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A Review of Performance of Twisted Tapes in Turbulent Regime

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Abstract

Twisted tapes are being extensively used as passive technique for heat transfer augmentation due to ease of fabrication and use. Twisted tapes have been used in turbulent region by a large number of researchers, using different geometries, configurations and media. Different configurations of the tapes create different flow patterns, which affect the thermohydraulic performance. The effect of flow pattern caused by use of twisted tape has been presented. Thermohydraulic performance evaluation criterion has been presented. An attempt has been made in this review is to present the various geometries and configurations of twisted tapes, their effect on the flow mechanism, heat transfer enhancement, pressure drop and thermohydraulic performance enhancement in heat exchanger tubes escpecially in turbulent regime.

Keywords: *geometry, flow mechanism, thermohydraulic performance, turbulent, twisted tape.*

1. Introduction

Heat exchangers are widely used as the essential units in thermal power plants, process industries, air-conditioning equipment, refrigerators, radiators for space vehicles, automobiles, etc. as heat extraction and recovery systems.

The performance of heat exchanger can be substantially improved by a number of augmentation techniques. An increase in the efficiency of the heat exchanger through an augmentation technique results in considerable saving in the material cost. The heat transfer rate can be improved by introducing a disturbance in the fluid flow (breaking the viscous and thermal boundary layers), but in the process pumping power may increase significantly and ultimately the pumping cost becomes high. Therefore, to achieve a desired heat transfer rate in heat exchanger at an economic pumping power, several techniques have been proposed and used in recent years [5][6].

Heat transfer augmentation techniques can be classified into three broad categories [5][7][27]:

1. Active method, involves some external power input for the enhancement of heat transfer and has not shown much potential owing to complexity in design,

2. Passive method, the additional power needed to enhance the heat transfer is taken from the available power in the system, which leads to fluid pressure drop. Use of inserts, extended surface, surface modifications and additives in fluid are passive methods.

1.1 Inserts, refer to the additional arrangements made as an obstacle to fluid flow so as to augment heat transfer. Different types of inserts used are twisted tapes, wire coils, ribs, baffle plates etc.

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1.2 Extended or finned surfaces, increase the heat transfer area, and heat transfer is by natural or forced convection, which could be very effective in case of fluids with low heat transfer coefficients. A variety of extended surfaces like, offset strip fins, louvered fins, perforated fins and wavy fins are in use.

1.3 Surface modification: The modification in characteristics/structure of heat transferring surface is done to achieve higher thermal performance. Coatings using organic compounds, hydrophobic compounds, inorganic compounds, polymers or surface alloys have been used, though they introduce additional thermal resistance. Ion implantation has also been tested.

1.4 Additives: Additives when added to fluids are found to have operational benefits by lowering the frictional losses. Polymeric additives induce a visco-elastic characteristic to solution which promotes secondary circulation in bulk flow. Some of additives used are polystyrene spheres suspension in oil, injection of gas bubble, nano or micro fluids etc.; and

3. Compound method is a hybrid method in which both active and passive methods are used in combination. Due to complexity of design compound method has limited applications.

Several researchers have used different methods for heat transfer augmentation. A number of authors have also written reviews on use of different heat transfer augmentation techniques [38] [39]. The passive methods of heat transfer augmentation have shown promising results.

Generally twisted tape and wire coil inserts are more widely applied and have been preferred in the recent past to other methods, probably because techniques such as the extended surfaces insert suffer from relatively high cost and a mesh insert suffers from high pressure drop and fouling problems.

The use of twisted tape with different geometries as inserts for heat transfer augmentation has been done by different researchers. Twisted tape has been used in laminar as well as turbulent regime of flow. A preliminary review of different research shows that twisted tape has been largely used in application involving turbulent flow [37]. Different authors have used different criteria for analyzing the performance of twisted tapes.

In an attempt to review the thermo-hydraulic performance of twisted tapes in turbulent region the following have been presented:

1. The various geometries and configurations of twisted tape.
2. The flow mechanism which is responsible for augmentation of heat transfer by use of twisted tapes,
3. The criteria for thermo-hydraulic performance evaluation; and
4. Review the results obtained by using different geometries of twisted tapes for heat transfer augmentation in turbulent flow.

2. Twisted Tape Geometry

The basic geometry and nomenclature related to twisted tapes to develop an understanding of its construction is as follows:

1.Width; w: Width of the strip from which, tape has been fabricated, which can be equal to or less than the tube diameter.

2.Thickness; δ: The thickness of strip used for fabrication of tape.

3.Pitch; H: Pitch is defined as the distance between two points that are on the same plane, measured parallel to the axis of a twisted tape.

4.Twist ratio; y: The twist ratio is defined as the ratio of pitch to width of twisted tape. y = H/w

Geometry of a typical twisted tape is shown in Fig. 1 [11].

3. Application of Twisted tapes by various researchers

Twisted tapes have been extensively used with various shapes and construction. Most commonly employed geometries of twisted tapes will be discussed here.

3.1 Full length twisted tape

Full length twisted tapes have length equal to length of test section. Full length twisted tape have been used in used in circular tube [11], horizontal circular tube with ethylene glycol as media [15], in horizontal double pipe with water [16], with Al_2O_3 nano fluid [20], used in solar water heater [25][26], used in spirally grooved tube [24], used with corrugated pipe [10]; and also used full length twisted tape in conjuction with conical rings [18]. Other researchers also used full length twisted tapes in their experiments [1] [2] [17].

3.2 Varying length twisted tape

These are distinguished from a typical twisted tape with regards that they are having the length lesser than the length of test section, for example, 1/4, 1/2 or 3/4 length of the test section with a view to reduce pressure drop. Researcher [19] used short–length twisted tapes in round tube with hot air.

3.3 Regularly spaced twisted

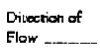


Fig. 1. Twist

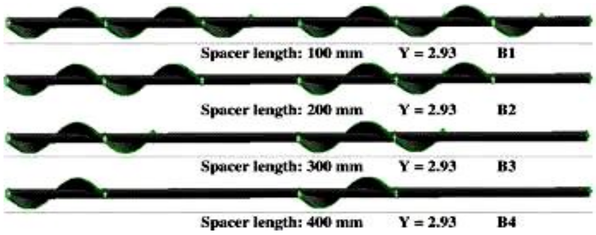
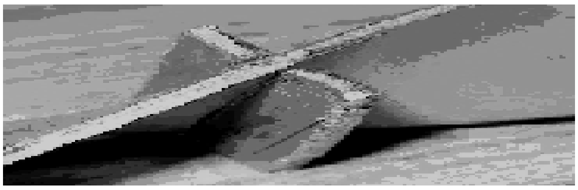
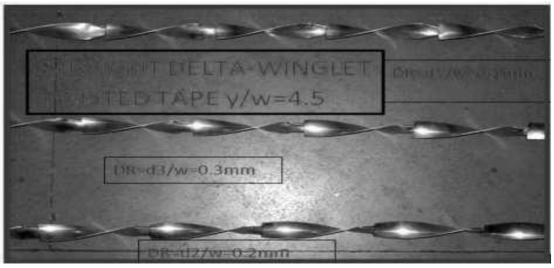


Fig. 2. Regularly spaced twisted tapes



(a)

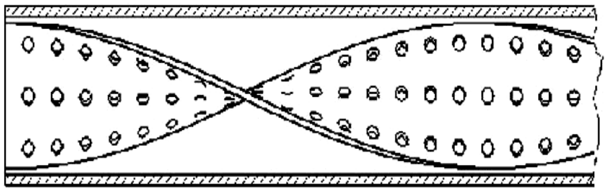


(b)

Fig. 3. Tape with attached (a) baffles, and delta winglet

(a)

(b)



(c)

Fig. 4. (a) Trapezoidal cut twisted tapes, (b) twisted tape with hole, and (c) tape with perforations.

