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Review Article

The heat transfer enhancement techniques and their Thermal Performance Factor

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ABSTRACT

Heat transfer devices have been used for conversion and recovery of heat in many industrial and domestic applications. Over five decades, there has been concerted effort to develop design of heat exchanger that can result in reduction in energy requirement as well as material and other cost saving. Heat transfer enhancement techniques generally reduce the thermal resistance either by increasing the effective heat transfer surface area or by generating turbulence. Sometimes these changes are accompanied by an increase in the required pumping power which results in higher cost. The effectiveness of a heat transfer enhancement technique is evaluated by the Thermal Performance Factor which is a ratio of the change in the heat transfer rate to change in friction factor. Various types of inserts are used in many heat transfer enhancement devices. Geometrical parameters of the insert namely the width, length, twist ratio, twist direction, etc. affect the heat transfer. For example counter double twisted tape insert has TPF of more than 2 and combined twisted tape insert with wire coil can give a better performance in both laminar and turbulent flow compared to twisted tape and wire coil alone. In many cases, roughness gives better performance than the twisted tape as seen in case of flow with large Prandtl Number. The artificial roughness can be developed by employing a corrugated surface which improves the heat transfer characteristics by breaking and destabilizing the thermal boundary layer. This paper provides a comprehensive review of passive heat transfer devices and their relative merits for wide variety of industrial applications.

Contents

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Nu	Nusselt Number	ρ	density of the fluid
Re	Reynolds Number	u	mean velocity of the fluid
TPF	Thermal Performance Factor	D_h	hydraulic diameter of the test section
TT	Twisted Tape	y/w	Twist ratio of the twisted tape
Pr	Prandtl Number	θ	Twist angle
Nu	Nusselt number with enhancement technique	LR	Tape length ratio
Nu_0	Nusselt number without enhancement technique	s/w	Spaced-pitch ratio
f	Friction factor with enhancement technique	d/w	Perforation hole diameter ratio
f_0	Friction factor without enhancement technique	p/D	Pitch ratio
h	heat transfer co-efficient	R_B	Winglet to duct height ratio
l	characteristic length	R_P	Winglet pitch to tape width ratio
k	thermal conductivity		
ΔP	pressure drop along the test section		

1. Introduction

Heat transfer devices have been used for the conversion and recovery of heat in many industrial and domestic applications. Some examples are boiling of liquid and condensation of steam in power plants, thermal processes involved in pharmaceutical and chemical industries, sensible heating and cooling of milk in dairy industries, heating of fluid in concentrated solar collector and cooling of electrical machines and electronic devices among others. Enhancing the performance of a heat transfer device is therefore of great interest since it can result in energy, material and cost saving.

Heat transfer enhancement techniques generally reduce the thermal resistance either by increasing the effective heat transfer surface area or by generating turbulence in the fluid flowing inside the device. Rough surfaces or extended surfaces are used for the purpose of increasing the effective surface area whereas inserts, winglets, turbulatorsetc. are used for generating the turbulence. These changes are usually accompanied by an increase in pumping power which can results in higher cost (Manglik, 2003). The effectiveness of a heat transfer enhancement technique can be evaluated by the Thermal Performance Factor (TPF) which represents the ratio of the relative effect of change in heat transfer rate to change in friction factor. It is defined by following equation

$$\eta = \frac{Nu/Nu_0}{(f/f_0)^{1/3}}$$

where Nusselt number $Nu = \frac{hl}{k}$ and friction factor $f = \frac{(\Delta P)}{(\rho u^2/2)(l/D_h)}$

In this paper, an effort has been made to review the analysis carried out by various researchers for passive heat transfer enhancement techniques provided with their Thermal Performance Factor.

2. Effect of enhancement techniques

Various heat transfer enhancement techniques have different advantages and limitations. They vary in geometrical configuration and construction complexity while operating under different flow and thermal conditions. On the basis of these parameters this review is classified as follows.

2.1. Effect of swirl producing devices on heat transfer

The twisted tape inserts have been used as a heat transfer enhancement device in last few decades and particular most widely used in heat exchangers to reduce their size and cost. Depending upon the application, twisted tapes are used with different twist ratio, with varying twist direction, fit and loose tape insert, full and short tape insert, perforated insert, insert with peripheral cuts, etc.

