Experimental Study on an Enhanced Performance Solar Water Heater

Chandresh Sharma
Ph.D. Scholar and Lecturer,
Department of Mechanical Engineering
Government Polytechnic College, Jodhpur 342001

Rajendra Karwa
JIET School of Engineering and Technology
Mogra, N.H. 65, Jodhpur 348002

ABSTRACT
The paper presents preliminary results of an experimental study on solar water heater with full width and 75% twisted tapes as heat transfer enhancement device. The study shows that the thermal efficiency due the use of the twisted tape increases by 4.5-8%; higher for the 75% twisted tape.

Keyword
Solar water heater (collector), tube-in-fin, twisted tape, thermal efficiency, performance enhancement

1. INTRODUCTION
Solar water heating has potential to reduce electricity consumption and emissions. By the end of 2012, global solar thermal capacity in operation reached an estimated 282 GWth, out of which glazed water collectors have a share of 255 GWth **[1]**. China has total capacity of 180.4 GWth with most demand from the residential sector. India is bestowed with abundant solar energy but legs behind China. The high initial cost of the solar water heating system is considered to be a major hurdle to its large-scale deployment.

In general, a solar water heater system consists of a flat-plate or evacuated-tube collector, a storage tank, piping, valves, controls and pumps. They have been classified as passive and active (forced circulation) type. A passive system depends on natural convection (thermosyphon effect) to circulate water and thus does not need control, pump or check valve. The water circulates through the collector several times a day and the temperature rise in each circulation is small, therefore, this system often cannot supply hot water at desired temperature in the morning.

In a once-through system [2], the cold water enters from the lower end and hot water flows out of the upper end of the collector tube without any re-circulation in the system. The driving force for the flow is the head of the cold water supply, which is usually the tap water. Hot water may be collected in an insulated tank, which can be placed at a convenient place below the collector. During a sunny day, this system can supply hot water much earlier than the natural circulation system. Compared with a natural circulation system, the size of piping work can be cut down considerably and insulation is not required on the cold water pipe.

A solar collector, the heart of a solar water heating system, is basically a heat exchanger that converts solar energy to heat, which is transferred to the working fluid flowing through the collector. A flat-plate collector is generally used to provide heated fluid at low to medium temperatures (less than about 70°C). The most commonly used design of the flat-plate solar water heater (SWH) basically consists of a number of parallel copper tubes equally spaced and bonded with copper plates working as fins (a tube-in-fin design). The sun facing side of the tube-fin assembly is painted black to impart high absorptance for the solar radiation. One or more glass covers are placed on the top of the blackened tube-fin assembly to arrest heat loss to the ambient. The collector assembly is installed at a suitable angle to the horizontal facing south. A part of the absorbed solar radiation absorbed at the blackened tube-fin surface is transferred to the water flowing through the tubes. The remaining part of the absorbed radiation is lost to the ambient by radiation and convection from the heated absorbing surface.

The efforts of the researchers have been directed towards enhancing the thermal performance of SWH so that for a given heat duty, its size and hence its initial cost can be reduced. Various techniques such as application of selective coating on the radiation absorbing surface, increased number of glass covers, optimization of tube diameter and spacing, tracking of the sun, etc. have been used.

2. THERMAL EFFICIENCY IMPROVEMENT BY HEAT TRANSFER ENHANCEMENT
Poor heat transfer coefficient at the water-tube surface interface is another important issue because the water flows through the tubes at very low Reynolds number (once-through system) or under thermosyphon effect in the conventional fin-in-tube design. Hence, the strategy for thermal performance improvement can be the heat transfer enhancement from the heated copper tube to the flowing water. The enhancement, while transferring greater amount of heat to the water, reduces the average temperature of the absorber surface and thus the heat loss is also reduced.

In the last decade, various studies on natural and forced laminar flow through tubes of various types of heat exchangers and SWH with different types of heat transfer enhancement devices have been reported. Some examples are the use of mechanicals aids, surface vibration, fluid vibration, electrostatic fields and jet impingement which require an external power supply. The passive method of enhancement generally uses surface or geometrical modifications to the flow channel (rough surfaces, extended surfaces), use of inserts and swirl flow devices, coiled tubes, etc.