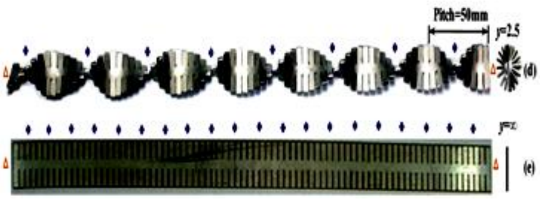


Fig. 5. Broken twisted tapes

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tapes

These are short length tapes of different pitch, spaced by connecting together with suitable spacer rods as shown in Fig. 2. Regularly spaced twisted tapes have been used in double pipe heat exchanger with hot water [14], with spacers at the trailing edge of Left-Right twisted tape, and with spacers in solar water heater [26].

3.4 Tape with attached baffles

Baffles are attached to the twisted tape at some intervals so as to achieve more augmentation. As shown in Fig. 3 twisted tape with baffles in rectangular channel with air have been used [12], straight delta winglet twisted tapes were used with water [35].

3.5 Slotted tapes, tapes with holes and tapes with perforation

Slots and holes of suitable dimensions made in the twisted tape so as to create more turbulence. Trapezoidal cut twisted tape in circular tube with water as medium has been employed [23], perforated tape with air have also been tested [33], as shown in Fig. 4.

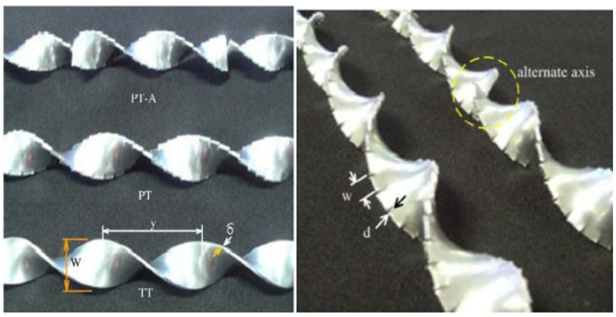
3.6 Tapes with different surface modifications

Some insulating material is provided on tapes so that fin effect can be avoided. In some cases dimpled surfaced material used for tape fabrication. Broken twisted tapes in circular tube are shown in Fig. 5 [19]. Peripherally cut twisted tapes with an alternate axis in double pipe heat exchanger are shown in Fig. 6 [29].

4. Flow Mechanism

Heat transfer enhancement in a tube flow by inserts is mainly due to flow blockage, partitioning of the flow and secondary flow [4]. Flow blockage increases the pressure drop and leads to increased viscous effects because of a reduced free flow area. Blockage also increases the flow velocity and secondary flow. Secondary flow further provides a better thermal contact between the surface and the fluid, as secondary flow creates swirl and the resulting mixing of fluid improves the temperature gradient, which ultimately leads to a high heat transfer coefficient.

Twisted tape inserts cause swirl and pressure gradient in the radial direction. The boundary layer along the tube wall gets thinner with increase of radial swirl and pressure, resulting in more heat flow through the fluid. The swirl causes the flow to be turbulent and results to even better convection heat transfer [17].



(a) (b)

Fig. 23. Peripherally cut twisted tapes (TT, PT and PT-A) that were used: (a) front view and (b) isometric view

The tangential velocity component and lower flow cross sectional area, the mixing of fluid between fluid at the wall region and fluid at core region induced by generated centrifugal force enhance heat transfer rate [16].

Twisted tapes, when inserted into tubes tend to promote turbulence as well as to intensify mixing of the hot fluid and cold fluid. This in turn improves the heat transfer process but in this process pumping power may increase

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significantly and ultimately the pumping cost becomes high. When a twisted tape is placed inside circular tube, the flow field gets altered in several different ways:

1. Increased axial velocity and wetted perimeter due to the blockage and reduction in net free cross sectional area which tend to semi-circle and reduce hydraulic diameter,
2. Longer effective flow length in the helically twisting partitioned duct, and
3. Tape's helical curvature-induced secondary fluid circulation or swirl.

The most dominant mechanism is swirl generation which effects transverse fluid transport across the tape partitioned duct, thereby promoting greater fluid mixing and higher heat transfer coefficients. The growth and structure of this tape-induced swirl in the laminar flow regime have been characterized by experimental flow visualization and computational simulations. At the laminar region where Reynolds number is very low, the enhanced heat transfer results from flow blockage and the longer flow path, together with thermally developing boundary layer and free convection superimposed secondary flow and the swirl effects are minimal. As the *Re* increases, swirl flow is superimposed on the axial flow. The transition region is characterized by fluctuations opposed by the centrifugal forces. The net effect is that the discontinuity in the friction factor–Reynolds number curve characteristic of plain tubes no longer occurs. Whereas, at fully developed turbulent, swirl flow corresponding to Reynolds number greater than 10,000, enhanced heat is highly affected by the swirl-induced vortex mixing.

The continuous twisted tape insert in a tube generates swirls that modify the near-wall velocity profile due to the various vorticity distributions in the vortex core. For turbulent flow, the pair of swirls in the tube with a twisted tape insert is characterized by rather uniform axial velocity in a form of vortexes that exist in any sectional plane of the tube. Due to the swirl induced tangential flow velocity component, the fluid mixing between the duct core and the near-wall region is enhanced [31].

Additional heat transfer improvements by fitting the twisted tape in a tube are acquired due to the partitioning and blockage of ducted flow, the fin effect and the elongated twisted flow path. Accompanying the swirl induced heat transfer enhancement, the shear stress and pressure drag in a tube with the twisted tape insert are accordingly increased.

5. Peformance Evaluation

5.1Thermal performance

Thermal performance is based on the evaluation of heat transfer coefficients (or Nusselt number), and are calculated from the energy balance. Generally equation (1) is used:

$$h = \frac{mc_p(T_o - T_i)}{A(T_s - T_b)}$$

(1)

5.2Hydraulic performance

Hydraulic performance is concerned with pressure drop (Δp). Pressure drop can be represented in non-dimensional form by using the following relationship (2) for friction factor (*f*),

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$$f = \frac{\Delta p}{\left(\frac{L}{d_i}\right)\left(\frac{\rho v^2}{2}\right)}$$

(2)

5.3 Thermohydraulic performance

It is desirable that design of heat transfer augmentation element should be made in such a way that it should provide maximum heat transfer between the flowing fluids with minimum drop in pressure. Therefore in order to analyze overall performance of a twisted tape, thermohydraulic performance is evaluated by considering thermal and hydraulic characteristics of the tube and twisted tape simultaneously. The thermo-hydraulic performance is analysed using constant pumping power criteria [3].

$$R_3 = \left(\frac{h}{h_o}\right)_{d_i, L, P} = \frac{Q}{Q_o}$$

(3)

For a particular Reynolds number, the thermo-hydraulic performance of an insert is said to be good if the heat transfer coefficient increases significantly with a minimum increase in friction factor. Thermohydraulic performance estimation is generally used to compare the performance of different inserts such as twisted tape, wire coil, etc., under a particular fluid flow condition.

