>Mass flow rate [kg/s]</td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number of air [dimensionless]</td>
</tr>
<tr>
<td>Qu,th</td>
<td>Theoretical useful energy [W]</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number [dimensionless]</td>
</tr>
<tr>
<td>Tamb</td>
<td>Ambient temperature [°C]</td>
</tr>
<tr>
<td>T_f,i</td>
<td>Inlet fluid temperature [°C]</td>
</tr>
<tr>
<td>T_f,o</td>
<td>Outlet fluid temperature [°C]</td>
</tr>
<tr>
<td>U_l</td>
<td>Overall heat loss coefficient [W/m² °C]</td>
</tr>
</tbody>
</table>

**Greek symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>Absorptance [dimensionless]</td>
</tr>
<tr>
<td>θ</td>
<td>Aperture angle [red]</td>
</tr>
<tr>
<td>η_th</td>
<td>Theoretical thermal efficiency [dimensionless]</td>
</tr>
<tr>
<td>ν_a</td>
<td>Kinematic viscosity of air [m²/s]</td>
</tr>
<tr>
<td>ν_w</td>
<td>Kinematic viscosity of water [m²/s]</td>
</tr>
<tr>
<td>ρ</td>
<td>Reflectivity [dimensionless]</td>
</tr>
<tr>
<td>σ</td>
<td>Stefan- Boltzman constant [5.6697*10^8 W/(m²K⁴)]</td>
</tr>
</tbody>
</table>
2. TESTS OF THE MANUFACTURED COLLECTOR

The hourly beam has been calculated during the time interval between 8.00 h to 16.00 h in winter season of 2015 and in summer season of 2016 at IIT(ISM) Dhanbad, Jharkhand (India). At this location the values of Latitude and Longitude are such as 23.8144° N, 86.4412° E. The cylindrical parabolic concentrating solar collector which consists of a cylindrical parabolic concentrating reflector and copper absorber tube is placed along the focus line of the reflector as shown in fig. (1). Present theoretical work is carried out assuming the geometry of cylindrical parabolic concentrating solar collector such as: parabolic trough length 1.9m; slope of the collector 23°; reflectivity of the collector 0.9. For copper absorber tube, internal diameter 0.040m, external diameter 0.045m, absorptivity 0.8, and conductivity 385W/m°K. This tube is painted with a black color, in order to receive the solar rays from the reflector.

![Figure 1 Schematic sectional view of parabolic trough collector](image1)

![Figure 2 Twisted tape (twist ratios Y = H/Di)](image2)
3. TECHNICAL SPECIFICATION OF THE CYLINDRICAL PARABOLIC TROUGH COLLECTOR

Cylindrical parabolic reflector
- Length 1.9 m
- Arc length 2 m
- Focal length 0.21 m
- Material SS

Absorber tube
- Outer tube diameter 0.045 m
- Inner tube diameter 0.040 m
- Material copper
- Length 1.9 m

Twisted tape
- Length 1.9 m
- Material SS
- Diameter 0.04 m

Glass envelope (Pyrex glass)
- Outer diameter 0.066 m
- Inner diameter 0.064 m

4. DATA PROCESSING

4.1. Calculation of Solar Radiation

The incident solar beam radiation on the horizontal surface can be calculated by ASHRAE model [16]

\[
I_b = I_{bn} \cos \theta_z
\]

\[
I_{bn} = A_1 \exp[-B \cos \theta_z]
\]

The values of extraterrestrial solar intensity \(A_1\), the atmospheric extinction coefficient \(B\), where estimated by joudi (1988) [17] for any day of the month by the following equations:

\[
B = 0.175*\left[1 - 0.2*COS(0.93*ND)\right] - 0.0045*\left[1 - COS(1.86*ND)\right]
\]

\[
A_1 = 1158*\left[1 + 0.066*COS(360*ND / 365)\right]
\]

\[
\delta = 23.45\sin\left(\frac{360(284+n)}{365}\right)
\]

Hour angle is calculated as shown by the equation (6) [18].

\[
\omega = 15*[12 - LST]
\]

Where, \(LST\) is local solar time. It is compulsory to covert standard time to solar time by applying two corrections. First there is a constant correction for the difference in longitude between the observer’s meridian location and the meridian on which the local standard time is based, the sun takes four minutes to transverse 1° of longitude.
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\[ LCT = IST - (Lst - Llocl) \times 4 \]

\( LST \) - Local solar time, and \( LCT \) - Local civil time

\[ LST = LCT + E \]

