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Experimental Studies on Heat Transfer and Friction Factor Characteristics of Forced Circulation Solar Water Heater System Fitted with Left-Right Twisted Tapes

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Abstract – *Experimental investigation of heat transfer, friction factor and thermal performance of left-right twisted tape solar water heater with various twist ratios have been studied and compared with a plain tube collector at the same operating conditions with Reynolds number varied from 3000 to 23000. The empirical correlations developed for Nusselt number and friction factor with various left-right twist ratio(Y= 3, 4, 5, 6) were fitted with the experimental data with in ±15%. Results confirmed that the heat transfer augmentation in left-right twisted tape collector was better than plain tube collector. Compared to various twist ratios, heat enhancement and pressure drop were higher with minimum twist ratio, 3. While comparing the absorber plate temperatures for twist and plain tube collector, it was found to be minimum for twisted tape collector, because higher heat transfer rate reduces the heat losses and increases the thermal performance.*

Keywords – Friction factor, left-right twist tape, Nusselt number, Reynolds number, solar water heater.

1. INTRODUCTION

Depletion of fossil fuels in the fast growing scenario poses a major threat to the human community. Renewable energy utilization has grown in this regard and occupies a good position among other sources of energy. Hence at present the research is focused on exploring new technologies on the performance improvement of such systems. Among the various applications, solar to thermal energy conversion is cheap with minimum conversion losses compared to other methods. Solar water heater plays a vital role in solar to thermal energy conversion. Hence attention is focused on the improvement in the efficiency of the conventional system. Several factors were analyzed by the researchers with respect to conventional solar water heating systems.

Plate efficiency factors performing a major role for the design of solar water heaters was analyzed by [1] and mathematical derivations were proposed for several heat collectors and heat exchangers. Similarly collector efficiency factor and loss factors was also derived analytically by [2]. It proved useful for predicting the performance of collectors with selected flow rates. Besides these efficiency factors, thermal conductivity of absorber plate also decides the performance of solar water heater. It was analyzed by using transient simulation system (TRNSYS) by [3]. Shape of the absorber plate is also one of the factors which determine the thermal performance of solar collectors. The cross-corrugated type absorber plate with solar collector was studied experimentally and verified analytically by [4] and it proved that improved thermal efficiency is obtained by the same.

Besides these, convective heat transfer has a major role to play in the operation of the Solar Water Heating systems. Extensive work had been carried out to improve the convective heat transfer rate by inserting twisted tapes in circular tube, which are mainly applied in heat exchangers. Various types of twisted tape geometry such as helix, kenics, helical screw, coils, wires etc. were used in heat exchanger applications. Among these, kenics have good mixing effect with minimum twist ratio which enhances the heat transfer. This was reported by [5]. Similarly the increase in tube side heat transfer coefficient by the addition of suitable internal elements (kenics) was analyzed by [6]. Kenics in addition to increasing the heat transfer increases the friction factor also. The heat transfer and friction factor characteristics of circular tube fitted with left-right helical screw inserts of equal and unequal length of different twist ratio had been conducted by [7] and they reported that the enhancement of heat transfer is higher in left-right twists instead of helical twists.

Similarly Silapakijwongkul *et al.* [8] conducted the experiment in double pipe heat exchanger by using clockwise and counter-clockwise twisted tape and proved that the convective heat transfer increased nearly by 219% than the plain tube system.

Kumar and Prasad [9] analyzed the barrier in convective heat transfer rate and they used the helical twists in riser tube which resulted in an increase in the Nusselt Number and friction factor in series flow solar water heaters.

The present investigation is focused on to improve the convective heat transfer by inserting left-right twisted tapes in parallel flow Solar water heater and compare its thermal performance to that of the plain tube collector.

2. EXPERIMENTAL SETUP

The experimental setup consisted of flat plate collector of 1m^2 aperture area named as plain tube collector as shown in Figure 1a. The system operated in such a way that the cold water enters the collector from the lower header and was evenly distributed in the riser tubes. The riser tubes were brazed to the bottom of a black absorber plate that

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absorbed solar energy and conducted to the riser tubes. The heat transfer is by convection from the tube wall to the fluid. Finally the hot water was collected from the upper header. A single transparent glass cover of 3mm thickness was used to transmit the solar energy to the absorber plate. The collector and the pipe connections were well insulated to minimize the heat losses. Absorber plate, riser tubes and headers were made up of copper. Taps were provided to measure inlet and outlet temperature of water, absorber plate temperature, riser tube temperature and pressure drop in each riser tube. Figure 1b represented the cross sectional details of the plain tube collector. The twisted tape collector has the same design and dimensions as that of the plain tube collector and was fitted with left-right twisted tapes in the riser tubes as shown in Figure 2. The detailed technical specifications of the collector can be seen from Table 1.