The overall enhancement ratio (4) derived from performance criteria is defined as the ratio of the heat transfer enhancement ratio to the friction factor ratio for rough and smooth tubes respectively [11] [36].

$$\eta = \frac{\left(Nu/Nu_o\right)}{\left(f/f_o\right)^{1/3}}$$

(4)

6. Evaluation of Performance of Twisted Tape Inserts

Researchers have used various geometries, configurations and media for twisted tape in turbulent region. In this section the performance results along with the suggested flow mechanism have been reviewed and are presented for different experiments. Geometry, flow conditions and results reported in literature are summarized in Table I at Appendix I.

6.1 Full length twisted tapes

The influence of full length twisted tape inserts on heat transfer and flow friction characteristics in a concentric double pipe heat exchanger, using air as working fluid were experimentally studied. Plexiglas concentric straight pipe as shown in Fig. 7, were joined at regular interval of 1.0 m by flanges. The inner diameter of the outer pipe was 50 mm and the annulus (flow passage) was of 20 mm in the radial direction throughout. Stainless steel twisted tapes having thickness of 1.0 mm with different twist ratios y = 5 and 7 were used. The width of twisted tape was taken as 19.5mm. Hot air was supplied in the tube and cold water was pumped on the annulus side. Experiments were conducted under isothermal conditions. Reynolds number for inner tube was in the range of

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2000 – 12000 [17].

It was observed that in the case of the twisted tape inserts, the Nusselt numbers increased about 188% for y = 5.0 and 159% for y = 7.0, when compared with the plain tube. Small twist ratio (y) tapes lead to higher Nusselt numbers. The twisted tape inserts caused swirling flow into the tube and lead to high friction of 3.37 and 2.94 times of the plain tube, for y = 5.0 and 7.0, respectively in comparison with the plain tube.

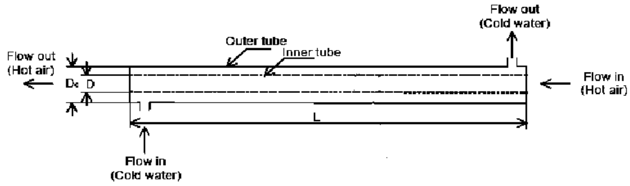

Fig. 6. Schematic diagram of test section

At low Reynolds number, due to the weak swirl & low flow velocity the effect of the twisted tape inserts decreased. Hence the increase in Nusselt number was low at smaller Reynolds number, while it became greater at the higher Reynolds numbers due to phenomenon related to the speed of the swirl-flow of the hot air and the results of the destruction of the boundary layer level. Graphs for enhancement efficiency with Reynolds number were presented, as shown in Fig. 8. They suggested that the use of twisted tapes is feasible in terms of energy saving at higher Reynolds numbers.

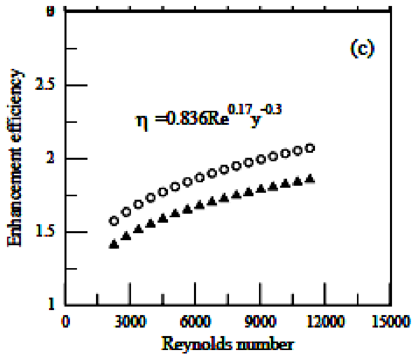

Fig. 7. Enhancement efficiency versus Reynolds number for the tube fitted with twisted tape at different twist ratios (y)

Experimental investigation for the heat transfer and pressure drop characteristics in pipes with twisted tape inserts using water as working fluid were carried out [16].

The experimental set up, as shown in the Fig. 9, consisted of horizontal double pipes with twisted tape insert. The test section was made from the copper tube with length of 2000 mm and the inner diameter and outer diameter of the inner tube were 8.10 and 9.54 mm, respectively. The twisted tapes of pitch (H) 2.5 cm and 3.0 cm were made from the aluminum strip was 1 mm thick and 2000 mm long.Cold water was kept on shell side and hot water on tube side. The hot water flow rate ranged from 0.04 to 0.08 kg/s and temperature between 40-45˚C. The cold water flow rate ranged from 0.01-0.07 kg/s and temperature between 15 - 20˚C. Reynolds number varied from 7,000 - 23,000.

It was shown that at the specific temperatures of cold and hot water entering the test section, the heat transfer rate increased with increasing tube-side Reynolds number. Also, at the same Reynolds number, the heat transfer rates obtained from the tube with twisted tape insert were higher than those from tube without twisted tape insert across the range of Reynolds number.

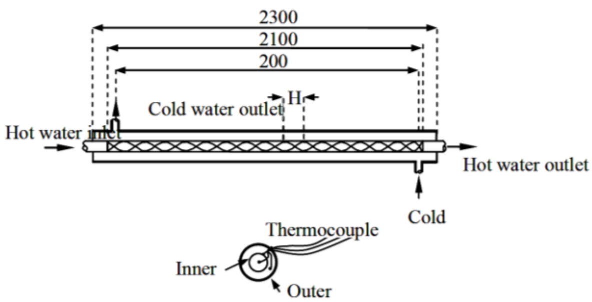

Fig. 8. Schematic diagram of the test section

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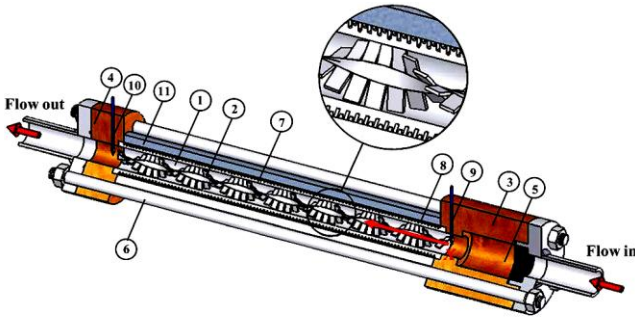
6.2 Broken twisted tapes

Experimental study was conducted to understand the axial heat transfer distribution and pressure drop coefficients for circular tubes fitted with broken twisted tapes as shown in Fig. 5 [19].

The test section, as shown in Fig. 10, consisted of a circular seamless stainless steel tube with 20 mm inner diameter, 5 mm wall thickness and 420 mm length. Heating was done using nickel-chromium alloy resistance wires, which were spirally wound outside the tube. Adequate insulation ensured uniform heat flux condition.

Broken twisted tape of twist ratio, y = 1.0, 1.5, 2, 2.5 and ∞, were made from the straight tape with the ‘‘flat’’ spikes (y = ∞) machined by the electric beam. The width of each twisted tape was taken as the tube inner diameter (hydraulic diameter) of 20 mm. These broken twisted tapes were formed by the spikes from a central twisted stripe of width 5 mm. Each spike was 5 mm wide, 7.5 mm long and 1.5 mm thick. The experiment used dry air as the test coolant. Measurements were taken for Reynolds number range of 1,000 – 40,000.



(1) Test tube
(2) Broken twisted tape
(3) Entry insulating bush
(4) Exit insulating bush
(5) Plenum chamber
(6) Draw bolt

(7) Thermocouple measuring wall temperature
(8) Heating wire
(9) Thermocouple measuring flow entry temperature
(10) Thermocouple measuring flow exit temperature
(11) Teflon stiffing tube

Fig. 9. Heat transfer test module with broken twisted tape insert

To assess the heat transfer augmentation generated by the broken twisted tape, the heat transfer data generated in the tube fitted with a broken twisted tape were compared with the Dittus-Boelter equation ($Nu_{\infty,}$ Nusselt number in plain tube) for the laminar and turbulent flows.

