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Performance Analysis of V-trough Solar Water Heater using Curve Shaped Riser Tubes

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ABSTRACT

An experimental study has been carried out in a V-trough solar water heating system (SWHS) equipped with curve shaped riser tubes (CSRT). By adding CSRT, the performance of the V-trough SWHS has improved. Experiments were carried out at different mass flow rates and different pitch values CSRT. Due to incorporation of reflector and shape of riser tubes leads to better efficiency and performance of the collector. In comparison to a plain tube CSRT offers better thermal performance. The results obtained indicate that curve shaped riser tubes have a larger frictional factor and Nusselt number than the plain riser tubes. As compared to the plain tube, the rise in Nusselt number is 41.04% and 49.43% at 100mm pitch, corresponding to a Reynolds number of 5500 and 14500 respectively.

1. Introduction

Due to rapid population growth, there is a huge requirement for hot water in both residential and commercial settings. Utilizable thermal energy is converted right away from heat energy in solar water heating devices. By using the passive method, solar energy may be transformed into thermal energy without requiring external electricity. This explains why the passive approach is so widely used in both urban and rural settings. However, some of the researches are being conducted at present to increase solar water heaters' thermal efficiency. Zimparov [1] explored the creation of mathematical models to forecast the performance. In order to improve thermal efficiency, Chang *et al.,* [2] conducted a study between a tube having walls that were smooth and perforated tape inserts with twist ratios of 1.56, 1.88, and 2.8.

Eiasma-ard and Promvonge [3] have demonstrated a dual-sided delta wing tape inserts via a front wing in a heat-exchanging tube. The same author additionally carried out a substantial experimental

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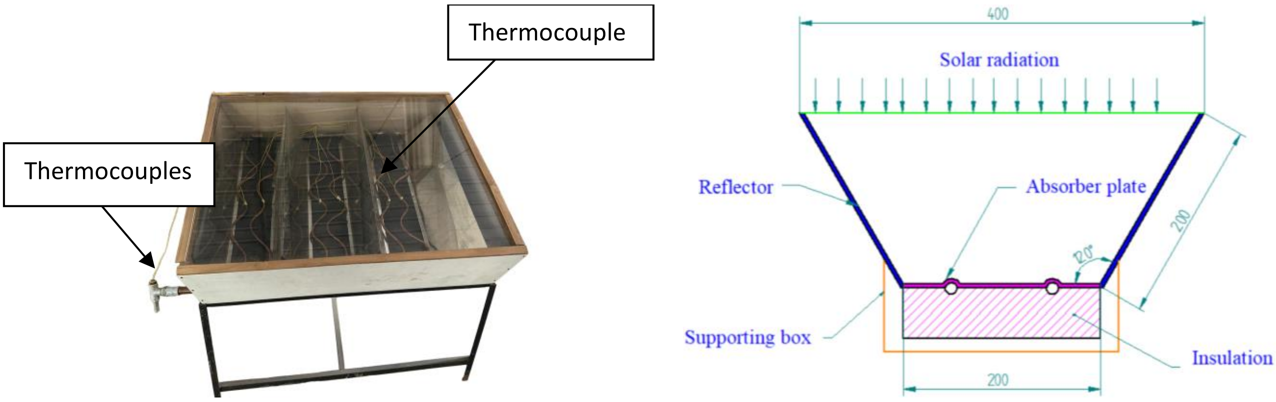
investigation to enhance Nusselt number using helical tape inserts through core rod inserts, spiral tape elements in tandem, and helical-cut tape inserts [4-6].

Kumar and Prasad [7] investigated SWHS using twisting tape inserts to improve the performance. Whenever twisted tape inserts are utilized instead of plain tube, thermal efficiency is improved by 30%. Jaisankar *et al.,* [8] employed spiral twisted tape to enhance heat transfer. The main disadvantage of working with inserts using tape that is twisted is that it boosts the friction factor, which lowers flow rate. The study of the performance improvement of collector with tolerable increases in frictional factor may be found in the studies by Jaisankar *et al.,* [9,10]. Recently, Ananth and Jaisankar [11] used equally spaced twisted tape insert coupled with a bar and spacer to examine performance of the collector.

