Parametric Study of Heat Characteristics of Fluid in Cylindrical Parabolic Concentrating Solar Collector.

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ABSTRACT

This paper presents a numerical investigation of heat transfer characteristics of fluid in Cylindrical Parabolic Concentrating Solar Collector in Ogbomoso Climatic Conditions (lat $8^{o}01^{I}$, long $4^{o}11^{I}$). The parametric studies were conducted to investigate the effects of twist tape ratio, $^{H}/_{D}$ in different fluids and length on the system performance as function of instantaneous efficiency in order to obtain the optimum performance of the system.

A computer simulation program written in C++ language was developed to study the effect of Reynold numbers (Re) from 2,000 to 12,000 for the fixed value of incident solar insolation flux (Ib) of 186 W/m^2 on the system thermal performance, Nusselt number (Nu) as a function of Reynolds number (Re) rate with variable tape twist factor (X = H/Di) for different Prandtl number, Pr in the range of 0.0001 < Pr < 100 (different fluids); liquid metals (Pr << 1), air (Pr = 0.71) and Oil (Pr >> 1).

The results show that oil has highest heat transfer characteristics, Nusselt number values both with and without tape twist factor. It is observed that tape twist factor enhances the heat transfer characteristics of the fluids in cylindrical parabolic concentrating solar collector. The higher value of heat transfer characteristics is obtained with Nusselt number (Nutw) having tape twist factor (X = H/D_i: 1, 3, 6, 9, 12 and 15) in all the fluids considered. It is observed that performance of the cylindrical parabolic trough collector with twisted tape has been enhanced appreciably. These results can guild practicing engineers and designers in the evaluation of the existing real systems and design of future system.

(Keywords: solar collector, twist ratio factor, fluid, Prantl number)

INTRODUCTION

Flat-plate solar collectors are vastly employed in low temperature energy technology and have drawn the attention of a large number of investigators. Several designs of solar air heaters have been industrialized over the years in order to improve their system thermal performance. The thermal performance of solar air heaters is generally low because of the low value of the convective heat transfer coefficient between the absorber plate and the air, leading to high absorber plate temperature and greater heat losses to the surroundings.

It has been found that the main thermal resistance to the heat transfer is due to the formation of a laminar sub-layer on the heat transferring surface. Efforts of improving the heat transfer rate have been directed towards artificially destroying the sub-layer. The suitable design of solar air heaters for high temperatures applications have been the subject of many theoretical and experimental investigations.

Recently, researchers have employed wire screen matrices , expanded metal mesh, finned, corrugated and packed bed as absorbing porous media for directly incident solar radiation in the solar air heater due to improve its performance because as the surface area and turbulence producing air flow path through the bed increase, heat transfer rate increases. The high heat transfer area to volume ratio for the air flowing through these matrices enhances the heat transfer capability. Prasad and Mullic [7]; Momin [12]; Bhagoria [14]; Han [8]; Taslim [10]; Lau [9]; Park [11]; Mital [18] and Saini [13] have carried out investigation on the performance of solar air heater. These studies have indicated that such air heaters have superior performance as compared to that of flat plate collectors.

Recently, much attention has been given to concentrating solar collectors, which are capable of reaching higher temperatures compared to flat plate collectors. Hong [1]; Kumar & Prasad [6] Sharma et al. [16]; and Togrul & Pehlivan [17] have carried out investigations on the twisted tape and reported for enhancement in performance. These works need investigation of the heat and fluid flow phenomena in the absorbing tube by evaluating friction factors, pumping power and convective heat transfer coefficients and comparisons for the alternative cases and may bring into light the factors to construct an economically viewable solar air collector for high temperature applications.

The objective of this paper is to investigate the heat transfer characteristics coupled with twist tape ratio factor, $^{H}/_{D}$ in different fluids; liquid metals (Pr << 1), air (Pr = 0.71) and Oil (Pr >> 1) of fluid in Cylindrical Parabolic Concentrating Solar and effect of Twist Tape factor on the system thermal performance Collector in Ogbomoso Climatic Conditions (lat $8^{o}01^{l}$, long $4^{o}11^{l}$).