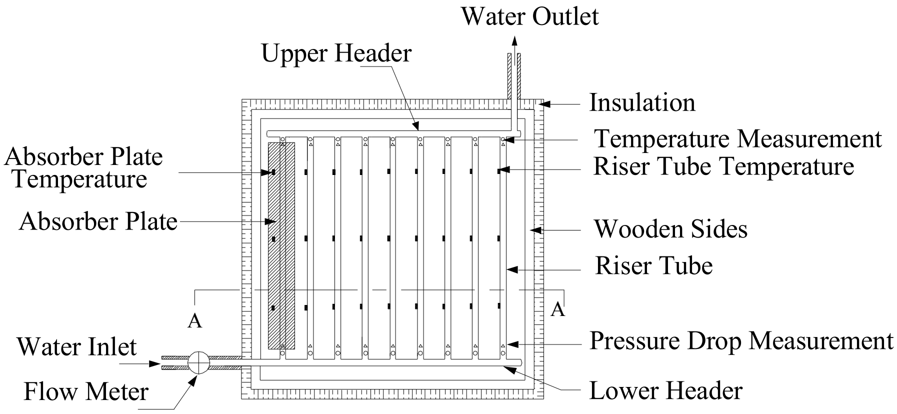

Fig. 1a. Solar water heater (plain tube).

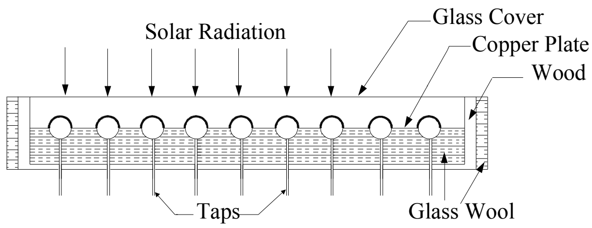

Fig. 1b. Cross section of the solar water heater (plain tube).

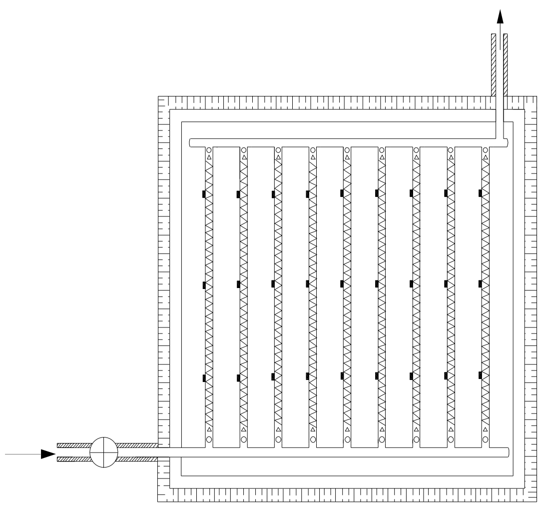

Fig. 2. Solar water heater (left-right twisted tape).

Table 1. Technical specifications of the solar water heating system.

Design materials/parameters	Specifications
Tilt Angle	18^o (South facing)
Aperture area Ac	$1m^2$
Collector glazing	Single transparent glass of 3mm thickness
Lower Header	ID 25.4mm
Upper Header	ID 25.4mm
Riser tubes	OD 12.5mm, ID 11mm, Length 1000 mm
Absorber plate	Width 120 mm, Length 1000 mm
Bottom Insulation	100mm glass wool
Side Insulation	50 mm glass wool covered by aluminium frame
Absorber plate coating absorptivity	0.9
Transmittance of glazing	0.9
Number of riser tubes	9

3. TECHNICAL DETAILS OF LEFT-RIGHT TWIST INSERT

The twisted tape elements were made from thin, flat strips of copper material of thickness 0.3mm and diameter 11mm and were twisted through 180^0 to form helices having twist ratio (length to diameter) of 3 to 6. Helices of alternating left and right hand rotations were formed for a length of 1000 mm as shown in Figure 3.