2.1.1. Effect of twisted tape dimensions

Instead of full length twisted tape, Saha et al. (2001) used regularly spaced twisted tape. They investigated experimentally the effect of twist ratio, space ratio, tape width, phase angle on heat transfer and concluded that reduction in tape width gives poor heat transfer and higher than zero phase angle creates complexity in tape manufacturing rather than improving the heat transfer. Eiamsa-ard et al. (2006) conducted experiments with a twisted tape with twist ratio of 6–8 for a full length tape and free space ratio of 1, 2 and 3 for a regularly spaced twisted tape insert. They concluded that the heat transfer coefficient increases with decrease in twist ratio and space ratio. Eiamsa-ard et al. (2009) also investigated the effect of short length twisted tape insert. They used twisted tape with fix twist ratio and different length ratio. Short length inserts generated strong swirl at the tube entrance while the full length tape produced strong swirl flow over the entire length. Outcome of their research revealed that the maximum Thermal Performance Factor obtained for full length tape is 1.04 at Re = 4000 and decreases as the length ratio decreases. They proposed following correlation of TPF in term of length ratio and Re: $\eta = 1.82Re^{-0.068}(LR)^{0.067}$.

Sarada et al. (2011) observed that the width of the twisted tape significantly affects the heat transfer rate. It was found that the heat transfer enhances as the width of insert increases. Piriyarungrod et al. (2015) presented the effect of taper in the twisted tape to enhance the heat transfer performance. Their experiments for different taper angles revealed that the taper twisted tape does not achieve the Thermal Performance Factor more than 1.05 but increases the heat transfer rate. Thus, taper tape is not a feasible method for heat transfer enhancement. Esmaeilzadeh et al. (2014) also analyzed the effect of thickness of twisted tape with nanofluid and showed that the increase in thickness of the tape increases the heat transfer rate, friction factor and TPF. Eiamsa and Promvonge (2010) assessed the performance of alternate clockwise and counter clockwise twisted tape inserts. They used tapes in experiments having twist ratios of 3,4 and 5 each with three twist angles of 30°, 60° and 90° and conclude that the heat transfer rate and TPF of alternate twisted tapes are higher than typical twisted tapes at similar operating conditions. Heat transfer rate and TPF (1.3–1.4) increase with decrease in twist ratio and increase in phase angle. They proposed the following correlation: $\eta = 2.93Re^{-0.1}(y/w)^{-0.14}(1+\sin\theta)^{0.31}$

2.1.2. Effect of twist ratio

Patil and Vijaybabu (2012, 2014) conducted experiments to understand the effect of the twist ratio on heat transfer augmentation. They concluded that the heat transfer increases with decrease in twist ratio. Also the use of twisted tape in laminar flow can result in energy saving. Twisted tape with increasing–decreasing twistratio (Fig. 1) has a TPF of 1.98–1.60 at low Re = 100 (Patil & Vijaybabu, 2014). Eiamsa-ard et al. (2012) employed sequentially, repeatedly and intermittently twisted tape with increasing-decreasing twist ratios. Among the tapes tested, the repeatedly increasing-decreasing twist ratios offered the maximum TPF of around 1.03.

2.1.3. Effect of helical insert

Helical twisted tapes have also been used to enhance the heat transfer rate (Sivashanmugam & Suresh, 2007; Sivashanmugam & Nagarajan, 2007). These authors used the full length helical inserts with different twist ratios (Fig. 2), with equal and unequal lengths with right and left turns. Their experiments showed that the helical tape insert improves the heat transfer compared to a plain tube and the TPF with right-left helical insert could be obtained an up to 3 for different configurations. Moawed (2011) used the helical screw tape inserts in an elliptical tube. For low Re, it was found that the maximum TPF of 1.2 could be obtained with a combination of pitch ratio of 1 and twist ratio of 0.22. Multiple helical twisted tapes have been analyzed by Bhuiya et al. (2012) at different helix angles (9°, 13°, 17° and 21°). The power consumed by the blower increases 2–3 times with decrease in helix angle. TPF achieved is from 1.08 to 1.30. Maakoul et al. (2017) numerically investigated TPF of a double pipe heat exchanger fitted with helical baffles in the annulus side. They used Fluent to solve three dimensional computational fluid dynamics model. From their analysis, it was found that in all cases TPF was less than one which was mainly due to higher pressure drop in entrance region effect.