Swirl-flow devices, such as twisted tape and wire coil inserts, have been used for more than a century to improve heat transfer in industrial heat exchangers. Since a wire coil mixes the flow in the viscous sublayer near the wall, it is more effective in turbulent flow compared with a twisted tape. In the case of a laminar flow, the resistance to heat transfer extends to a thicker region compared with the turbulent flow. A twisted tape insert mixes the bulk flow hence it is more effective in laminar flow. A twisted tape, placed in a tube, also reduces the hydraulic diameter of the passage. Heat transfer enhancement is also due the secondary flow generated by the tape, which creates swirl. The resulting mixing of fluid improves the temperature gradient leading to an increase in the heat transfer rate. Wang and Sunden [3] found that the heat transfer enhancement was higher with twisted tapes for fluids with higher Prandtl number because such fluids have thicker boundary layers. Hence, for the solar water heaters operating in laminar region, the twisted tape must be more effective in heat transfer and thermal efficiency enhancement.

2.1 Recent Studies on Twisted Tapes in Laminar Flow

Some of the recent studies on use of twisted tape insert in heat exchangers and SWH are presented in Table 1 showing the experimental conditions and important results. Some of the important observations by the researchers regarding the flow structure are discussed below.

Jaisankar and co-authors [10, 11] opined that the tangential flow of fluid created by the twisted tapes increased the surface contact area. They found that, in the case of full length twist, the swirl flow was maintained throughout the length of riser tube. Compared to full length twisted tape, the swirl generation decreased slightly for the tape fitted with rod. As the rod length increased, the intensity of swirl decreased gradually. But, for the twist fitted with spacer, the swirl flow decayed immediately after the twist. Sharma and Karwa [13] carried out flow visualization studies for laminar flow of water in a smooth tube with different width twisted tape inserts. They found that, in the case of 75% twisted tape (Fig. 1), the low temperature fluid in the central core is pushed to the heated wall and flows near the wall with a significant velocity. The observation is in line with that of Patil [7]. Hence, such tapes can provide greater heat transfer enhancement than the full width tapes in SWH with laminar flow.

3. OBJECTIVE

From the studies presented above, it can be inferred that twisted tapes can be employed for thermal performance enhancement of convectional tube-in-fin solar water heater with natural or low Reynolds number laminar flow. However, the literature survey reveals that the effects of full width (= the tube diameter) and 75% twisted tape inserts on the performance of the solar water heaters have not been investigated. Hence, the objective of the present work is to fabricate an outdoor test facility and carry out an experimental investigation to study the effect of the above mentioned twisted tapes as insert in the tubes on the thermal efficiency of solar water heater.

4. EXPERIMENTAL SETUP

Figure 2 presents the schematic of the experimental setup and solar water heater used for the present experimental study. The solar water heater consists of two similar parallel copper tubes (risers), smooth surfaced 19.5 mm inside diameter and 1.5 m long, equally spaced. Copper plates brazed on both dies of the tubes work as fins as depicted in Fig. 2(c). One of the tubes carries the twisted tape.

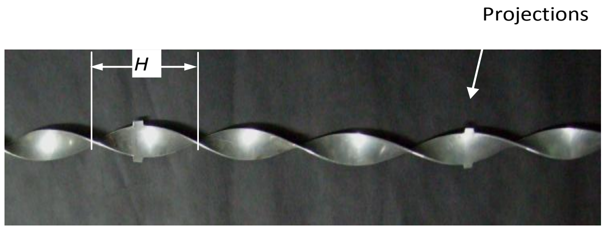


Figure 1. A 75% twisted tape, *y* = 7.8 [13].

Table 1. Some recent studies on twisted tape inserts*.

S. No.	Investigators	Enhancement device	Geometric and flow conditions	Main results
1.	Agarwal and Raja Rao (1996)	Twisted tape inserts	▪ Servotherm oil (Pr = 195-375) ▪ Re = 70-4000 ▪ y = 2.41-4.84	▪ Friction factor 3.13-9.71 times ▪ Nusselt number enhancement at minimum y is 2.28-5.53 at constant flow rate and 1.21-3.70 at constant pumping power.
2.	Kumar and Prasad (2000)	Twisted tape inserts, solar water heater	▪ Re = 400-21000 ▪ y (= H/D_i) = 3-12 ▪ L = 1.2 m, D_i = 16 mm ▪ m = 0.04-0.2 kg/s	▪ Heat transfer increases by 18-70% ▪ Pressure drop increases by 87-132% ▪ Thermal performance improves by 30% ▪ $Nu/Nu_s = 1.3 + 2.88/y$
3.	Patil (2000)	Varying width twisted tape inserts	▪ Power law fluid ▪ Laminar flow ▪ Width = 0.5-1.0 D_i	Thermo-hydraulically, 75% wide tape gave a comparable or slightly better performance than full width tape.
4.	Abu-Khader (2006)	Twisted tape for shell and tube heat exchanger	▪ Laminar to turbulent flow ▪ y = 6-19 ▪ Tube diameter, D_i = 30-70 mm.	For large tube diameter, twisted tape has no effect on Nusselt number in laminar regime but is significant for smaller diameter tube.