METHOD AND MATERIALS

Performance Analysis of Cylindrical parabolic Concentrating Collector

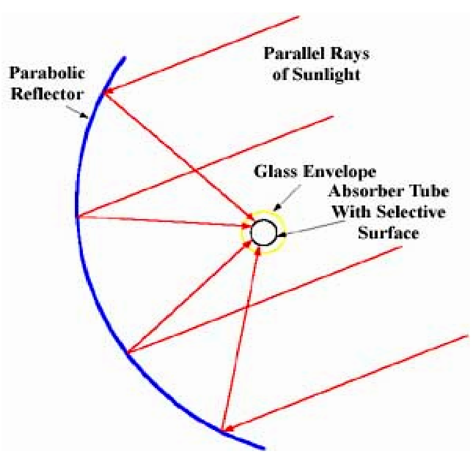

Figure1: Cross Section of Cylindrical parabolic Concentrating Collector.

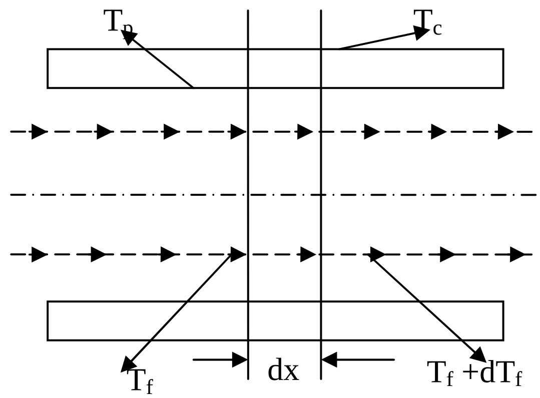

Figure 2: Energy Flow Diagram of Cylindrical Parabolic Concentrating Collector.

Performance Analyses

The structure of a cylindrical parabolic concentrating collector of glass envelope absorber tube with selective surface (Figure 1) of such system having concentrator width aperture ‘W’, length ‘L’, and tilt angle ‘r_b’ .

The performance of a cylindrical parabolic concentrating collector is assumed for the same radiation flux all along the length and the negligible temperature drop across the absorber tube and the glass cover. The energy equations under the steady state conditions can be indicated by Figure 2 and described by the following expression:

$$dq_u = \begin{bmatrix} I_b r_b (W - D_o)\rho\gamma(\tau\alpha)_b \\ + I_b r_b D_O (\tau\alpha)_b \\ - U_L \pi D_o (T_p - T_a) \end{bmatrix} dx \qquad \textbf{(1)}$$

The left side term represents the useful heat gain rate for a length, dx. The first term on the right side represents the incident beam radiation absorbed in the absorber tube after reflection, the second term represents the absorbed incident beam radiation which falls directly on the absorber tube and the third term represents the loss by convention and radiation. Also ργ(τα) represents the optical properties of the system. The intercept factor, ‘γ’ is defined as the reflected fraction of the incident radiation on the absorbing surface of the receiver. τ is the transitivity of transparent cover. α and ρ are the absorptivity and the reflectivity of the absorber and concentrator, respectively.

The absorbed flux 'S' can be given as:

$$S = I_b r_b \rho\gamma(\tau a)_b + I_b r_b D_O(\tau a)_b \left(\frac{D_O}{W - D_o}\right) \quad \textbf{(2)}$$

The inlet fluid temperature (T_{fi}) and outlet fluid temperature (T_{fo}) are established by applying boundary conditions at inlet (x = 0. T_f = T_{fi}) and at outlet (x=L, T_f = T_{fo}). They are written as:

$$T_{f\,i} = \exp\left\{\frac{-F^1 \pi D_O U_L x}{mC_p}\right\} \quad \textbf{(3)}$$

$$T_{fo} = 1 - \exp\left\{\frac{-F^1 \pi D_O U_L x}{mC_p}\right\} \quad \textbf{(4)}$$

Thus the useful gain rate can be expressed as:

$$Q_u = mC_p\left(T_{fo} - T_{fi}\right)$$
$$= F_r\left(W - D_O\right)L\left[S - \frac{U_L}{C}\left(T_{fi} - T_a\right)\right] \quad \textbf{(5)}$$