The *Nu* levels in the tube with the broken twisted tape insert were about 1.28 – 2.4 times of the heat transfer levels in the tube with the likewise continuous twisted tape insert. This type of broken twisted tapes augmented the laminar heat transfer to larger extents with the *Nu* values rise to 6.3 – 9.5 times of the plain tube level.

The twist ratios of y = 1.5 and y = 2, respectively, provided the highest Nu/Nu_∞ ratios for laminar and turbulent flows. The mean Fanning friction factors (f) in each tube fitted with the broken twisted tape of, y = 1, 1.5, 2, 2.5 or ∞ decrease exponentially with a tendency of approaching the asymptotic value as *Re* increased. The f factors consistently decreased as y increased in the tube with the broken twisted tape insert at each *Re* tested.

The ratios of f/f_∞ for the tubes fitted with the broken twisted tape were constantly higher than those in the tubes fitted with the continuous twisted tape and fell in the range of 2 – 4.7 times of the f/f_∞ ratios in the tube with the continuous twisted tape insert.

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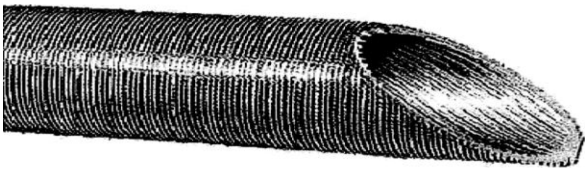

Fig. 13. 75 - start grooved tube

Within the range of $1 \le y \le 2.5$ for present series of broken twisted tapes, the η factors consistently increased as y increased due to the accompanying decrease in f factors. With the Re range of 1,000–40,000, the tubes fitted with the broken twisted tapes of $1 \le y \le 2.5$ show the highest η factors than those of the tubes fitted with the continuous and serrated twisted tapes. But the improved performances in η factors for the tubes fitted with the broken twisted tape systematically decreased as Re increased.

6.3 Full length twisted tape with nanofluid

Heat transfer enhancement was experimentally estimated at different Reynolds number with nano-fluid flowing through a copper tube [20]. The γ- Al_2O_3 particles in de-ionised water with different volume concentrations, ranging from 0.20 to 0.80 were used under constant heat flux boundary condition. Twised tape inserts were used for heat transfer enhancement.

The experimental set up shown in Fig. 11, comprised of a 1500 mm long copper pipe with, 19 mm internal diameter and 1.5 mm wall thickness. A 30 litre capacity reservoir contained the nano-fluid which was circulated with help of a pump. The γ- Al_2O_3 nanoparticles had an average size of 47 nm. The particles were dispersed in deionized water. Mixture was considered as a single phase liquid in order to study the thermo-hydraulic behaviour of nanofluid. The nanofluid had 0.02% volume concentration Heating was done using two 500 W, flexible heating elements in series and controlled by a variac. Twisted tape having twist ratio of 10 was used. Reynolds number was varied from 10,000 - 20,000. The Nusselt number values obtained from the experiment with twisted tape insert were compared with Dittus-Boelter equation for water in plain tube. Graphs were presented showing comparison of values obtained with nano-fluid of same concentration, with plane tube, estimated as shown in Fig. 12 [9].

A maximum enhancement of 28% was observed when flowing with nanofluid and tape insert when compared with water flowing in the plain tube at the same mass flow rate.

6.4 Full length twisted tape with spirally grooved tube

Experiments were carried out to determine pressure drop and heat transfer characteristics in a 75-start spirally grooved tube, with and without twisted tape inserts, and water as working fluid ($Pr \approx 5.4$) [24].

A copper tube, as shown in Fig. 13, with internal diameter 14.808 mm, outer diameter = 15.875 mm, length = 1040 mm spiral angle α = 23°, groove height e = 0.3048, groove base t_b = 0.265 mm, groove tip t_t = 0.0475 mm^2 was used. The grooves inside the tube were clockwise with respect to the direction of flow. Twisted tape

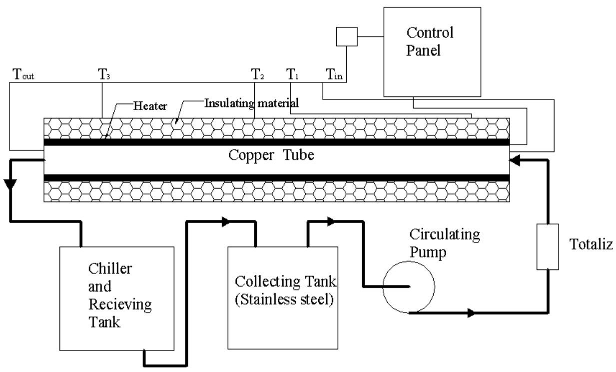

Fig. 10. Schematic diagram of experimental set up

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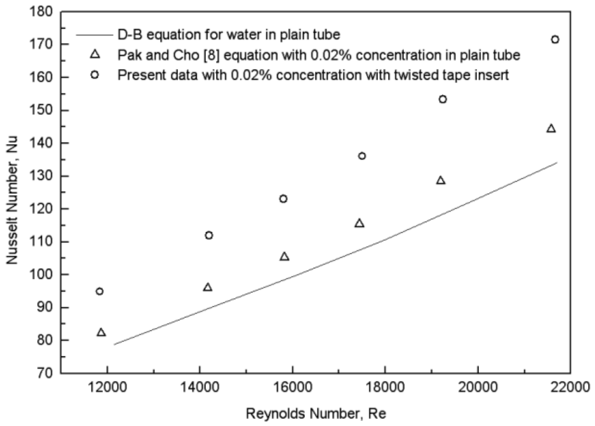

Fig. 11. Nusselt number with and without twisted tape insert for nanofluid with 0.02% concentration

inserts with different twist ratios, $y \approx 10.15$, 7.95 and 3.4 with clockwise and anticlockwise twist directions were manufactured from stainless steel strips. The width of twisted tape was been taken equal to d_i - e (tube internal diameter - groove height).

The heat transfer experiments were conducted under constant wall heat flux conditions. Reynolds number was varied from laminar (*Re* = 200) to fully turbulent condition (*Re* = 35000). The volume flow rate has been kept as 5 litres per second in laminar flow and 20 litres per second in the turbulent flow.

Constant pumping power comparisons with smooth tube characteristics showed that in spirally grooved tube with and without twisted tape, heat transfer increased considerably in laminar and moderately in turbulent range of Reynolds numbers. Spirally grooved tube without twisted tape yielded maximum heat transfer enhancement of 400% in the laminar range and 140% in the turbulent range. However, reduction in heat transfer was noticed for smooth tube Reynolds number, in the range 2500 to 9000. Spirally grooved tube with twisted tape showed a maximum enhancement of 600% in the laminar range and 140% in the turbulent range. However, deterioration in heat transfer was observed at twist ratio, $y \approx 10.14$ (anticlockwise) for smooth tube Reynolds number, in the range 6000 to 13000.