However, just a few studies have shown the benefits of utilizing reflectors. In their discussion of the impacts of ideal geometries for both single faced as well as double faced symmetrical side wall reflectors, Mannan and Bannerot [12] discovered that, in comparison to one facet designs, two facet designs with a maximum acceptability angle of 9° provide more focus. Puri [13] has investigated how length affects absorbance in a collector with a trapezoidal groove. Similar to this, Kostić and Pavlović's [14] study stated ideal location for the reflector of a collector came to the conclusion that this location maximizes the radiation intensity. These issues can be resolved by using volumetric absorbers, like metal foams, which improve thermal dispersion and provide a more even temperature distribution [15]. WafirulHadi *et al.,* [16] investigated the thermal properties of phase changing materials. There are no experimental investigations in the literature that look at flow in curve-shaped riser tubes. The current research uses tests to assess the efficiency of a V-trough SWHS with curve shaped riser tubes. The novelty of the current work is to study the performance of the collector using curve shaped riser tubes.

2. Methodology

V-trough unit consists of two riser tubes measuring 11 mm in diameter and 1 meter in length, is covered by a 20 cm wide black-coated absorber plate and two reflectors angled 120° with reference to the absorber plate. In a similar manner, three V-Trough units are connected in series. To connect all of the riser tubes on the bottom side, a single lower header is utilized. Similarly, all of the riser tubes in the top side are connected via an upper header. The top side of the absorber plate is covered in 3 mm thick high transmittance glazing glass. Trapezium-shaped floating glass covers the two extremities of the V-trough reflector. Finally, the complete unit is tilted 12° to the south. The lower header permits water from the reservoir to reach the collector, where it is evenly distributed via the riser tubes. The absorber plate uses convective heat transfer to heat the fluid. Figure 1(b) displays the cross-section details for the single V-trough unit. Specifications of SWHS is shown in Table 1.



(a) (b)

Fig. 1. (a) Photograph and specification of SWHS with curve shaped riser tube (b) Specifications of SWHS

Table 1
Specification of the V-Trough SWHS

S. No	Particulars	Value
V-trough collector		
1	Aperture area, A_c	1 m^2
2	Dimension of each riser tube	Outer diameter 13.5 mm, inner diameter 12 mm, length 100 cm
3	Lower side header	Inner diameter 26 mm
4	Tilt angle	12^o (south facing)
5	Insulation	48mm (polystyrene)
6	Number of V- trough collector	3
7	Transmittance of glazing	0.91
8	glazing	40cm x 102 cm x 0.4cm
9	Total number of riser tubes	6
10	Absorber plate of each V- trough collector	20cm x 102 cm x 0.5 cm
11	Absorptive for Absorber plate coating	0.92
12	Upper side header	Inner diameter 26 mm
Reflector		
13	Total number of reflectors for each V- trough collector	2
14	Type of reflector	Glass mirror
15	specification of reflector	19.5cm x 100cm x 0.4
16	Inclined angle of each reflector	60^o

2.1 Experimentation and Data Collection

The site location for this experiment setup is JSS academy of technical education, Bengaluru, Karnataka, India (12° 58' 18.984'' N and 77° 35' 37.284 E). The readings from each trail of the experiment were recorded between March and May of 2024. The experiments were carried out using three curved shape riser tube of 100, 200, 400 mm pitch to evaluate the performance of the collector and the range of the Reynolds number is 5500-14,500. The criteria for The Reynolds number selection are to make sure the turbulent flow regime. The experimental trials were carried out from 9:30 am to 4:00 pm. A data logger is utilized to record the temperature of the absorber plate, the intake and output of each riser tube and the average is calculated. Ambient temperature, inlet and outlet temperature of water, the absorber plate, pressure drop, volume flow rate of water, and the sun's intensity were all observed at regular intervals of time. The trial was conducted on bright, sunny days with a maximum air temperature of 40°C, a maximum wind speed of 2.7 m/sec, and a relative humidity value of about 71%.

2.2 Collector Effectiveness

Experiments were conducted at varied water input temperatures in accordance with ASHRAE guideline 93-86 [17]. Data was collected on various flow rates, intake and exit temperatures, global radiation intensity, and the surrounding temperature. Heat gain (Q_{us}) was calculated using Eq. (1) and Eq. (2), which are presented below.

$$Q_{us} = \dot{m}C_p(T_{out} - T_{in}) \tag{1}$$

$$Q_{us} = A_s F_R[G_t \tau\alpha - U_o(T_{in} - T_{amb})] \tag{2}$$

T_{in} and T_{out} denote the temperature of water at the collector intake and outlet, respectively, while Q_{us} represents the useful heat gain in watts. And $\dot{m}$ (kg/s) represents the mass flow rate, and C_p (J/kg K) is the heat capacity. The product of transmittance-absorptance is represented by $\tau\alpha$. The Hottel-Willier-Bliss equation is used for the evaluation of effectiveness of the collector [18-20].

$$\eta_{ins} = \frac{Q_{us}}{A_s G_t} = \frac{\dot{m}C_p(T_{out} - T_{in})}{G_t} \tag{3}$$

$$\eta_{ins} = F_R\tau\alpha - F_R U_o\left(\frac{T_{in} - T_{amb}}{G_t}\right) \tag{4}$$

By replacing global radiation (G_t) and useful heat absorption (Q_{us}) in Eq. (3), one can calculate the effectiveness of the collector.