4. EXPERIMENTATION AND DATA COLLECTION

The work was carried out in Centre for Energy and Environmental Science and Technology (CEESAT) UK-India-REC project located at National Institute of Technology, Tiruchirappalli, India.

Both the plain tube and tube fitted with left-right twisted tape collectors were kept in outdoor condition and faced south direction with a tilt angle of 18^0.

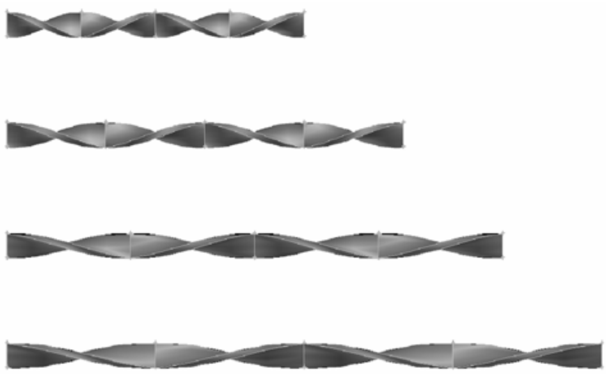

Fig. 3. Left-right twisted tapes (Y=3, 4, 5 and 6)

The experiment was carried out from 09.00 - 13.00hr. Calibrated RTD PT100 type temperature sensors of 0.1^0C accuracy were used to measure inlet, outlet, plate, ambient and tube temperature and were stored in Yokogowa temperature recorder. A small powered pump was used to force water flow through the riser tubes from a recirculating tank. Flow rate was measured by flow meter connected to the inlet of collector. Solar radiation was measured by Kipp and Zonnen pyranometer and pressure drop inside the riser tubes were measured by inclined tube manometer.

5. DATA REDUCTION

The Nusselt number, friction factor and thermal performance were calculated for both the collectors.

Heat Transfer

The Heat Transfer rate in the single riser tube was calculated using the fundamental equation [10].

$$Q = mc_p(T_{out} - T_{in}) = U_0 A_0 (T_{wo} - T_m) \tag{1}$$

where

$$\frac{1}{(U_0 A_0)} = \frac{1}{(h_i A_i)} + \frac{\ln(D_0/D_i)}{(2\pi k_w L)} \tag{2}$$

The internal convective heat transfer co-efficient, h_i was determined by combining Equations 1 and 2. The experimental Nusselt Number was calculated by:

$$Nu = h_i D_i / k \tag{3}$$

All the fluid thermophysical properties were determined at the bulk mean temperature, T_m.

Pressure Drop

The pressure drop for each riser tube over the length was measured by inclined tube manometer, from which the average pressure drop and the friction factor were calculated.

$$f = \frac{\Delta P}{\left(\frac{L}{D_i}\right)\left(\frac{\rho u_m^2}{2}\right)} \tag{4}$$

where ΔP is the pressure drop over the length L.

Thermal Performance

The thermal performance of the solar water heater was calculated using the Hottel-Whillier-Bliss [11] equation as shown

$$\eta = F_R(\tau\alpha) - F_R U_L \frac{(T_i - T_a)}{H_t} \tag{5}$$

The heat removal factor (F_R), transmittance-absorptance product ($\tau\alpha$) was calculated by [12].

Experimental uncertainty was calculated following Coleman and Steele method [13] and ANSI/ASME [14] standard. The uncertainties associated with the experimental data were calculated on the basis 95% confidence level. The uncertainty calculation showed maximum of ±8%, ±10%, ±9% and ±11% for Reynolds number, friction factor, Nusselt number and efficiency respectively.

6. RESULTS AND DISCUSSION

The results obtained in this study were presented, compared with available equations in literature and suitable correlations were developed.

Heat Transfer Rate for Plain Tube Collector

The turbulent flow heat transfer data obtained for plain tube collector was compared with Levenspiel equation for Reynolds number 2100 to 10,000,

$$Nu = 0.116\left(\mathrm{Re}^{2/3} - 125\right)\mathrm{Pr}^{1/3}\left(1+\left(\frac{D_i}{L}\right)^{2/3}\right)\left(\frac{\mu}{\mu_w}\right)^{0.14} \quad (6)$$

and with Dittus – Boelter equation for Re > 10,000

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \quad (7)$$

The experimental Nusselt number was fitted with the above equations for plain tube collector with the discrepancy within ± 13.38% as shown in Figure 4.

Observations made from the Figure indicate that Nusselt number increases with increase in Reynolds number. The increase in Reynolds number creates turbulence inside the riser tube which increases the heat transfer also.