Overall, among the three twist ratios tested (y = 10.15, 7.95 and 3.4), the heat transfer performance of clockwise twisted tape with twist ratio, y = 7.95 was found to be the highest in laminar, transitional and turbulent ranges of Reynolds numbers. They also found that the direction of twist (clockwise and anticlockwise) influenced the thermo-hydraulic characteristics. In general, clockwise tapes performed better for all ranges of Reynolds number and twist ratios. For y = 10.15 and the clockwise twisted tape, the clockwise twist of the tape generated an aiding swirl to the clockwise grooves of the tube and hence performed better in turbulent region. At lower twist ratios, y = 3.5, influence of Reynolds number was seen, suggesting that the swirl effect overrides the roughness effect.

6.5 Full length twisted tape with trapezoidal–cut

Experimental investigation for heat transfer and friction factor characteristics of circular tube fitted with full length twisted tape with trapezoidal–cut was carried out using a double pipe heat exchanger with inner copper tube having internal diameter 28.5 mm and length 2000 mm. Hot water was flown on the tube side and cold water in counter flow through annulus. Trapezoidal-cut twisted tape inserts as shown in Fig. 14, with twist ratios, $y \approx 6.0$ and 4.4 were made of aluminum strip having thickness 1.5 mm and width 23.5 mm. The trapezoidal-cut had dimensions of 8 mm depth, 8mm base and 12mm width at top and trapezoidal–cut was taken alternately on both top and bottom of the tape. The cold water flow rate was maintained constantly flowed at 10 litre per minute whereas

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the hot water flow rate was varied from 2 litre per minute to 7 litre per minute with 0.5 litre per minute in order to maintain the Reynolds number range of 2,000 - 12,000 [23].

Fig. 14. Twisted tape with trapezoidal-cut

The mean *Nu* for trapezoidal–cut twisted tape with *y* = 6.0 and 4.4, were respectively 1.37 & 1.72 times better than that of plain tube. This means an improvement of 27 and 41% for enhanced tube.

The friction factor observed for trapezoidal–cut twisted tape was higher than the plain tube and the smaller twist ratio lead to higher friction factor. The mean fanning friction factor for the trapezoidal–cut twisted tape with *y* = 6.0 and 4.4, were respectively 1.97 and 2.85 times over the plain tube.

Performance ratio with, *y* = 6.0 and 4.4 were in the range of 1.0 – 1.23 and 1.07 – 1.48 for trapezoidal–cut twisted tape as shown in Fig. 15.

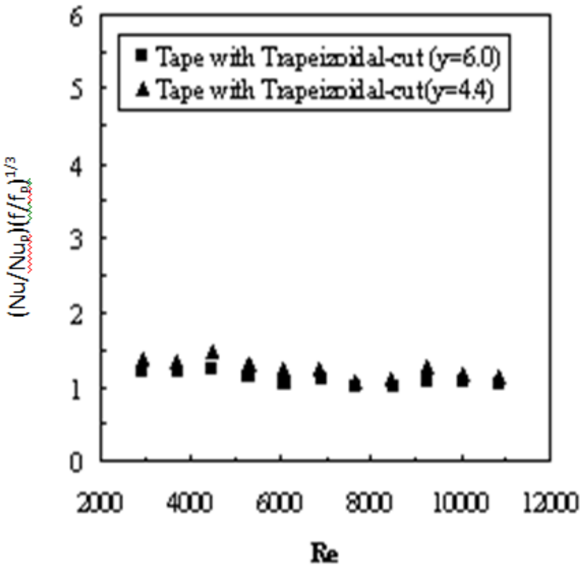

Fig. 15. Performance ratio with Reynolds number for tape with trapezoidal -cut of twist ratios 6.0 and 4.4

6.6 Half length twisted tape

A U-bend double pipe heat exchanger using oil were investigated experimentally consisted of 2 m lengths in each arm and 0.465 m length of U-bend section as shown in Fig. 16, and was made up of stainless steel tubes. The inner diameter of inner tube was 2.11 cm, and outer diameter of inner tube was 2.5 cm. Inner diameter of annulus pipe was 5 cm. Twisted tapes were made out of 0.8 mm thick stainless steel strip of twist ratio 7 and width was 1 mm less than the inside diameter of test section [22].

The flow rate of water through annulus tube in counter-flow configuration was maintained constant at 15 litre per minute. The oil flow rate through inner tube was kept as 4, 8, 12, 18, 24, 30 litre per minute.

Based on equal mass flow rate basis, it was found that the heat transfer coefficient was increased by approximately 40% on average when compared to those of smooth tubes, using half-length twisted tape. On the unit pressure drop basis it was observed that thermal

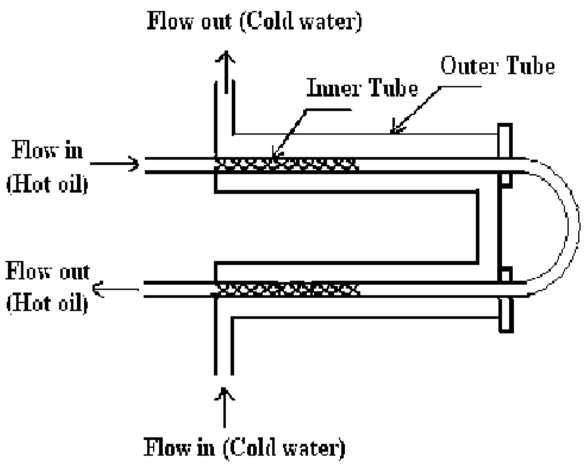

Fig. 16. The inner tube fitted with half length twisted tape

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performance of smooth tube is better than half length twisted tape, by 1.3-1.5 times as shown in Fig. 17. It is because the gain in terms of increase in heat transfer coefficient is partially offset by the increased pumping power.

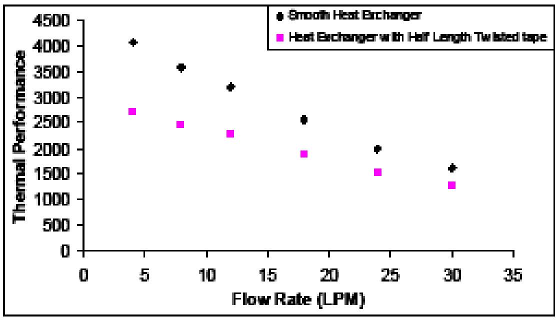

Fig. 17. Flow rates versus thermal performance ratio

6.7 Peripherally-cut twisted tape

The effect of peripherally-cut twisted tape with alternate axis on the fluid flow and heat transfer enhancement characteristic in a circular tube was studied and compared with typical twisted tape under similar conditions with water as working fluid under uniform heat flux conditions [29].

All twisted tapes used in the experiment as shown in Fig. 6, were made from an aluminum strip having 0.8 mm thickness, 19 mm width and 1000 mm length. (i) The typical twisted tape (TT) was fabricated by twisting the strip at constant twist ratio of 3.0. (ii) Three peripherally-cut twisted tape with alternate axis (PT-A) were formulated by cutting along the peripheral lines of twisted tape with three different peripherally-cut width ratios (W = 2 mm (W/w = 0.11), 4 mm (W/w = 0.22) and 6 mm (W/w = 0.33)) while the peripherally-cut depth length was kept constant at d = 2 mm (d/w = 0.11). To form the alternate axis, the tape was cut on both side sat every twist length (180°). At each pair of the cuts, both sides of the tape were subsequently twisted simultaneously to angle difference of 90°. (iii) Three peripherally-cut twisted tapes with three different peripherally-cut width ratios (w/W = 0.11, 0.22 and 0.33) were also prepared for comparative tests. Experiment was conducted for Reynolds number of 5,000 to 20,000.