2.3 Experimental Uncertainties

The measured data, such as fluid flow and solar radiation intensity, takes into account in the uncertainty analysis. The following equation is applied for the uncertainty analysis:

$$U_q^2 = \sum_{i=1}^{n} U_{p,i}^2 \tag{5}$$

where Uq is the error associated with the calculated parameter q, whereas $U_{p,i}$ is the measured scatter root sum square. Eq. (5) uses tolerance assessment to evaluate the error analysis of collector efficiency ($U\eta$).

$$(U_\eta)^2 = \left(\frac{\Delta\dot{m}}{\dot{m}}\right)^2 + \left(\frac{\Delta(T_{out} - T_{in})}{T_{out} - T_{in}}\right)^2 + \left(\frac{\Delta G_t}{G_t}\right)^2 \tag{6}$$

Based on the findings from the experiment, the maximum error of collector efficiency is around 5.65%.

3. Results and Discussion
3.1 Nusselt Number

Useful heat gain (Q_{us}) is calculated using Eq. (7) [7,8].

$$Q_{us} = \dot{m}C_P(T_{out} - T_{in}) \tag{7}$$

In order to obtain heat transfer coefficient (h_{ex}), Eq. (8) is replaced with the outcome of Eq. (6), wall temperature of the riser tube (T_w) and bulk average temperature (T_b).

$$h_{ex} = \frac{Q_{us}}{A_s(T_w - T_b)} \tag{8}$$

where $A_s = \pi dL$; $T_w = \frac{T_1+T_2+T_3}{3}$ and $T_b = \frac{T_i+T_o}{2}$.

Eq. (9) can be utilized to obtain the experimental Nusselt number (N_{uexp}) by substituting the thermal conductivity (k) and diameter of the riser tube (d) [7,8].
Experimental Nusselt number (N_{uexp})

$$N_{uexp} = \frac{h_{ex}d}{k} \tag{9}$$

The Prandtl number (P_r) is computed by replacing specific heat (C_p), viscosity (μ), and thermal conductivity of the fluid in Eq. (10) [7,8].

Prandtl number

$$\mathrm{P_r} = \frac{\mu C_p}{k} \tag{10}$$

Initially, experimentation was done on riser tubes without any helical coil. The outcomes of the experiment, and as per the results of data from Gnielinski [21] and the maximum deviation obtained is 3.5% and results are shown in Figure 2. Figure 3 show the experimental Nusselt number at various pitches of the coil. It is evident from the Figure 4 that Nusselt number raises as the Reynolds number and pitch value of helical coil increases. Improvement in Nusselt number is mainly due to the effects of direction of fluid flow and the profile of the riser tubes. The rise in Nusselt number is mainly due to change in direction of fluid flow and increase in surface area of the riser tube. It is evident from the Figure 3 that as the Reynolds's number increases the value of Nusselt number increases, this is due to Nusselt number is function of Reynolds number. The highest value of Nusselt number is achieved at a Reynolds's number of 14500.

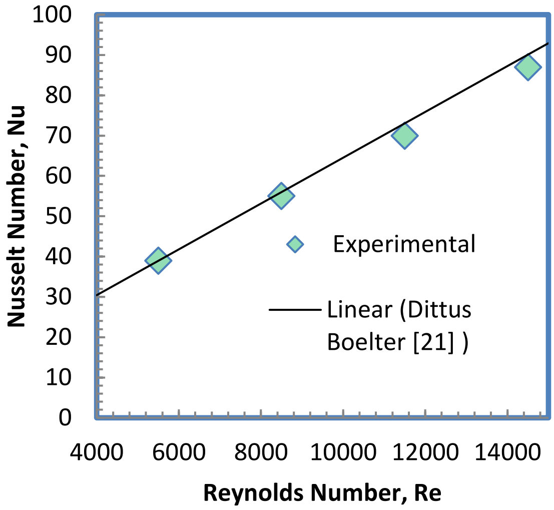


Fig. 2. Comparison of Experimental Nu with Gnielinski [21]