Where Fr, the heat removal factor is expressed as:

$$F_r = \frac{mC_p}{\pi D_O U_L L}\left[1 - \exp\left\{\frac{-F^1 \pi D_O U_L L}{mC_p}\right\}\right] \quad \textbf{(6)}$$

Equation (5) is the equivalent of the "Hotel-Whillier-Bliss" equation for the flat plate collector. The Instantaneous efficiency can also be determined on the basis of beam radiation alone, if the ground reflected radiation is neglected and it given in Equation (7).

$$\eta_i = \frac{Q_u}{I_b r_b W L} \quad \textbf{(7)}$$

Heat Transfer Coefficients

In order to determine the performance of cylindrical parabolic concentrating solar collector, the correlations are required for calculating the values of convective heat transfer coefficient between the absorbed tube and cover, outside surface of the cover and inside surface of the absorbed tube respectively.

The following correlations are used to calculate the natural convection heat transfer coefficient (hp-c) for the enclosed annular surface between the horizontal absorber tube and the concentric cover [Raithby & Holland].

$$K_{eff} / K = 0.317(Ra)^{1/4} \quad \textbf{(8)}$$

where K_{eff} is the effective thermal conductivity.

The convective heat transfer coefficient (hw) on the outside surface of the cover may be calculated by this equation [Hilpert]:

$$Nu = C_1 \,\mathrm{Re}^n \quad \textbf{(9)}$$

The convective heat transfer coefficient (hf) on the inside surface absorbed tube can be calculated using Dittus-Boelter equation:

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \quad \textbf{(10)}$$

The heat transfer coefficient for twisted tape may be determined using the correlation given by Hong and Burgles.

$$Nu = 5.172\left[1 + 0.005484\left\{\mathrm{Pr}\left(\mathrm{Re}/X\right)^{1.78}\right\}^{0.7}\right]^{0.5} \quad \textbf{(11)}$$

Where X is the Tape Twist Ratio and written as:

$$X = {}^{H}/_{Di} \quad \textbf{(12)}$$

The calculation of the overall heat loss coefficient based on convection and radiation losses proceeds in a manner similar to that adopted for the top loss coefficient. The absorber tube and the glass cover around constitute a system of long concentric tubes. The equation can be written as:

$$\frac{Q_u}{L} = h_{p-c}\left(T_{pm} - T_c\right)\pi D_O$$
$$+ \frac{\left\{\pi D_O\left(T_{pm}^4 - T_c^4\right)\right\}}{\left\{1/\varepsilon_p + \left(1/\varepsilon_c - 1\right)D_O / D_{c1}\right\}}$$
$$= hw\left(T_c - T_a\right)\pi Dc_O + \pi D_O \varepsilon_c\left(T_c^4 - T_{sky}^4\right) \quad \textbf{(13)}$$

Where ${}^{Qu}/_{L}$ is the heat loss per unit length, T_{pm} is the average temperature of the absorber tube, T_c is the temperature attained by the cover and h_w is the wind heat transfer co-efficient.

A simple and flexible program, writing in C++ language was developed based on models above to obtain results under different design and operating conditions. The flowchart for implementing the program is shown in Figure 3.