The heat transfer rates in the tube equipped with the PT-A were13 to 38%, 17 to 81% and 50 to 184% greater than those in the tube fitted with the PT, TT and plain tube alone. This was attributed to the combined effects of three actions by the PT-A including (1) a common swirling flow by the twisted tape (2) a periodic change of swirl direction by an alternate axis which leads to a strong collision of the recombined streams in the rear of each alternate axis and (3) a high turbulence intensity of fluid in the vicinity of the tube wall generated by the peripheral cut along the edge of the twisted tape. Friction factor increased with decrease in Reynolds number. Friction factor in the tube with the PT-A is increased up to 1.7, 2.1 and 7.7 times compared to those in the tube with PT, TT and plain tube, respectively.

The thermal performance factors, under constant pumping power, obtained in the present study were as high as 1.25 for PT-A, 1.11 for PT and 1.02 for TT which were achieved at the lowest values of Reynolds number, Re = 5000 in the range. Thermal performance factor decreased with increasing Reynolds number for all tape inserts, due to larger pressure loss at higher Reynolds number.

6.8 Full-length dual and regularly-spaced dual twisted tapes

A comparative investigation of enhanced heat transfer and pressure loss by insertion of three different types of inserts; (i) single twisted tape (ii) full-length dual and (iii) regularly-spaced dual twisted tapes under uniform heat flux condition was presented [30].

The copper test tube had 47 mm inside diameter and 50 mm outside diameter and length of 1250 mm. Twisted tapes were made of aluminum alloy with thickness of 0.8 mm. The typical single twisted tape had a width of 46 mm while both types of the dual tapes were 23 mm wide.

Three different twist lengths were used; 138, 184 and 230 mm for the single tape and 69, 92, and 115 mm for the full-length dual tapes which corresponded to the same set of twist ratios 3.0, 4.0 and 5.0 The regularly-spaced dual twisted tapes were prepared with four different space ratios, defined as a ratio of free-spacing length to inside diameter of the test tube; s/d_i =0.0 (full-length tapes or tapes without free spacing), 0.75 (s = 35.25 mm), 1.5 (s = 70.5 mm), and 2.25 (s = 105.75 mm). The twisted geometry is shown in Fig. 18. The Reynolds number of the bulk air was varied from 4000 to 19,000.

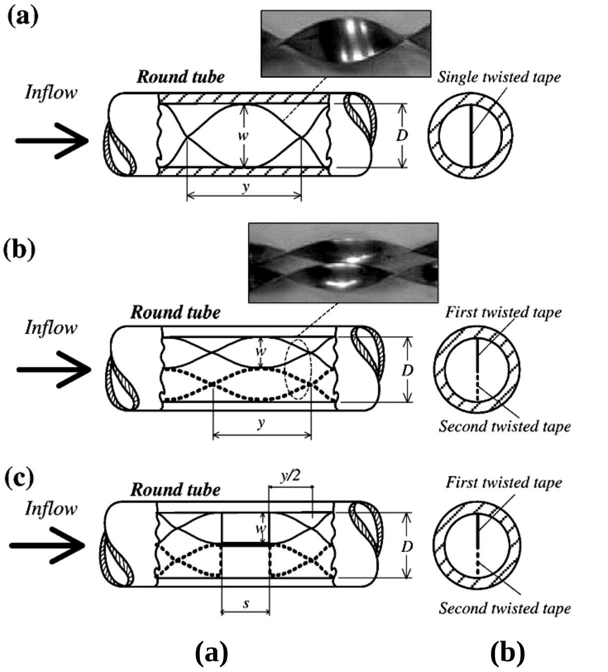

Fig. 18. Test tube with twisted tape inserts: (a) single twisted tape, (b) full-length dual twisted tapes, and (c) regularly-spaced dual twisted tapes.

The heat transfer rate for the dual twisted tapes was increased from 12% to 29% in comparison with the single one, for twist ratios 3.0 to 5.0. Depending on the flow conditions and twist ratio, the increase in heat transfer rate over the plain tube were about 146%, 135% and 128% for twist ratios 3.0, 4.0 and 5.0, respectively.

For all twist ratios, the swirling flow produced by the dual twisted tapes provided higher heat transfer rate than those by the single twisted tape. The dual twisted tapes generated a double swirl flow leading to the increase in residence time of the flow due to its separation into two streams (upper and lower tapes) and increase in turbulent intensity of the flow giving better mixing of fluid between the tube wall and the core.

The use of the smaller space ratio (s/d_i = 0.75) yielded the highest heat transfer than the larger space ratio but lower than the full length tape (s/d_i = 0.0). It was also found that at the small space ratio, s/d_i = 0.75, there was a slight difference in heat transfer compared with the full-length tape (s/d_i = 0.0).

The friction factor from using the dual twisted tapes was found to increase up to 23% over the single twisted tape. The friction factor decreased with the rise of Reynolds number and twist ratio values.

Experiments showed that dual twisted tap with smaller twist ratio 3 lead to higher enhancement efficiency, and reduces when twist ratio increases. Enhancement efficiency varies from 1.03 to 1.11, 1.01 to 1.08, and 0.95 to 1.06 for twist ratios 3, 4, 5, respectively as shown in Fig. 19. The use of dual twisted tapes is not suggested due to higher energy loss at higher Reynolds number. Though these can used with various other swirl generators to reduce pressure drop and increase heat transfer.

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The Nusselt numbers for the tube with dual twisted tape elements in tandem at s/di=0.0, 0.75, 1.5 and 2.25, were about 146%, 140%, 137% and 132% over the plain tube, respectively. The efficiency value is found to be 1.03 to 1.11, 1.02 to 1.09, 1.01 to 1.08 and 1.0 to 1.07 for space ratios, s/di=0.0 (full-length tape), 0.75, 1.5 and 2.25, respectively, as shown in Fig. 20. Thus, the dual twisted tape elements in tandem arrangement should be preferably applied at low Reynolds number and space ratio (s/di) to obtain an optimum gain.

6.9 Perforated twisted tape

Researcher [33] conducted an experimental study for heat transfer and pressure drop characteristics in a circular tube with perforated twisted tape inserts using air.

The tube had 70 mm inside diameter and 1500 mm length, with suitable insulation. Mild steel perforated twisted tapes of different pore diameters, as shown in Fig. 4, were inserted along the length. The tapes were 55 mm wide, and 3 mm in thickness. The twist ratio (y) of the insert was kept 4.55. Seven test specimens having same twist ratio, but different pore diameters were used. The pore diameter was varied from 3 mm to 9 mm in 1 mm steps. The distance between two adjacent holes was axially 15 mm and transverse wise 20 mm as shown in Fig. 21.

Perforation of the inserts varied from 2.5% to 20.8%. Constant heat flux condition was maintained and the Reynolds number was varied 13000-52000.

The average Nusselt number for tube with perforated twisted tape varies from 4-4.5 times when compared with plain tube, as shown in Fig.