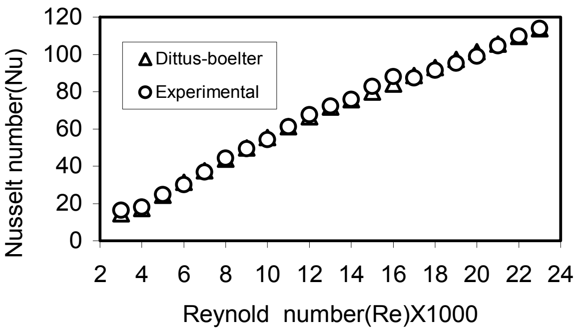

Fig. 4. Nusselt number data verification for plain tube collector

Effect of Left-Right Twists with Various Ratios on Heat Transfer

The variation of Nusselt number with Reynolds number for the riser tube fitted with twist inserts of various Y ratios (Y=L/D) is presented in Figure 5. As evident from the Figure, the Nusselt number increases with increase in Reynolds number. The mixing effect with increase in Reynolds number enhances the degree of turbulence and swirlness effect thereby increasing the heat transfer rate. Also the periodic change in direction of fluid flow magnifies the intensity of swirlness in every pitch distance and increases the hydraulic length of fluid flow. This is found to be more pronounced for a twist ratio of 3 than for higher ratios.

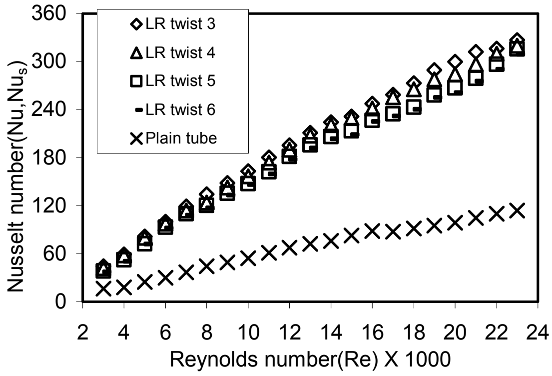

Fig. 5. Variation of Nusselt number with Reynolds number for left-right twists of various twist ratios

For various Y ratios, correlation developed for Nusselt number is as follows

$$Nu_s = 0.00207(\mathrm{Re})^{1.047}(\mathrm{Pr})^{1.4}(Y)^{-0.251} \quad (8)$$

where Nu_s is Nusselt number for twisted tapes. The fitted values of Nusselt number from Equation 8 were compared with the experimental values and are represented in Figure 6. The fitted values were found to agree with the experimental data within ± 15%.

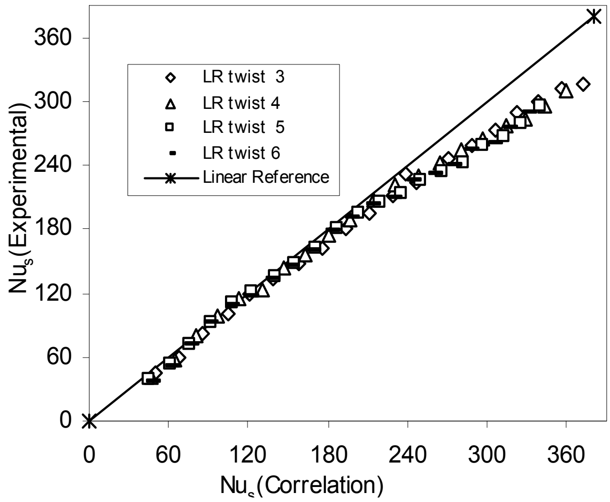

Fig. 6. Comparision of experimental Nusselt number with correlation values

Discussion on Friction Factor Results

The experimental friction factor was fitted with the Blasius equation for plain tube collector with the discrepancy of less than ±8.29% as shown in Figure 7. As evident from the Figure the friction factor decreases with increase in Reynolds number.

Effect of Left-Right Twists with Various Ratios on Friction Factor

As evident from the Figure 8, the friction factor decreases with increase in Reynolds number. Friction factor for left-right twist collector is higher than that for plain tube collector for a given Reynolds number, because greater increase in friction factor due to flow mixing effects caused by the tangential, clockwise and counterclockwise movement of fluid and increased wetted surface area.

Hence the velocity increases which affects the pressure loss of fluid flow near the tube wall.