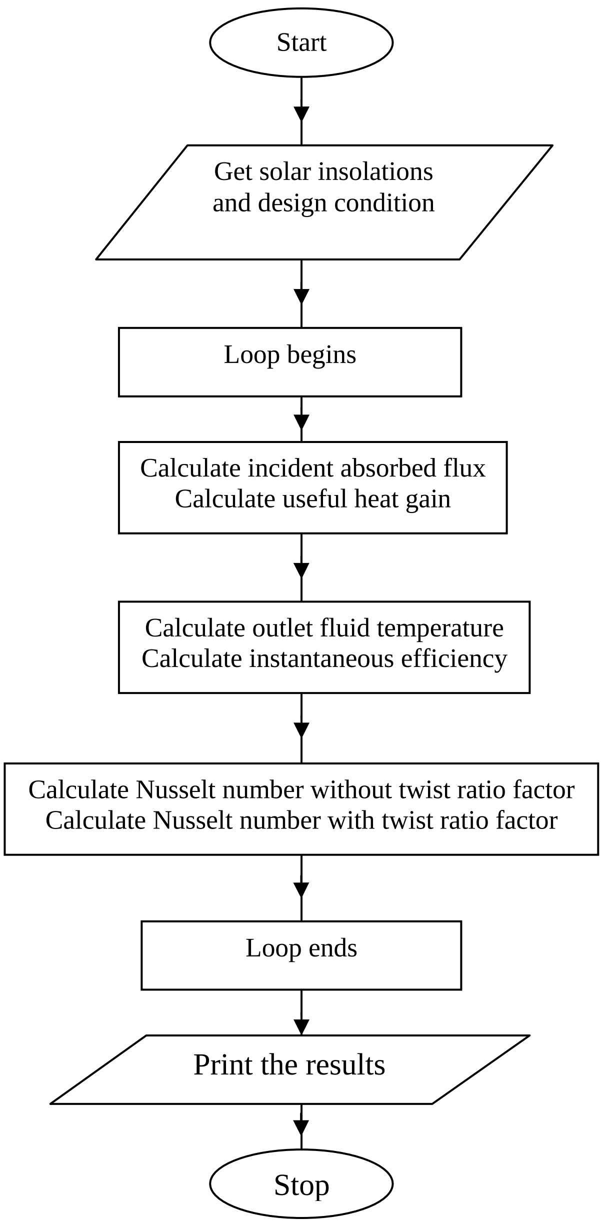

Figure 3: Flow Chart for Solar Collector Calculations.

RESULTS AND DISCUSSIONS

The results obtained from the program developed are presented as profiles in Figures 4 – 15. The effect of Reynolds number (Re) ranges from 2000 to 12000 on the system thermal performance parameter were investigated for different values of Tape Twist Ratio, X = H/Di, (1, 3, 6, 9, 12 and 15) for a fixed constant value of incident beam solar flux (I_b = 186 w/m^2) in Ogbomoso climatic conditions.

Figure 4 shows the plot of Nusselt number (Nu) as a function of Reynolds number (Re) rate without variable tape twist factor (X = H/Di) for different Prandtl number, Pr in the range of 0.0001 < Pr < 100 (different fluids); liquid metals (Pr << 1), air (Pr = 0.71) and Oil (Pr >> 1). It is evident that higher value of Nusselt number is obtained with corresponding higher value of Prandtl number. It is observed that oil has highest heat transfer characteristics without variable tape twist factor.

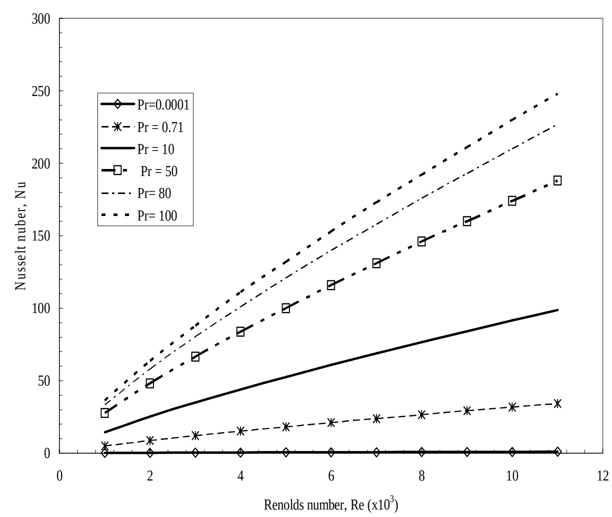

Figure 4: Effect of Reynolds Number, Re-Coupled without Twist Tape Ratio Factor on Nusselt Number, Nu.