2.1.4. Effect of modified twisted tape

Research was carried out by Rahimi et al. (2009) to investigate the effect of modified twisted tape insert on heat transfer characteristics. They performed experiments using simple twisted tapes, perforated twisted tapes, notched twisted tapes and jagged twisted tapes in their investigation. Their results obtained from CFD analysis and experiments revealed that a jagged twisted tape has best TPF of 1.21 due to higher turbulence developed close to the tube wall. Shubanian et al. (2011) analyzed heat transfer enhancement in an air cooler equipped with three types of tube inserts namely the butterfly, classic and jagged twisted tape (Fig. 3). Their results indicated that the increase in Nu is accompanied by the rise in Re. Ratio of Nu/Nu_0 is higher in a butterfly insert compared to jagged and classic twisted tape insert in the range of Re considered. It was also observed that the tube fitted with tube inserts showed a substantial increase in the friction factor compared to the plain tube. Friction factor is high at low Re and tends to decrease with increase in Re. Heat transfer enhancement can also be obtained at the expense of increase in pressure drop. TPF varies between 1.28–1.62, 1–1.23 and 0.88–1.03 for butterfly, jagged and classic

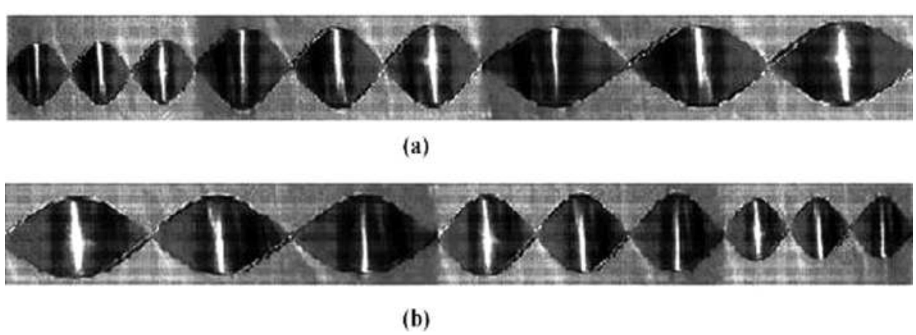

Fig. 1. Twisted tape insert (a) increasing twist ratio; (b) decreasing twist ratio (Patil & Vijaybabu, 2014).

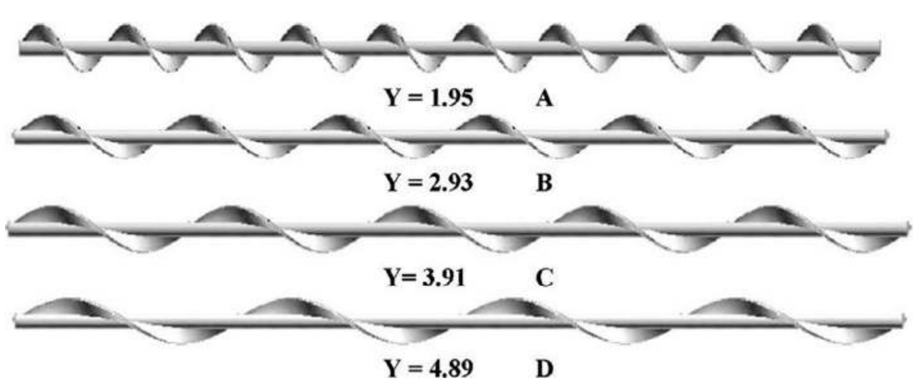

Fig. 2. Helical screw inserts of different twist ratio (Sivashanmugam & Suresh, 2007).

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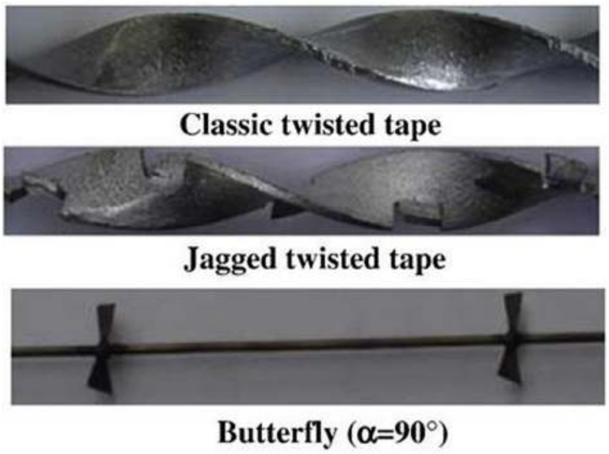

Fig. 3. Classic, Jagged and Butterfly twisted tape (Shabanian et al., 2011).