5.	Chang et al. (2007)	Broken twisted tape (with spikes)	▪ Re = 1000-40000 ▪ y = 1.0, 1.5, 2.0, 2.5, straight tape.	Thermal performance factor $(Nu/Nu_s)/(f/f_s)^{1/3}$ is highest for $1 \leq y \leq 2.5$.
6.	Jaisankar et al. (2009a)	Twisted tape in thermo-syphon SWH	▪ Re ≈ 900-1200 ▪ y = 3, 4, 5, 6 ▪ L = 1 m, D_i = 11 mm.	Thermal performance of twisted tape with minimum twist ratio (y = 3) is found to be the best.
7.	Jaisankar et al. (2009b)	Twisted tape with rod and spacer at trailing edge in thermosyphon SWH	▪ Re ≈ 200-500 ▪ y = 3 and 5 ▪ Spacer = 100, 200, 300 mm ▪ L = 1 m, D_i = 11 mm.	Twist tape fitted with rod instead of full length twisted tape has greater advantage in friction factor with less impact on heat enhancement.
8.	Jaisankar et al. (2009c)	Left-right twisted tape with rod and spacer at trailing edge in thermosyphon SWH tubes	▪ Re ≈ 800-1500 ▪ y = 3 and 5 ▪ Spacer = 100, 200, 300 mm ▪ L = 1 m, D_i = 11 mm.	The heat transfer enhancement in full length twisted tape is better than the tape fitted with rod and spacer.
9.	Bhardwaj et al. (2009)	Spirally grooved tube with twisted tape	▪ Re ≈ 1000-25000. ▪ Twist ratio, y = 10.15, 7.95 and 3.4. ▪ Anti-clock and clock-wise grooves in tube.	Enhancement at constant pressure is 600% in laminar region and 140% in turbulent region.

*

D_i	Inner diameter of the tube
f	friction factor
H	pitch
L	Length of tube
m	Mass flow rate
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
y	Twist ratio