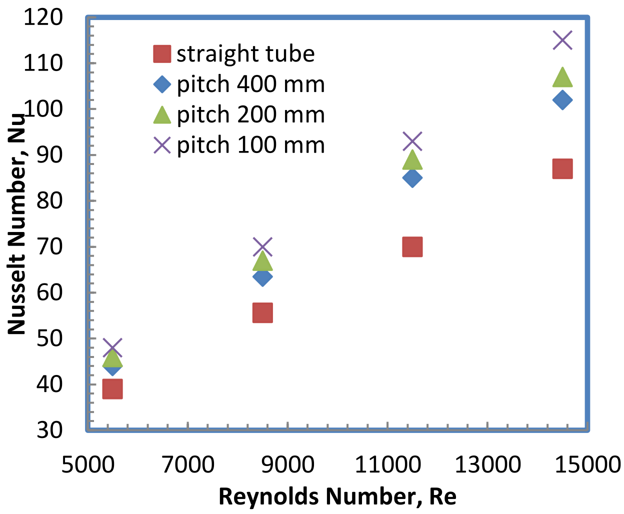


Fig. 3. Experimental Nu with Reynolds number

The riser tubes with helical coils absorbs more heat than the plain tube, since the surface area of the helical coil based riser tubes is higher than that of the plain tube. Improvement in Nusselt number for a 400 mm pitch is 14.37% and 30.46%, at Reynolds numbers of 5500 and 14,500, respectively, in compared to a traditional straight riser tube. Similarly, the riser tube with 100 mm pitch, the Nusselt number augmentation is 39.03% and 45.5% for Reynolds numbers of 5500 and 14,500, respectively, compared to plain tube.

3.2 Friction Factor

Friction factor for the conventional tube of collector is evaluated using Eq. (11) [7,8]. The values of friction factor from the experiments are validated with the results of Blasius equation and shown in Figure 3 and it is represented by the Eq. (12) [7,8,22].

$$f_{exp} = \frac{dp}{\left(\frac{L}{d}\right)\left(\frac{\rho v^2}{2}\right)} \tag{11}$$

$$f \;=\; 0.3164\, {R_e}^{-0.25} \tag{12}$$

The maximum deviation between theoretical and experimental values is 2.5 %. Figure 4 and Figure 5 show the friction factor for different flow rate of working fluid. Eq. (11) is utilized to calculate experimental friction factor with coil inserts. For 400 mm pitch, friction factor is 1.142 times and 1.37 times higher in comparison with plain tube at a Reynolds numbers of 5500 and 14,500, respectively.