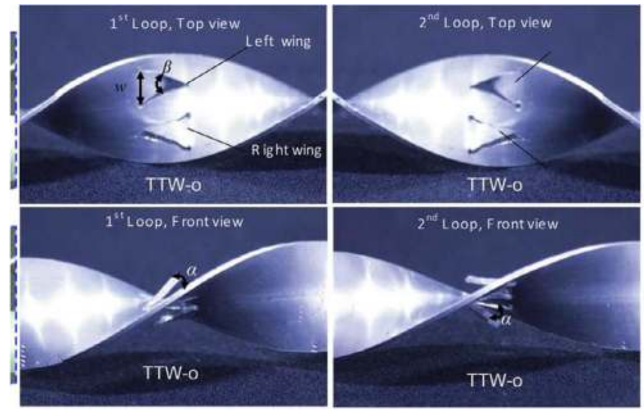

Fig. 5. Twisted tape with twin delta wings (S. Eiamsa-ard et al., 2013a).

inserts respectively. TPF depends on Re, inclination angle and twist ratio. Results obtained from CFD analysis using the k-ε turbulence model were shown to be in good agreement with the experimental results.

2.1.5. Effect of wings and winglet twisted tape

Smith Eiamsa-ard et al. (2010a, 2013a) and Eiamsa-ard et al. (2013b) investigated the effect of delta winglet twisted tape inserts on heat transfer and pressure drop characteristics. The investigation was made for straight and oblique delta winglet (S. Eiamsa-ard et al., 2010a) (Fig. 4) along with twin delta winged twisted tape insert (Smith Eiamsa-ard et al., 2013a) (Fig. 5). They analyzed twisted tapes for different twist ratios and depth of wing cut ratios. From results, it was concluded that oblique delta-winglet is more efficient than straight delta winglet. Over the range of Re studied, TPF for oblique delta winglet twisted tape and straight delta winglet twisted tape were found to be 0.92–1.24 and 0.88–1.21 respectively. The twin delta winged twisted tape wings were cut in three different positions: up, down and opposite (Smith Eiamsa-ard et al., 2013a). Wings were inclined at an angle of 15° with the tape surface. The effect was examined for three different wing tip angles of 20°, 40° and 60°. The result revealed that up side position performs well compared to down and opposite side wings; heat transfer rate increases with wing tip angle; twin tape wing up with 20° wing tip angle gives the highest TPF of 1.26. Instead of using twisted tape inserts, Deshmukh and Vedula (2014) used curved delta type vortex generator (Fig. 6) to analyze the heat transfer

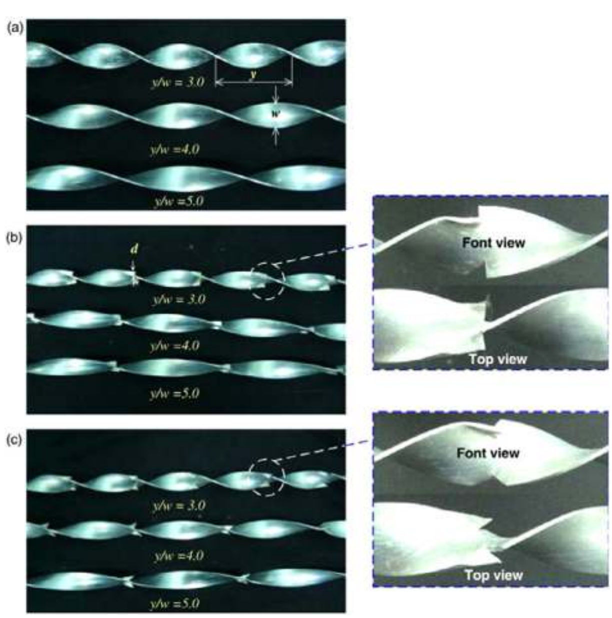

Fig. 4. Oblique delta winglet (S. Eiamsa-ard et al., 2010a).