In twist ratio 3 the mixing effect and wetted surface area are more. If the twist ratio increases, the mixing effects decrease. Hence, the friction factor for ratio 3 is maximum and gradually decreases with increase in Reynolds Number. For various Y ratios, correlation developed for friction factor is as follows

$$f_t = 1189.41(\mathrm{Re})^{-1.105}(Y)^{-0.335} \qquad (9)$$

where ft is friction factor for left-right twisted tapes. The fitted values of friction factor from Equation 9 were compared with the experimental values and are shown in Figure 9. The fitted values from the above equations were found to agree with the experimental data within ± 15%.

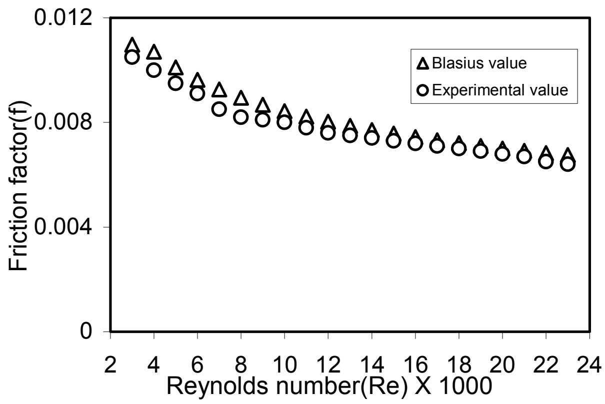

Fig. 7. Friction factor data verification for plain tube collector.

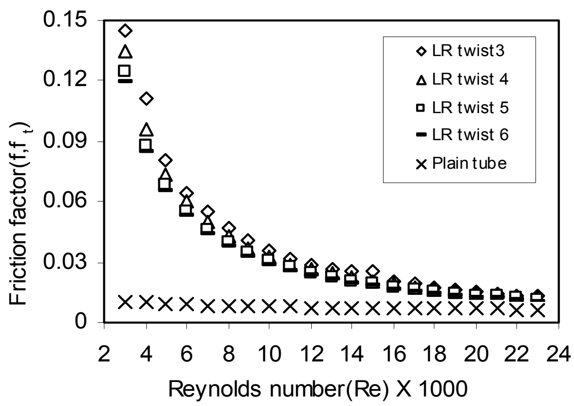

Fig. 8. Variation of friction factor with Reynolds number for left-right twists of various twist ratios.

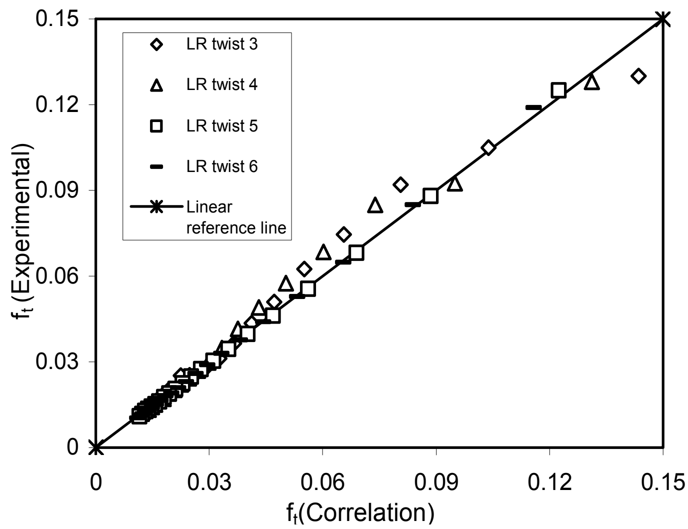

Fig. 9. Comparison of experimental friction factor with correlation values.

Discussion on Thermal Performance Results

The heat transfer enhancement in left-right twisted tape collector is better than plain tube collector. The comparison of instantaneous efficiency of the twisted and plain tube collectors with solar intensity is as shown in Figure 10.

From the aforesaid figure, the efficiency for plain tube collector is always lower than that for left-right twisted tape collectors. The efficiency is maximum for twist ratio 3 and gradually decreases with increase in twist ratio. The swirlness and turbulence is more in twist ratio 3. Hence the heat transfer enhancement is also maximum compared to other twists and decreases gradually as the twist ratio increases.

The value of average plate temperature has been found to be higher in case of plain tube collectors for the same value of solar intensity as shown in Figure 11. Higher value of plate temperature results in increased heat losses leading to lower value of thermal efficiency. The lower value of parameter Y leads to lower value of plate temperature which consequently leads to increase the thermal efficiency because of the effective convective heat transfer coefficient.