Figure 5 shows the plot of Nusselt number (Nu) as a function of Reynolds number (Re) rate with variable tape twist factor (X = H/Di) for different Prandtl number, Pr in the range of 0.0001 < Pr < 100 (different fluids); liquid metals (Pr << 1), air (Pr = 0.71) and Oil (Pr >> 1). It is evident that higher value of Nusselt number is obtained with corresponding higher value of Prandtl number. It is observed that oil has highest heat transfer characteristics with variable tape twist factor

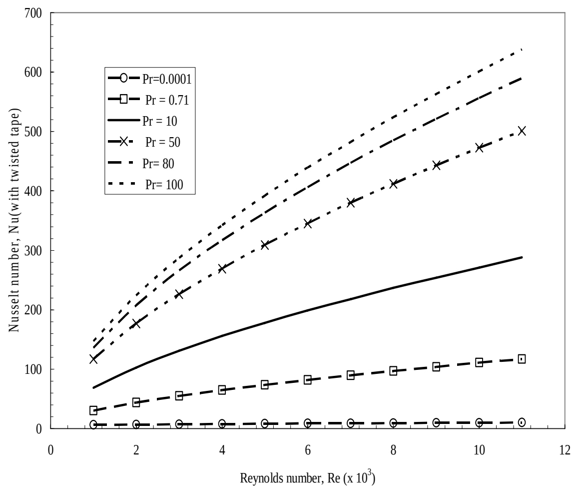

Figure 5: Effect of Reynolds Number, Re Coupled with Twist Tape Ratio Factor on Nusselt Number, Nu.

Figures 6, 7, and 8 present the plots of comparison of Nusselt number (Nu) without tape twist factor (X = H/Di) and Nusselt number (Nutw) with tape twist factor (X = H/Di) as a function of Reynolds number (Re) for different fluids; liquid metals (Pr =0.0001), air (Pr = 0.71) and Oil (Pr = 10). It is evident that higher value of heat transfer characteristics is obtained with Nusselt number (Nutw) having tape twist factor (X = H/Di) in all the three fluids considered.

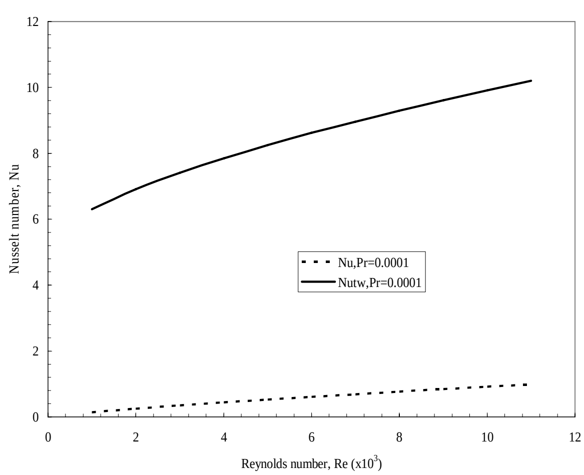

Figure 6: Comparison of Nusselt Number, Nu without and with Twist Tape Ratio Factor for Pr = 0.0001.

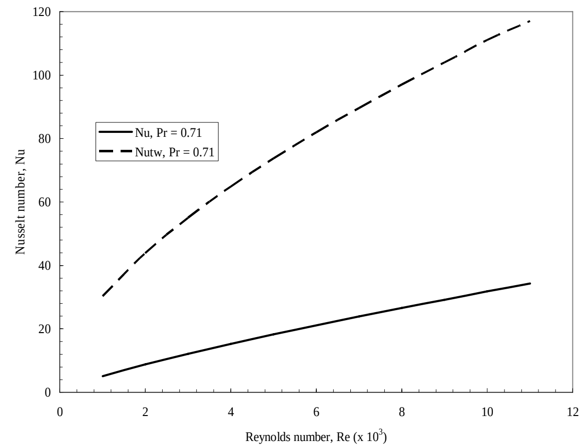

Figure 7: Comparison of Nusselt Number, Nu without and with Twist Tape Ratio Factor for Pr = 0.71.