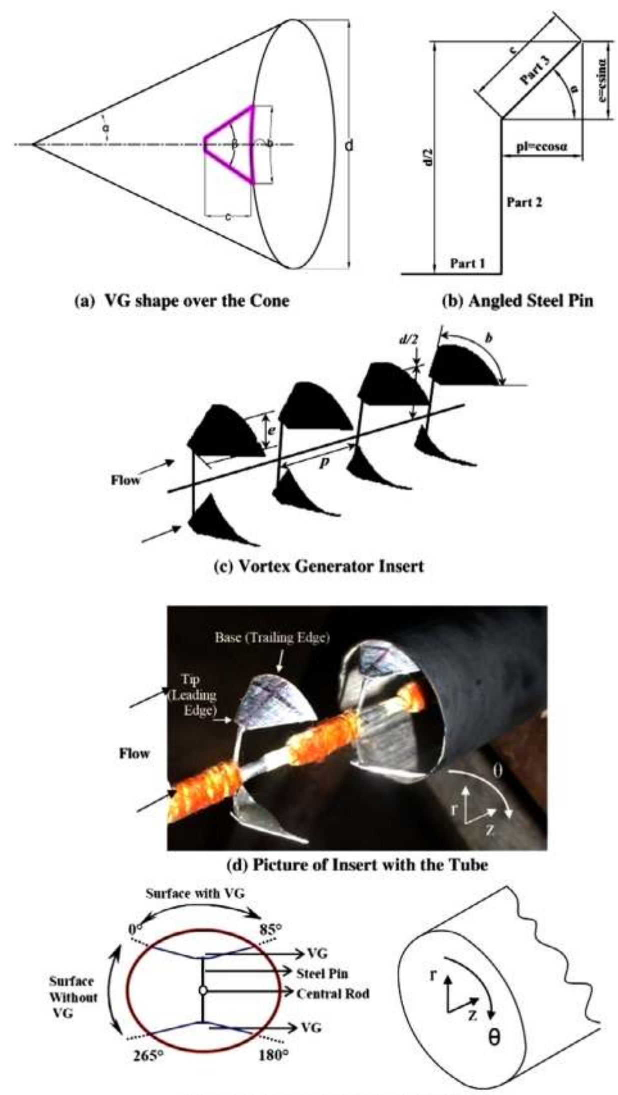

Fig. 6. Geometrical details of delta wing vortex generator (Deshmukh & Vedula, 2014).

and friction factor characteristics of flow through a circular tube. The insert was constructed with a central rod on which curved delta wings were attached at specific locations. Local heat transfer coefficient and average pressure drop were examined for different pitch to projected length ratio, height to tube inner diameter and angle of attack. Nu/Nu_0 ratio was found to be in the range of 1.3–5.0 and TPF from 1.0 to 1.8. Behfard and Sohankar (2016) conducted a numerical study of delta winglet vortex generator used in a rectangular duct. They found a TPF of 1.49. Augmentation of heat transfer by using wire-rod bundles was investigated by Nanan et al. (2013a). Analysis was done for 4, 6 and 8 wire bundles with three different pitch ratios. Heat transfer rate increased compared to the plain tube. But TPF was less than one in most of the combinations. The combined effect of the twisted tape and vortex generator was experimentally investigated by Promvonge et al. (2014). Experiments were conducted in a square duct with simple, two V winglets and four V winglets with a fixed angle of attack of 30°. Highest TPF of 1.62 was obtained which was 17% more than that of twisted tape. Arulprakasajothi et al. (2015) investigated the effect of staggered and non-staggered conical strip inserts in a circular tube under laminar flow condition. The conical strip of forward and backward direction was used as turbulators which led to enhanced heat transfer coefficient. Numerical simulation was carried out by Zheng et al. (2017) to investigate the effect of vortex rod in heat exchanger tube. Their results revealed that the vortex rod inclination angle, diameter ratio and Re affects heat transfer and friction factor considerably. Also by using Artificial Neural Network they concluded that the vortex rod with diameter ratio 0.058 and inclination angle 57.05 at Re = 426.767 gives the best TPF.