Subscript

s smooth

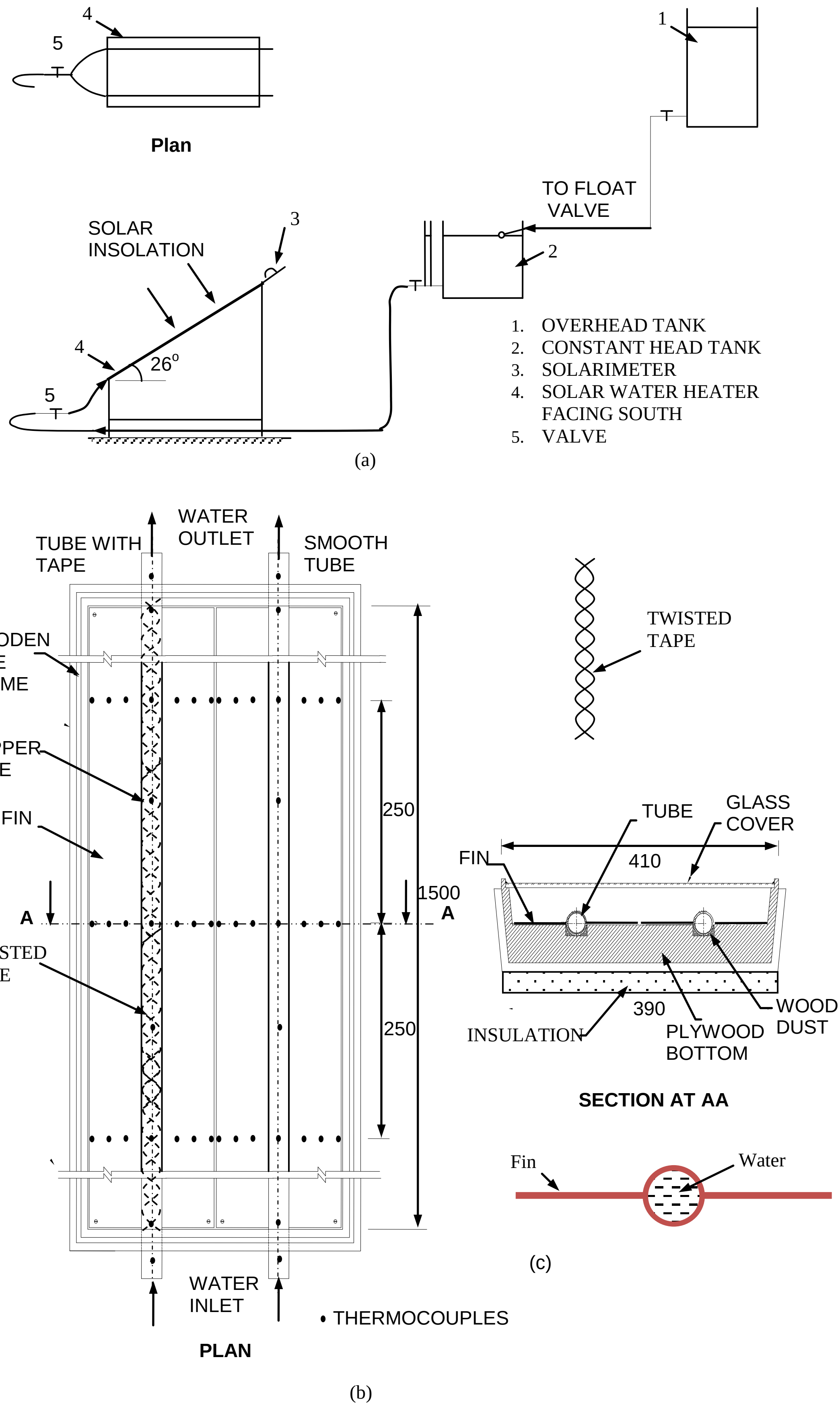


Fig. 2. (a) Schematic of experimental setup, (b) solar water heater, (c) copper tube with brazed fins.

Both the tube-fin assemblies are placed in plywood housing with 10 mm thick thermocole insulation on the back of the 40 mm thick plywood bottom as shown in the figure.

The outer surface (sun facing side) of the tubes and plate assembly, termed as absorber plate or surface, is painted black. A glass cover is placed on the top of the absorber plate at a gap of 40 mm. The collector assembly is placed at an angle of 26o (equal to the latitude of Jodhpur) to the horizontal facing south.

Twenty five calibrated copper-constantan thermocouples are affixed using epoxy resin on each tube-fin combination as shown in Fig. 2(b) to measure the absorbing surface temperature; seven in the flow direction on the tube surface and remaining transverse to the flow. Thermocouples at the inlet and exit ends of the pipes are placed to measure the water inlet and outlet temperatures, respectively. Thermocouple output was fed to a micro-voltmeter.

Water mass flow rate has been calculated by collecting water for a time interval to collect a reasonable quantity of water and weighing the same on an electronic balance.

Solarimeter has been installed at the upper end of the collector to measure solar insolation normal to the collector plane. Wind velocity at the mid-plane of the collector has been measured using a velometer. Mercury-in-glass thermometer, housed in the Stevenson screen, measures the ambient temperature.

Table 2 Experimental Conditions

Length of tube, L	1.5 m
Internal diameter of tube, d_i	0.0195 m
Outer diameter of tube, d_o	0.0235 m
Thickness of fin	2 mm
Length of fin	0.075 m
Gap between fins	2 mm
Glass thickness	4 mm
Collector tilt, β	26° facing South
Area of collector, A_c (for one tube-fin combination)	0.285 m^2
Mass flow rate, $\dot{m}$	≈ 5 – 20 kg/hr
Reynolds number	≈ 125 - 500
Wind velocity	≈ 0.1 m/s
Twisted tape:	
Material	Aluminium
Thickness	1 mm
Twist ratio, y	3.5
Length	1.5 m
Width	75% [13.8 mm (= 0.75 D_i)] and full width

The details of twisted tapes used in this study and other relevant system parameters are given in Table 2. The twist ratio y is defined as the ratio of pitch to inside diameter of the tube H/di, where H is the twist pitch length and di is the inside diameter of the tube.

The water flow rate was varied to give flow Reynolds number of about 125 to 500.

All readings have been recorded on a day with clear sky between 9 am and 3 pm at an interval of 30 minutes. Conditions with low wind velocity have been considered only for the experimentation. Four test runs have been taken for different mass flow rates of water; one mass flow rate each day of the experimentation.

5. DATA REDUCTION

Measuring the mass flow rate m, and the inlet and outlet water temperatures (Ti and To, respectively), the useful heat gain Q, which is the heat transfer rate to the water, can be computed using the following equation:

$$Q = mc_p (T_o - T_i), \tag{1}$$

where m is the mass flow rate of water and c_p is the specific heat of the water.