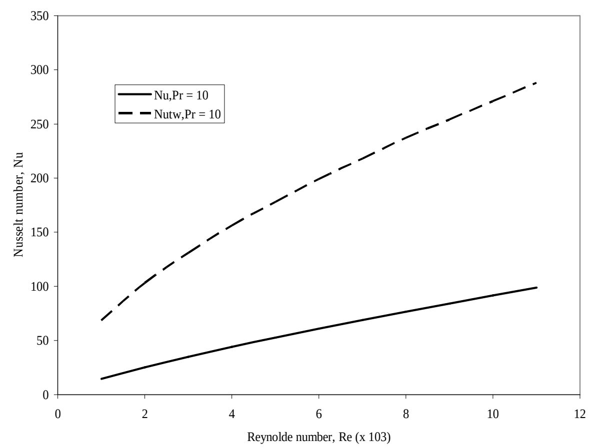

Figure 8: Comparison of Nusselt Number, Nu without and with Twist Tape Ratio Factor for Pr = 10.

It is observed that tape twist factor enhances the heat transfer characteristics of the fluids in cylindrical parabolic concentrating solar collector.

Figures 9, 10, 11 and 12 present the plots of Nusselt number (Nu) as a function of Reynolds number (Re) rate with variable tape twist factor (X = H/Di: 1 ,3, 6, 9, 12, 15) for different fluids; liquid metals (Pr = 0.0001), air (Pr = 0.71), and Oil (Pr = 10). It is evident that higher value of Nusselt number is obtained with corresponding higher value of Prandtl number.

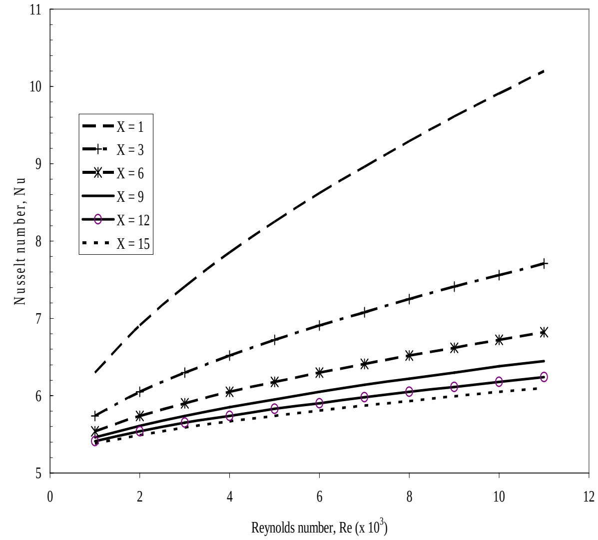

Figure 9: Effect of Reynolds Number, Re Coupled with different Twist Tape Ratio Factor on Nusselt Number, Nu for Pr = 0.0001.

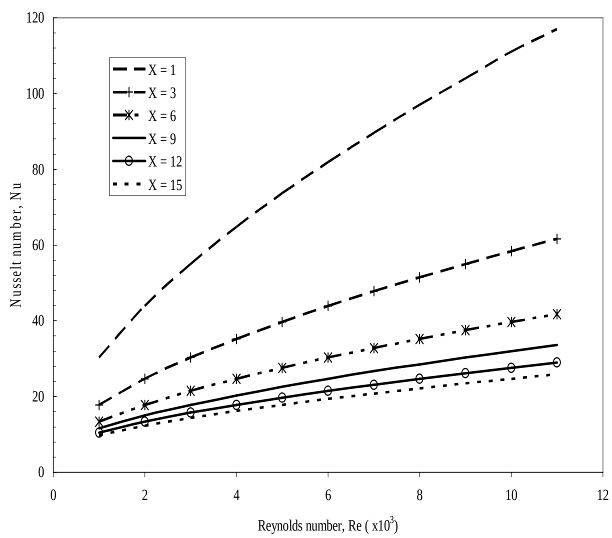

Figure 10: Effect of Reynolds Number, Re Coupled with different Twist Tape Ratio Factors on Nusselt Number, Nu for Pr = 0.71.

It is observed that oil has highest heat transfer characteristics with variable tape twist factor. It is evident that higher value of heat transfer characteristics is obtained with Nusselt number (Nutw) having tape twist factor (X = H/Di) in all the three fluids considered. This is due to the fact that high twisted tape inserted into the absorber increases the friction factor and pressure drop leads to higher pumping power.