Wongcharee and Eiamsa (2011) used a twisted tape with alternate axis and triangular, rectangular and trapezoidal wings for heat transfer enhancement (Fig. 7). Performance was evaluated for three different wing chord ratios of 0.1, 0.2 and 0.3 with constant twist ratio of 4. Wings were fabricated at an angle 60° relative to the adjacent plane. For the same operating conditions, Nu ratio, friction factor ratio and TPF were higher in trapezoidal cut compared to the other two. Maximum TPF was 1.43 with trapezoidal wings with wing-chord ratio of 0.3. Bali and Sarac (2014) investigated the effect of propeller type vortex generator. They used two propeller vortex generators as the swirling flow decayed after some distance. They examined the effect of joint angle and number of joint vanes for a range of Re. Murugesan et al. (2010, 2011a, 2011b) analyzed the effect on heat transfer characteristics due to square (Murugesan et al., 2010), triangular (Murugesan et al., 2011a) and trapezoidal (Murugesan et al., 2011b) cut on the periphery of a plain twisted tape. They carried out experiments for twist ratio 2, 4.4 and 6. Their results revealed that Nu and friction factor increased simultaneously. TPF of 1.02–1.22, 1.07–1.27 and 1.02–1.27 was achieved for trapezoidal, triangular and square cut respectively. Smith Eiamsa-ard et al. (2010e) performed experiments for peripherally cut twisted tape with constant twist ratio of 3 (Fig. 8). Experiments were performed for different tape width and depth ratios in the range of Re 1000–20,000. They concluded that the peripherally cut twisted tape had better performance compared to a plain tube. TPF achieved was 2.28–4.88 in laminar regime and 0.88–1.29 in turbulent regime. Smith Eiamsa-ard et al. (2010d) conducted experiments for center cut wings in twisted tape. The wings were constructed along the centerline with three different angles of attack (43°, 53° and 74°). Center cut twisted tape with 74° inclined wings were found most effective giving TPF up to 1.4. Lei et al. (2012) made a hole in the center of the twisted tape and observed that it performed well compared to the plain twisted tape. Another advantage of it was the material saving due to the material removal from the hole. TPF achieved was in the range 1.0–1.4 for different combinations of parameters.

Anvari et al. (2014) used the convergent and divergent type ring inserts. They placed the ring inserts in the tube at equal distance and uniform heat flux was applied from the outer surface. They concluded that the divergent type ring insert was more efficient than the convergent type ring. This approach is different since the fluid moves from periphery to the center where as in twisted tape fluid moves from center to the periphery. Numerical study of heat transfer characteristics in laminar flow have been carried out by Lin et al. (2017) using twisted tape having parallelogram

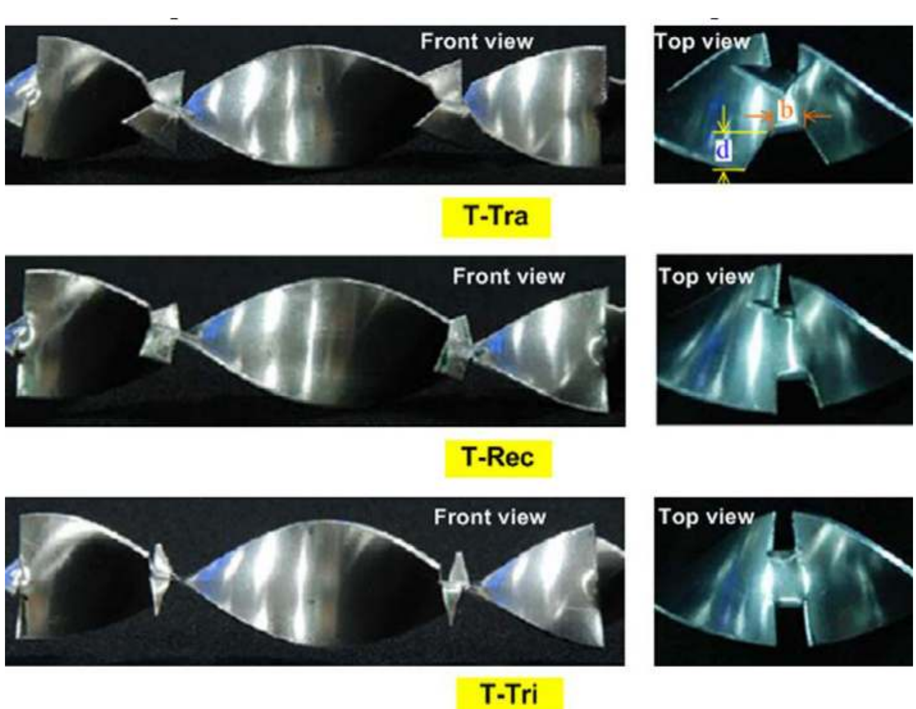

Fig. 7. Twisted tape with triangular, rectangular and trapezoidal wings (Wongcharee & Eiamsa-ard, 2011).