Thermal efficiency η of the collector is calculated from:

$$\eta = Q/(IA_p), \tag{2}$$

where $A_p = WL$ is the absorber plate area (W is width and L is length) and I is the incident solar radiation per unit area of the plate.

The Reynolds number Re has been determined from the calculated value of the mass flow rate m from:

$$\mathrm{Re} = GD_i/\mu, \tag{3}$$

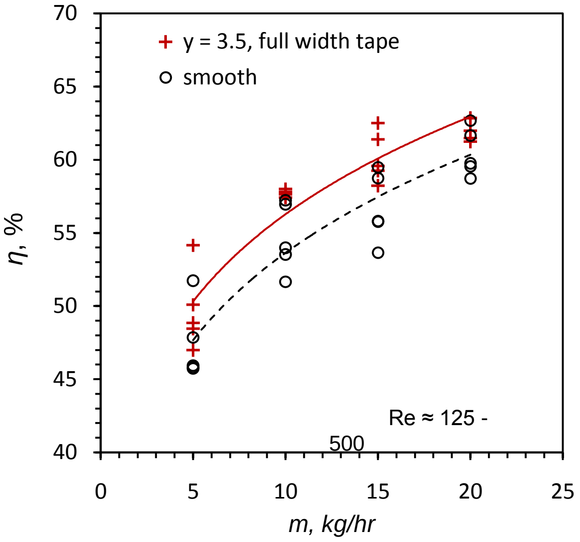
where $G = m/(\pi/4D_i^2)$ is the mass velocity of the water through the tube, D_i is the inside diameter of the tube and μ is the viscosity of the water.

Thermophysical properties of the water have been taken at mean water temperature in the tube from standard tables [14].

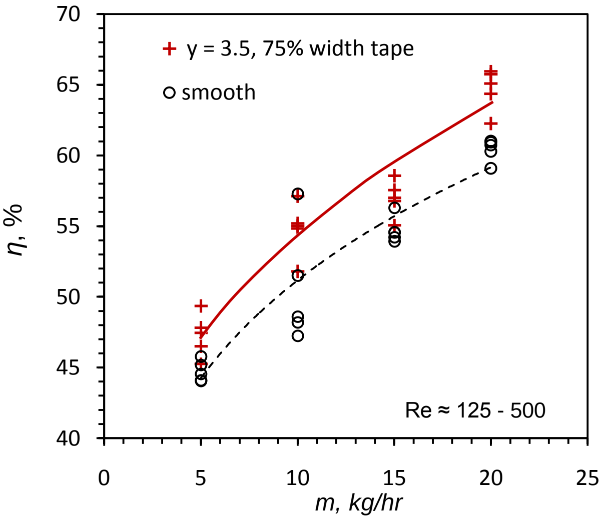
6. RESULTS AND DISCUSSION

The results of the study are presented in Fig. 3 as plots of the thermal efficiency versus the water flow rate. The Reynolds number values of the study are indicated on the figure. The employment of the twisted tape enhances the efficiency by about 4.5-5.5% for full width tape and about 6.5-8% for the 75% width tape, which can be termed as significant because the additional cost of the tape is negligible. The reasons for the enhanced heat transfer, based on the flow visualization studies of Sharma and Karwa [13], are presented below.

In the case of full width tape, the tube is basically divided into two parts with semicircular spiral flow paasseges. The divided flow remains laminar and follows the twist of the tape providing a swirl flow. The tangential (transverse to the pipe axis) component of the swirl flow due to the tape pushes the liquid in the spiral flow path towards the wall of the tube. The hydraulic diameter of the passage is also reduced. Swirl flow with reduced hydraulic diameter contribute to the heat transfer enhancement.



(a)



(b)

Fig. 3. Thermal efficiency versus the flow rate (a) Full width twisted tape, (b) 75% width twisted tape.

When a 75% tape (tape width = $0.75D_i$) is inserted, an annular space surrounding the tape is free from any obstruction due to the tape. The fluid in the core is pushed towards the annular passage near the wall due to the spiral tape induced swirl flow. It is to note that the water reaching into the annular passage has a tangential component of the swirl flow, which causes it to move circumferentially also. The fluid in the annular passage moves with a significantly high velocity. This high velocity is also possible because the annular passage provides a path of least resistance to the flow. All these factors lead to a greater enhancement in the heat transfer rate as compared to the full width tape.

7. CONCLUSIONS

An experimental study has been carried out to study the effect of full width (= the tube diameter) and 75% width twisted tape inserts on the thermal efficiency of a once-through solar water heater. The twisted tape inserts improve the thermal efficiency by 4.5-8%; higher gain has been observed for the 75% width twisted tape.

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