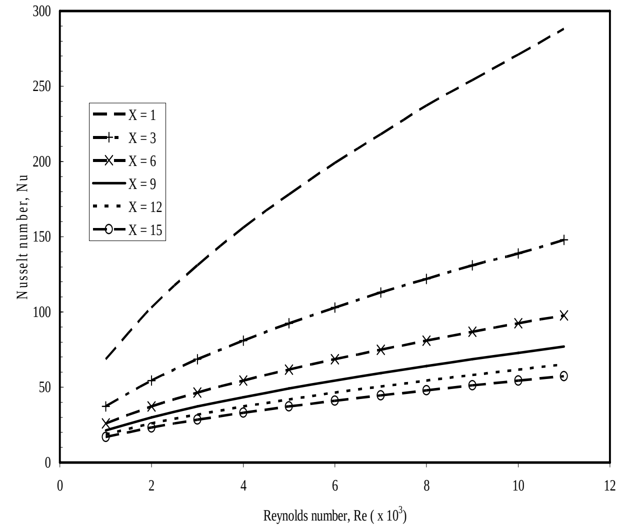

Figure 11: Effect of Reynolds Number, Re Coupled with different Twist Tape Ratio Factor on Nusselt Number, Nu for Pr = 10.

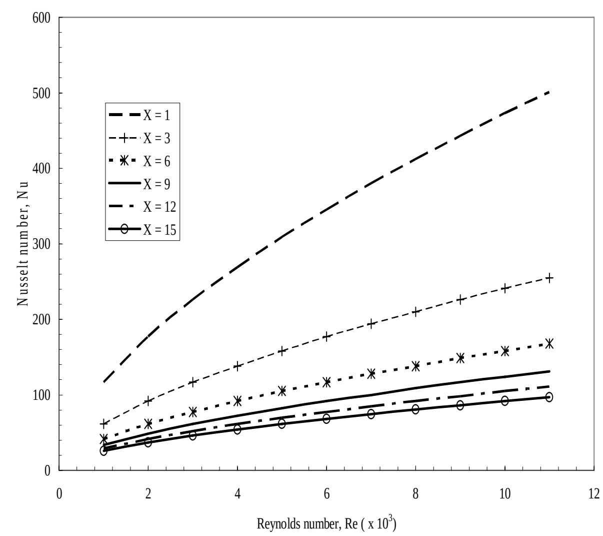

Figure 12: Effect of Reynolds Number, Re Coupled with different Twist Tape Ratio Factor on Nusselt Number, Nu for Pr = 50.

Figures 13 and 14 present the plots of fluid inlet and outlet temperature distribution as a function of mass flow rate (m) and length (L). It is deduced that the optimum design parameters are: length (L) is 1.30 m, mass flow rate is 0.036 kg/s, outlet and inlet fluid temperature is 0.505 with instantaneous collector efficiency of 47.38%, (Figure 15).

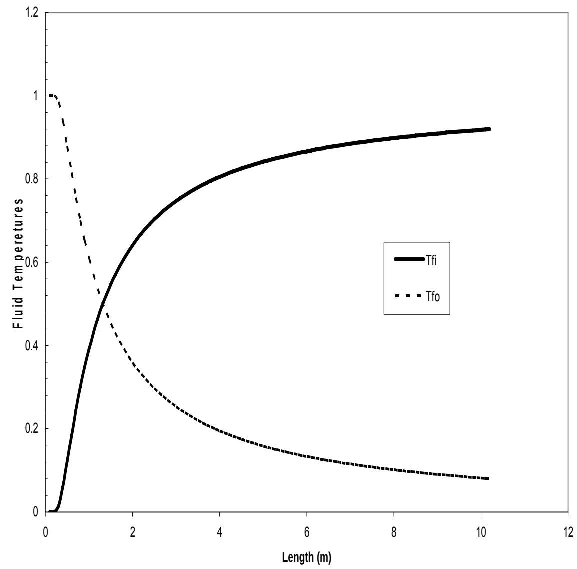

Figure 13: Effect of Length, L on Fluid Inlet and Outlet Temperature.