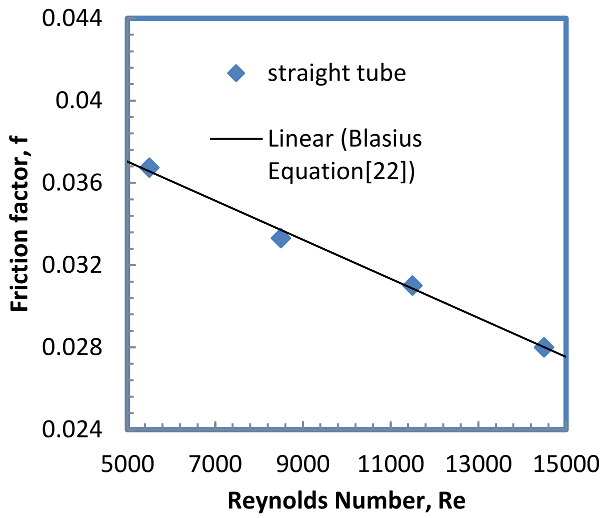


Fig. 4. Comparison of friction factor with Blasius's [22] equation

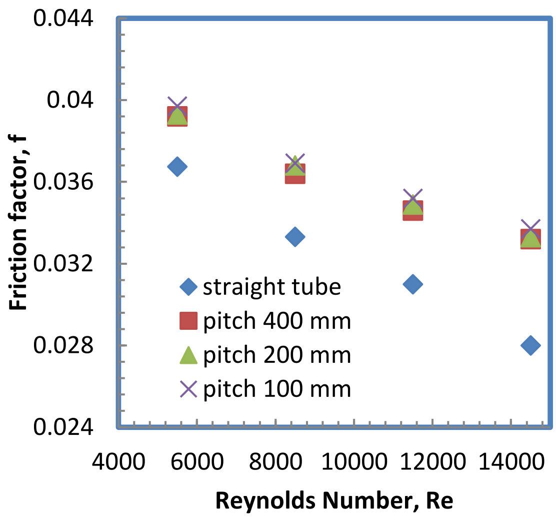


Fig. 5. Friction factor vs Reynolds number

3.3 Collector Efficiency

The effectiveness of collector at 100 mm pitch value of curve riser tube and plain tube is shown in Figure 6 and Figure 7 respectively. The outcome of T_i-T_{amb}/G_t and effectiveness of the collector is shown in Figure 6 and it is evident from the figure that collector effectiveness increases as T_i-T_{amb}/G_t value reduces.

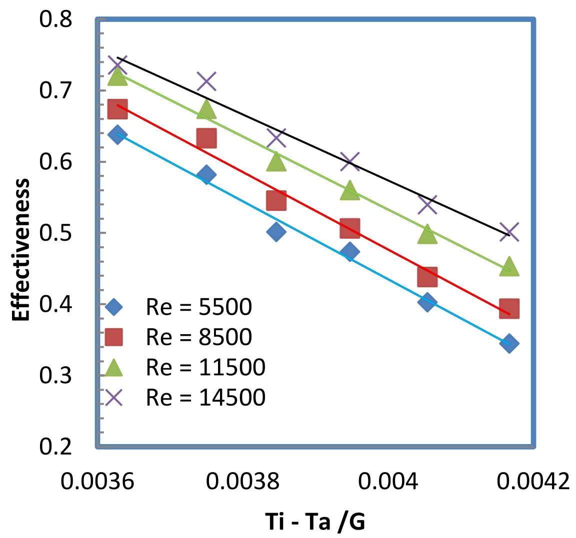


Fig. 6. Effectiveness vs Ti-T_a/G for 100 mm pitch riser tube

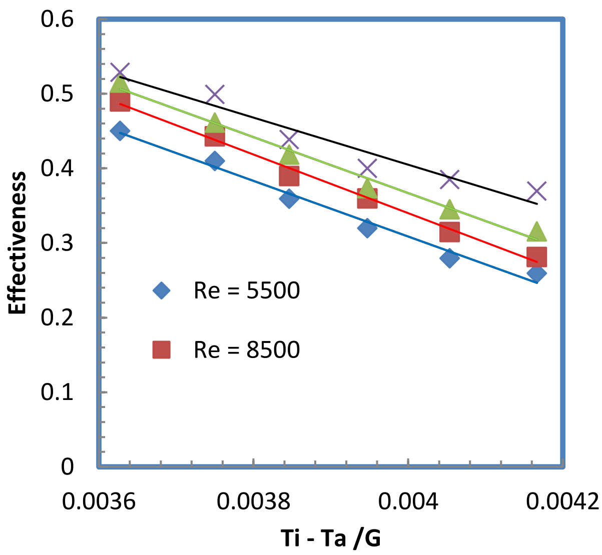


Fig. 7. Effectiveness vs Ti-T_a/G for plain tube

The findings related to pitch value is significant since the reduction in pitch value causes increase in residence time hence it boosts the absorber plate temperature. For a plain tube and 100 mm pitch, the effectiveness is 52.02 % and 75.04 % respectively, at a Reynolds number of 14,500. The main cause of temperature rise at the collector output is due to residence time and generation of turbulence, all of these enhance the effectiveness of collector.

4. Conclusions

Augmentation of collector effectiveness was tested experimentally using curve shaped riser tubes. In this study three distinct pitch values of 100, 200, and 400mm and various Reynolds numbers from 5,500 to 14,500 were investigated. As compared to the plain tube, the rise in Nusselt number is 41.04% and 49.43% at 100mm pitch, corresponding to a Reynolds number of 5500 and 14500 respectively. The enhancement of collector efficiency is 75.04 % corresponding to a Reynolds number of 14.500 in comparison with plain tube. The experimental friction factor with coil inserts. For 400 mm pitch, friction factor is 1.142 times and 1.37 times higher than the plain tube at a Reynolds numbers of 5500 and 14,500, respectively. These results demonstrate that the curve shaped riser tubes improve thermal performance of V-trough flat plate solar collector by increasing fluid flow turbulence under the same operating circumstances. The present work can be extended for additional improvement of performance and effectiveness by using nanofluids.

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