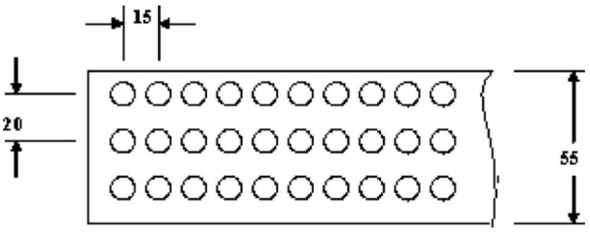

Fig. 21. Cross section of the test section with perforated twisted tape inserts

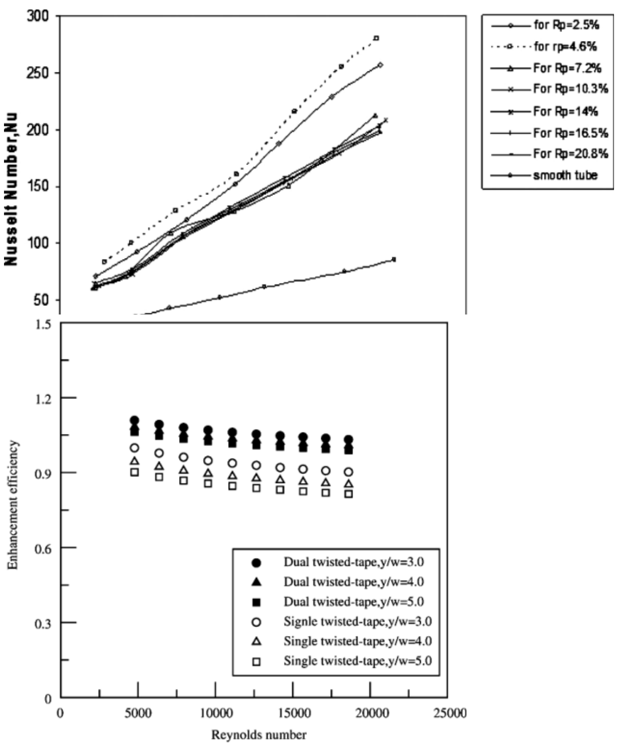

Fig. 19. Effect of single and full-length dual twisted tape inserts on enhancement efficiency

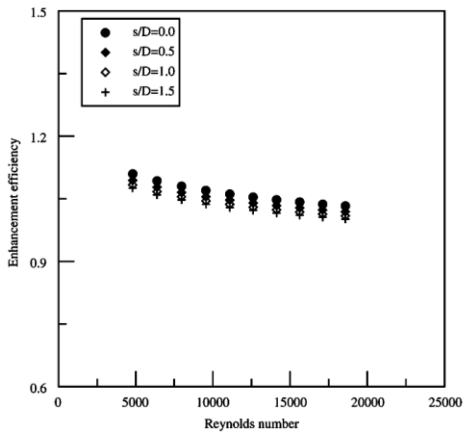

Fig. 20. Effect of single and full-length dual twisted tape inserts on enhancement efficiency

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22. It is maximum when *Rp* = 4.6%, at same Reynolds number. It was observed that at *Rp* = 4.6%, the wall temperature was lower than that of the tube with other inserts.

High perforation causes less swirling effect. The pumping power requirement also increased 1.2-2.25 times. Nusselt number was high in the entrance and exit regions i.e., *x/L* = 0.2 and 0.8 otherwise more or less constant where, *x* = 0 at entrance and *x* = *L* at exit.

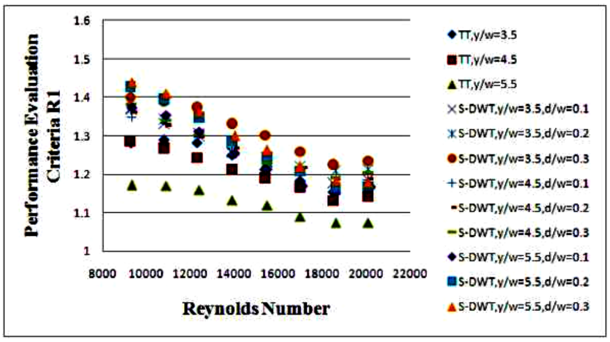

Fig. 24. Performance evaluation criteria (R1) versus Reynolds number for typical twisted tape and straight delta winglet twisted tape for all the cases.

It was also observed that the heat transfer coefficient achieved with the perforated twisted tape was 1.7 times higher than the twisted tape insert, 2.0 times higher than the longitudinal insert and 1.9 times higher than wire-coil inserts as shown in Fig. 23. However, insertion of inserts increases the pumping power.

6.10 Straight Delta Winglet Twisted Tape

Experimental investigation of heat transfer and friction factor characteristics in a double pipe heat exchanger fitted with straight delta winglet and typical twisted tape elements was conducted by [35].

The test section consisted of an inner copper tube which was 1600 mm long having internal diameter 20.5 mm and external diameter 26 mm. The twisted tapes were made of aluminum strips with thickness of 2.01 mm and the length of 1500 mm. Straight delta winglets twisted tape had twisted ratios of 3.5, 4.5 and 5.5 and depth of cut ratios, *d/w* = 0.1, 0.2 and 0.3 and are shown in Fig. 3. The twist ratios for typical twisted tape were also kept the same.

Hot water was on tube side at 48°C with mass flow rate ranging from 0.085203 – 0.181329 kg/sec to obtain Reynolds number range of 9,000 – 20,000.

The Nusselt number for the tube fitted with Straight delta winglet twisted tapes was higher than that for typical twisted tape for a given Reynolds number due to swirl flow. As the *Re* increased, the *Nu* increased due to increased convection. With decrease in twist ratio the *Nu* increased, and was maximum for twist ratio of 3.5.

Based on equal mass flow criteria, the Straight Delta Winglet Twisted Tape with twist ratio 3.5 and *d/w* = 0.3 was found to give best overall performance as shown in Fig. 24.

The friction factor for the tube fitted with Straight delta winglets inserts was higher than that for typical twisted tape and decreases with Reynolds number for a given twist ratio. However, the friction factor increased with decrease in twist ratio for a given Reynolds number and reached a maximum for the twist ratio 3.5.

7. Conclusion

In the present paper an attempt has been made to review the studies carried out by various researchers using twisted tape inserts. The results obtained using various geometries and configuration for heat transfer enhancement with different fluids like air, water, nanofluids, oil having different Prandtl number values have been reported in detail.

- Heat transfer enhancement is mainly due to flow blockage, partitioning of flow and secondary flow. The blockage increases the pressure drop along with increase in flow velocity. The secondary flow creates swirl and the resulting mixing of fluid improves the temperature gradient, which ultimately leads to a high heat transfer coefficient.
- For full length twisted tapes enhancement in heat transfer was of the order of 188% in air for Reynolds number upto 12000, 128% with use of nano-fluids for Reynolds number upto 35000 and 140% for spirally grooved tubes for Reynolds number up to 25000 in turbulent region.
- Short length twisted tapes perform better than full length twisted tapes. Thermal performance factor increase to 1.3-1.5 times over plain tube.
- Twisted tape with spacers, also provide better performance over full length twisted tapes in turbulent region.
- Overall performance ratios are as high as 1.48 for trapezoidal cut twisted tapes, 1.25 for peripheral cut twisted tape with alternate axis, and 1.7 for perforated twisted tape.

It is observed that use of twisted tape as insert is a good technique to improve thermal performance. Geometry, configurations, flow conditions and results reported in literature have also been presented in tabular form. Information provided in the present paper may be useful in this area of research.