The general definition of the incident angle \( \theta_z \) for any surface orientation can be expressed as [19]:

\[
\cos \theta_z = \sin \delta \cdot \sin \phi \cdot \cos \beta - \sin \delta \cdot \cos \phi \cdot \cos \beta \cdot \cos \gamma \cdot \cos \omega + \cos \delta \cdot \sin \phi \cdot \sin \beta \cdot \cos \gamma \cdot \cos \omega + \cos \delta \cdot \sin \beta \cdot \sin \gamma \cdot \sin \omega
\]

Where,

- \( \gamma \) is the surface azimuth angle. That is, the deviation of projection on a horizontal plane of the normal to the surface from local meridian with zero due to south facing.
- \( \beta \), slope of the solar collector (\( \beta = 23^\circ \) in summer and \( 45^\circ \) in winter season)
- Latitude angle (\( \phi \)).
- Azimuthally angle (\( \gamma \)). It is the angle of deviation of the normal to the surface from the local meridian with zero due to south facing.
- Zenith angle (\( \theta_z \)). It is the vertical angle between the sun’s rays and a line perpendicular to the horizontal plane through point.
- Slope (\( \beta \)). The angle between the horizontal and the plane.
- Hour angle (\( \omega \))
- Declination angle (\( \delta \))

4.2. Calculation of Thermal Efficiency

The data reductions of the measured results are summarized in the following procedures: The useful energy for a cylindrical parabolic trough solar collector is calculated as [20]

\[
Q_{u,a} = A_{ap} F \left[ H_{ab} - \frac{A_{r,ext}}{A_{ap}} U_f (T_{f,a} - T_{amb}) \right]
\]

\[ A_{ap} = (W - D_{r,ext})L \]

\[ A_{r,ext} = \pi D_{r,ext} L \]

The overall heat loss coefficient is calculated as shown by the equation [20]

\[ U_f = h_w + h_{r,r-a} \]

The convective heat transfer coefficient \( h_f \) between receiver and ambient is calculated by the equation (21)

\[ h_w = \frac{Nu_a \cdot k_a}{D_{r,ext}} \]

\[ Nu_a = 0.3 \cdot Re_a^{0.6} \quad \text{For } 1000M < Re < 50000 \]
The radiation heat transfer coefficient between absorber tube and ambient also calculated as shown below the equation \[21\]

\[ h_{r,a} = \varepsilon \sigma (T + T_a) (T_r^2 + T_a^2) \]

Stefan Boltzmann constant \((\sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4)\)

\[ H_{ab} = I_b \alpha \rho \]

\(\rho =\) reflectivity of the reflector

\(\alpha =\) absorptive of the reflector

\(H_{ab} = \) Absorbed radiation

The heat removal factor derived as shown below by the equation \(22\)

\[ F_r = \frac{MC_p}{A_{r,\text{int}}U_i} \left[ 1 - \exp \left( -\frac{A_{r,\text{int}}U_i F^-}{MC_p} \right) \right] \]

Collector efficiency factor derived as shown below by the equation \(22\)

\[ F^- = \frac{1}{U_i} + \frac{D_{r,\text{int}}}{D_{r,\text{ext}}} \ln \left( \frac{D_{r,\text{ext}}}{D_{r,\text{int}}} \right) \]

The convective heat transfer coefficient \(h_{c,i}\) between absorber and the fluid, proposed by as \(23\):

\[ h_{c,i} = \frac{k_e}{D_{r,\text{int}}} \left[ 3.6 + \frac{0.066 \left( \frac{D_{r,\text{int}}}{L} \right) \text{Re} \times \text{Pr}}{1 + 0.04 \left[ \left( \frac{D_{r,\text{int}}}{L} \right) \text{Re} \times \text{Pr} \right]^2} \right] \]

\[ R_e = \rho V D e / \mu \quad M = \rho A V \quad T_{f,o} = T_{f,i} + \frac{Qu}{MC_p} \]

The heat transfer coefficient for twisted tape may be calculated using the correlation as given by Hong and Bergles \(8\) as shown below by the equation \(10\)

\[ Nu = 5.172 \left[ 1 + 0.005484 \left( \text{Pr} \left( \frac{\text{Re}}{X} \right)^{1.78} \right)^{0.7 \times 0.5} \right] \]

Date and Singhams \(24\), they used twisted tap inserted inside the absorber tube and proposed the correlations between friction factor and Reynolds number

\[ f \text{Re} = C2 \times (\text{Re}/X) \times 0.3 \]

\[ C_2 = 8.8201 \times X - 2.1193 \times X^2 + 0.0069 \times X^4 \]

Using Nikuradse experimental result for turbulent flow through smooth tube friction factor calculated as shown by the equation \(25\),
The theoretical thermal efficiency is calculated as:

\[ \eta_{th} = \frac{Q_{u,th}}{I_s A_s} \]

5. RESULTS AND DISCUSSION

The results obtained from the analytically investigation of the performance analysis of the cylindrical parabolic concentrating solar collector are discussed in detail.