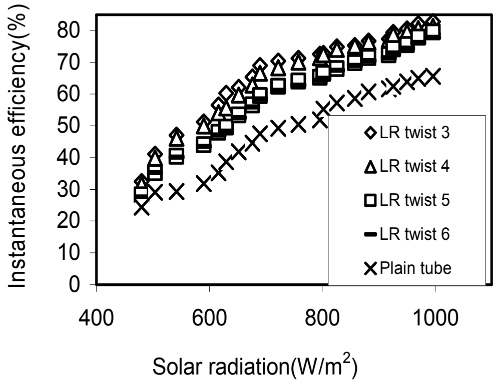

Fig. 10. Variation of Nusselt number with Reynolds number for left-right twists of various twist ratios

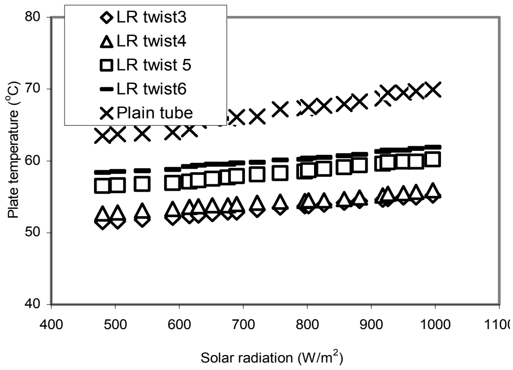

Fig. 11. Effect of twist ratio on average plate temperature in solar water heaters

7. CONCLUSION

Experimental investigation of heat transfer and friction factor characteristics of solar water heater with left-right twist of various twist ratios has been conducted and the findings are presented. The experimental data obtained for plain tube collector is validated with the available fundamental equation and found that the discrepancy is less than ±13.38 % and ±8.29 % for Nusselt number and friction factor respectively. The empirical correlations are developed and fitted with experimental data. Enhancement of heat transfer in left-right twisted tape collector is found to be better than the plain tube collector. Decreasing value of twist ratio (Y) leads to increase the heat transfer rate and pressure drop. Thermal performance of twisted tape collector is higher with decreasing twist ratio and increasing intensity.

NOMENCLATURE

A_c	Collector aperture area, m^2
A_i	Inside surface area of the riser tube, m^2
A_o	Outside surface area of the riser tube, m^2
C_p	Specific heat, kJ/kg °C
D_i	Inside riser tube diameter, m
D_o	Outside riser tube diameter, m
f	Friction factor for plain tube collector, dimensionless
f_t	Friction factor for twisted tape collector, dimensionless
F_R	Collector heat removal factor, dimensionless
H_t	Total solar radiation, W/ m^2
h_i	Average convective heat transfer coefficient W/ m^2 °C
k	Thermal conductivity of water, W/m °C
k_w	Thermal conductivity of the riser tubewall, W/m °C
L	Length of the riser tube, m
m	Mass flow rate kg/s
Nu	Nusselt number for plain riser tube, dimensionless, $Nu = h_i D_i / k$
Nu_s	Nusselt number for twisted tape inserted riser tube (Swirl flow)
Pr	Prandtl number, dimensionless $Pr= C_p\mu/k$
Q	Heat transfer rate, W
Re	Reynolds number based on the internal diameter of the riser tube, dimensionless
T_a	Ambient temperature, °C
T_m	Bulk mean temperature of fluid in the riser tube °C
T_{in}	Average inlet temperature of water, °C
T_{out}	Average outlet temperature of water, °C
T_{wo}	Average wall surface temperature outside riser tube section, °C
u_m	Bulk average water velocity, m/s
U_i	Overall inside heat transfer coefficient, W/ m^2 °C
U_o	Overall outside heat transfer coefficient, W/ m^2 °C
U_L	Overall loss coefficient, W/ m^2 °C
Y	Twist ratio, dimensionless (Length of one twist /diameter of the twist)

Greek letters

ρ	Density of water ,kg/ m^3
μ	Dynamic viscosity of water at bulk mean temperature ,Ns/ m^2
μ_w	Dynamic viscosity at wall temperature ,Ns/ m^2
ΔP	Pressure drop of water, N/ m^2
$T\alpha$	Transmittance-Absorptance product
η	Collector efficiency

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