Nomenclature

A	Heat transfer surface area, m^2
c_p	Specific heat of fluid, kJ/kg.K
d_i	Inside diameter of the test tube, m
d_o	Outside diameter of the test tube, m
d	Depth of peripheral cut, m
f	Friction factor
h	Heat transfer coefficient, W/m^2K
U	Overall heat transfer coefficient, W/m^2K
k	Thermal conductivity of fluid, W/mK
m	Mass flow rate, kg /s
L	Length of the test section, m
Nu	Nusselt number
P	Pressure N/mm^2
ΔP	Pressure drop, N/mm^2
Pr	Prandtl number
Q	Heat transfer, W
Re	Reynolds number
t	Thickness of the tube, m
T	Temperature, ˚C
T_{ln}	Logarithmic mean temperature difference
v	Velocity of fluid, m/s
w	Width of twisted tape, m
W	Width of peripheral cut, m
H	Twisted tape pitch, m
y	Twist ratio = H/w
R_p	Perforation rate
Greek symbols	
ρ	Fluid density, kg/ m^3
δ	Twisted tape thickness, m
μ	Fluid dynamic viscosity,Kg/m.s

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α Spiral angle

Subscripts

b bulk
c cold
h hot
in inlet
out outlet
ave average
s surface
TT typical twisted tape
PT peripherally-cut twisted tape
PT-A peripherally-cut twisted tape with alternate axis

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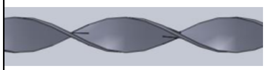
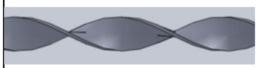
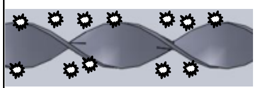
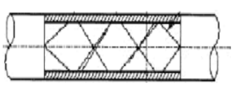
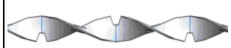
APPENDIX I

TABLE I. TWISTED TAPE GEOMETRY, TEST CONDITIONS AND MAIN RESULTS

Geometry of twisted tape	Researchers	Twisted tape geometry	Reynolds number range and fluid	Main results
• Full length twisted tape in double pipe heat exchanger • *y*=3.1 & 3.7	P. Naphon (2006)[16]		• Re = 7000 to 23000 • Water	• The heat transfer rate at lower twist ratio was higher across the range of Reynolds number.
• Full length twisted tape in double pipe heat exchanger • *y* = 5 & 7	W. Noothong et al (2006)[17]		• Re = 2000 to 12000 • Air	• Nu increased by 188% and f increased by 3.37 times for y = 5 •
• Broken twisted tape • y = 1.0 - 2.5 & ∞ •	S.W. Chang et al. (2007)[19]		• Re = 1000 – 40000 • Air •	• (Nu)Broken/Nuo = 1.28 - 2.4 • (Nu)Broken/Nuo = 6.3 - 9.5 • (f)Broken/fo = 2.4-4.7 • Thermal performance factor (Nu/Nuo)/(f/f0)1/3 was highest for 1 ≤ y ≤ 2.5.
• Full length twisted tape in circular tube • y = 10	L. Syam Sundar et. al (2007) [20]		• Re = 2000 to 35000 • γ-Al2O3 nanoparticles size = 47 mm in water	• Maximum enhancement in heat transfer =28% using nanofluid with twisted tape
• Full length peripherally-cut twisted tape with alternate axis (PT-A) in round tube. • *y* = 3.0	P. Seemawute and S. Eiamsa-ard, (2010) [21]		• Re = 5000 to 20000. • Water •	• The heat transfer rates with the PT-A were 13 to 38%, 17 to 81% and 50 to 184% greater than those in the tube fitted with the PT, TT and plain tube alone • Friction factor in the tube with the PT-A is increased up to 1.7, 2.1 and 7.7 times compared to those in the tube with PT, TT and plain tube, respectively. • The thermal performance factors, were as high as 1.25 for PT-A, 1.11 for PT and 1.02 for TT
• Half length twisted tape in double pipe U-bend heat exchanger. • y = 7	Anil Singh Yadav, (2009) [22]		• L = 2 m, di = 21.10 mm. • Oil	• Heat transfer coefficient increases by 40%. • At equal mass flow rate twisted tape is better. • At unit pressure drop the thermal performance of plain heat exchanger is 1.3-1.5 times better.
• Trapezoidal cut twisted tape in double pipe heat exchanger • y = 6.0 & 4.4 • Trapezoidal cut depth = 8 mm, base = 8 mm	P. Murugesan et al, (2009) [23]		• Re = 2000 to 12000 • Water	• Mean Nu for trapezoidal–cut twisted tape with y = 6.0 and 4.4, were respectively 1.37 & 1.72 times better • Friction factor for y = 6.0 and 4.4, were respectively 1.97 and 2.85 times over the plain tube.

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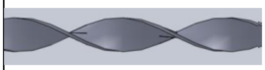
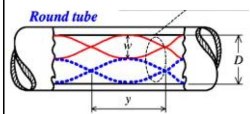
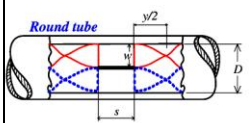
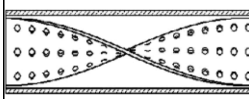
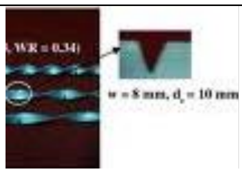
Geometry of twisted tape	Researchers	Twisted tape geometry	Reynolds number range and fluid	Main results
& width at top = 12 mm				• Performance ratio with, y = 6.0 and 4.4 were in the range of 1.0 – 1.23 and 1.07 – 1.48, i.e. > 1
• Spirally grooved (clockwise) tube with full length twisted tape. • y = 3.4 -10.15 (clockwise & anticlockwise)	P. Bhardwaj et al. (2009)[24]	 	• Re ≈ 1000-25000. • Water	• Enhancement at constant pressure is 600% in laminar region and 140% in turbulent region. • y=7.95 performed better. • Clockwise twisted tape was found to perform better.
• Full length dual twisted tapes and regularly-spaced dual twisted tapes in round tube. • y =3.0, 4.0 and 5.0 • s/di = 0.75 - 2.25	S. Eiamsa-ard et al. (2010) [30]	  	• Re = 4000 to 19000 • Air	• The heat transfer rate for the dual twisted tapes was increased from 12% to 29% in comparison with the single one, for y = 3.0 to 5.0 • The increase in heat transfer rate over the plain tube were about 146%, 135% and 128% for y = 3.0, 4.0 and 5.0, respectively. • The friction factor from using the dual twisted tapes was found to increase up to 23% over the single twisted tape
• Mild steel perforated twisted tapes in circular tube • y = 4.55. • Pore diameter = 3 mm to 9 mm in 1 mm steps.	J. U. Ahamed et al, (2011) [33]		• Re = 13000-52000. • Air •	• Nu for tube with perforated twisted tape varies from 4 - 4.5 times & maximum when Rp = 4.6%, at same Reynolds number. • High perforation causes less swirling effect • The pumping power requirement increased by 1.2-2.25 times • Heat transfer coefficient with the perforated twisted tape was 1.7 times higher than the twisted tape insert, 2.0 times higher than the longitudinal insert and 1.9 times higher than wire-coil inserts.
• Straight delta winglets twisted tapes in circular tube of double pipe heat exchanger • y = 3.5 - 5.5	S.D. Patil et al. (2012) [35]		• Re = 9000-20000. • Water •	• Nu was maximum for y= 3.5. • the Straight Delta Winglet Twisted Tape with twist ratio y = 3.5 and d/w = 0.3 was found to give best overall performance • friction factor reached maximum for the y = 3.5