![Figure 3](image3.png)

**Figure 3** shows the variation between beam radiation with time.

Figure 3 shows the variation between beam radiation with time and validation this theoretical result with that obtained from the experimental work of Govindraj kumarsan [25] with time. It is seen that the theoretical beam radiation and experimental beam radiation increase from 9:00 AM to a maximum value at noon and then descends until 4:00 PM. Also, the figure shows that the theoretical beam radiation is (7-12) % more than that of the experimental result [25].

![Figure 4](image4.png)

**Figure 4** Variation of Nusselt Number (Nu) with Reynolds number (Re) for the typical twisted tape at different twist ratio.
Figure 4 shows the variation of Nusselt Number with Reynolds number for the absorber tube with twisted tape inserted and without twisted tape inserted. Also, Nusselt Number increases with Reynolds number for a given twist ratio. Due to artificial turbulence exerted by twisted tape the rate of heat transfer increases. Nusselt Number increases with smaller twist ratio. This is also due to more intense swirl flow in case of the lower twist ratio. Nusselt number with twisted tape inserted absorber tube is more than that of a without twisted tape inserted absorber tube. Due to super mixing of fluid between fluid at the inside tube wall region and fluid at the core region.

Figure 5 shows the variation of pressure drops with mass flow rate of the inside of the fluid. It has observed that the pressure drop increases with the mass flow rate. The values of the pressure drop where potentially high with the increasing of Reynolds numbers. The pressure drop with twisted tape inserts is higher than that without twisted tape inserts because of the swirling flow and the dissipation of the dynamic pressure of the fluid.

Figure 6 shows that the variation of friction factor with Reynolds number for different twist ratios. It can be clearly seen that the friction factor decreases with Reynolds number. As expected, the friction factor data obtained from the absorber tube with twisted tape insert is significantly
higher than that without twisted tape insert. Moreover, the results demonstrated that the use of smaller twist ratio leads to the higher friction factor due to stronger swirl increased with shorter pitch length (H). Therefore, the twisted tape with $Y = 5.0$ has a maximum friction factor whereas, the one with $Y = 10.0$ has the lower friction factor.

![Graph](image)

**Figure 7** Variation of heat transfer coefficient versus mass flow rate (kg/sec).

Figure 7 Shows that the variation of heat transfer coefficient with mass flow rate. The heat transfer coefficient increases with mass flow rate due to this, the collector efficiency factor and the collector heat removal factor and the efficiency increase.

![Graph](image)

**Figure 8** Variation of useful heat gain with time (hr).

Figure 8 Shows that the variation of theoretical useful heat gains with time. It can be clearly observed that the heat gain rate significantly an increase from 8.00 h to noon and after noon starts to decrease up to 16.00. This is due to fact that beam radiation strongly increases between 8.00 h to 9.00 h and after that increases at a slower rate until noon to a peak value.
Figure 9 shows the variation of efficiency with time. Also, the above figure shows the comparison between the theoretical efficiencies obtained in winter and summer seasons. It is seen that the theoretical efficiency obtained in winter season is (7-15) % more than that obtained in summer season. 9:0 AM to noon a maximum value and then descends until 4:0 PM.

6. CONCLUSION

In the present work, theoretical study has been carried out to investigate the performance of cylindrical parabolic concentrating solar collector by means of twisted tape inserts in a absorber tube. From the present theoretical results, conclusions can be drawn as follows:

- The heat transfer enhancement increases with twist ratio 5 than that obtained using twist ratio 10. It is due to the more swirl effect created by the twisted tape of twist ratio 5.
- The friction factor increases with the smaller of the twist ratio due to swirl flow exerted by the twisted tape.
- The lower the twist ratio performs much better than the higher twist ratio inserts.
- The beam radiation calculated theoretically in winter season is more by 9.3% than that calculated in summer season.
- The theoretical useful energies obtained in summer and winter seasons are less than the
- The useful energy obtained in summer is 12% more than the energy obtained in the winter season.
- The thermal efficiency increases from 9:0 AM to noon a maximum value and then descends until 4:0 PM.
- The theoretical efficiency obtained in Winter season is (7-15) % more than the theoretical efficiency obtained in Summer Season.

REFERENCE

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