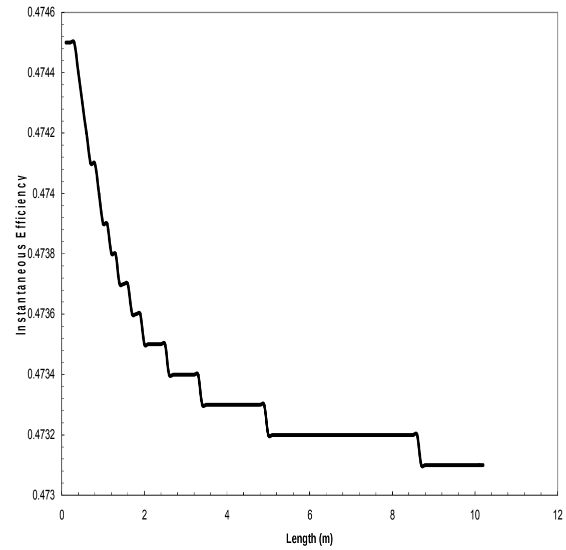

Figure 15: Effect of Variation of Length, L on Instantaneous Efficiency.

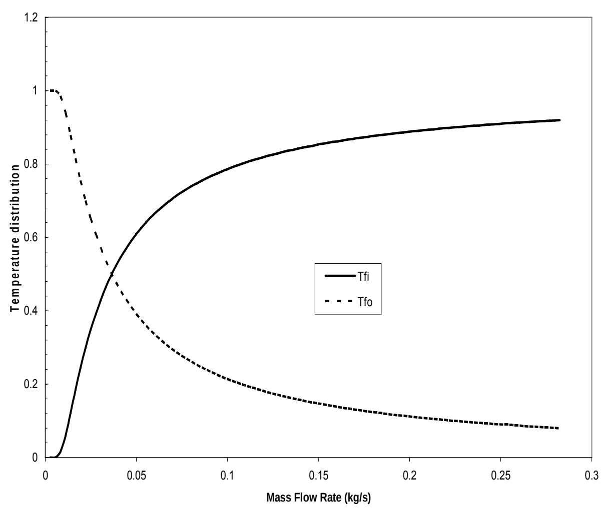

Figure 14: Effect of Mass Flow Rate, m on Fluid Inlet and Outlet Temperature.

CONCLUSIONS

The following conclusions are drawn from the parametric studies conducted investigating the heat transfer characteristics of fluids in the absorber in Cylindrical Parabolic Concentrating Solar Collector in Ogbomoso Climatic Conditions (lat 8°01', long 4°11'). Oil has highest heat transfer characteristics, Nusselt number values both with and without tape twist factor.

It is observed that tape twist factor enhances the heat transfer characteristics of the fluids in cylindrical parabolic concentrating solar collector. The higher value of heat transfer characteristics is obtained with Nusselt number (Nutw) having tape twist factor (X = H/Di) in all the three fluids considered. This is due to the fact that high twisted tape inserted into the absorber increases the friction factor and pressure drop leads to higher pumping power. that the optimum design parameters are: length (L) is 1.30 m, mass flow rate is 0.036 kg/s, outlet and inlet fluid temperature is 0.505 with instantaneous collector efficiency of 47.38%.

NOMENCLATURE

Fr	Collector heat removal factor
h_{p-c}	Heat transfer coefficient between absorber and cover (w/m^3 - K)
h_f	Convention heat transfer coefficient on the inside surface of the tube (w/m^3 - K)
η	Instantaneous Collector efficiency
δ	Stefan-Boltzmann constant (w/m^3 - K)
X	Tape twist ratio
γ	Intercept Factor

I_b	Incident beam radiation (w/m^3 - K)
U_L	Overall heat transfer coefficient (w/m^3 - K)
τ	Transmissivity of glass
α	Reflectivity of glass
ρ	Absorptivity of glass
ε	Emissivity of the plate
Re	Reynolds's Number
Nu	Nusselt Number
Ra	Rayleigh Number

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