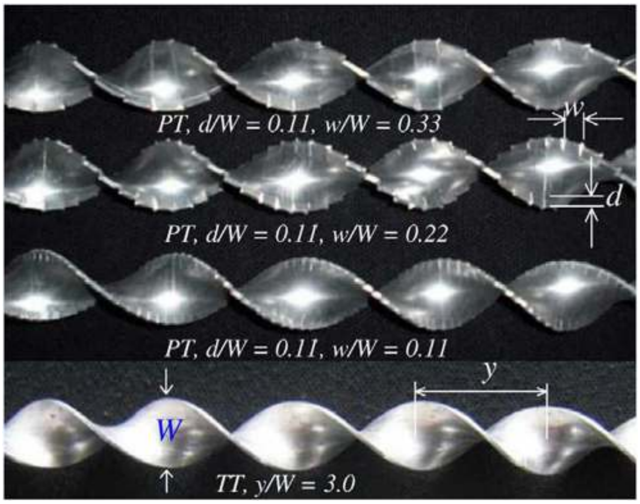

Fig. 8. Geometries of peripherally-cut twisted tapes and typical twisted tape (Smith Eiamsa-ard, 2010).

winglet vortex generator. This newly designed twisted tape has two ways to generate secondary flow which includes secondary flow generated by base tape and secondary flow generated by the parallelogram winglet. They observed improvement in TPF ranges from 1.25 to 1.85 for the studied range of Re.

2.1.6. Effect of multiple twisted tapes

Instead of making any modification in the twisted tape, some researchers worked on multiple twisted tapes. Eiamsa-ard et al. (2013b) investigated the effect of double twisted tape on heat transfer and friction factor. They used co-coupling and counter-coupling twisted tape (Fig. 9) for evaluation of heat transfer characteristics. Their results revealed that the counter-coupling twisted tape performs better than the co-coupling twisted tape. TPF was found to be more than one only in counter-coupling twisted tape with twist ratio 3. In the remaining cases, TPF was less than one which is not desirable. Eiamsa and Wongcharee (2013) conducted experiments to check the influence of double twisted tape in micro-fin tubes (Fig. 10). From the data obtained by experiments, it was concluded that TPF was better when the twisted tape acted in opposite directions to generate counter swirl and it was 2.03. Bhuiya et al. (2014) also worked on the double counter twisted tape inserts. Maximum TPF of 1.34 was achieved in the tested range of Re. Smith Eiamsa-ard et al. (2010c) worked on a dual twisted tape elements in tandem to study the thermal characteristics of heat exchangers. They used full length dual and regular spaced twisted tape to generate swirl. Heat transfer rate in spaced dual twisted tapes was found to be lower compared to the full length dual twisted tape. This occured due to the lower heat transfer rate in free space. TPF of full length twisted tape was 1.15–1.05 and decreased with increase in space ratio. Bhuiya et al. (2013a) also performed experiments for triple twisted tape inserts. Mild Steel triple twisted tapes were used with different twist ratios over the range of Re = 7200–50,200. TPF achieved was 1.42 for lower twist ratio. Thus, TPF of triple twisted tape is higher compared to that of a double twisted tape. However, the TPF of dual twisted tape fitted in the micro-fin tube was higher than the triple twisted tape insert. This shows that the micro-fin tube surface plays a significant role in improving the TPF. Twisted tapes in co-swirl and counter-swirl orientation (Fig. 11) were used by Vashistha et al. (2016) to enhance the heat transfer rate. Experiments were conducted by them for single twisted tape, double twisted tape with co-swirl and counter-swirl orientation, and four twisted tapes with co-swirl and counter-swirl orientation. They concluded that the counter-swirl performed better than the co-swirl and the four twisted tapes performed better than the double and single twisted tape. Maximum TPF of 1.26 was found with the four twisted tapes in the counter-swirl arrangement. Li et al. (2015) conducted a numerical study of heat transfer characteristics of a centrally hollowed narrow twisted tape. They introduced the concept of unilateral twisted tape. Their results revealed that the hollow twisted

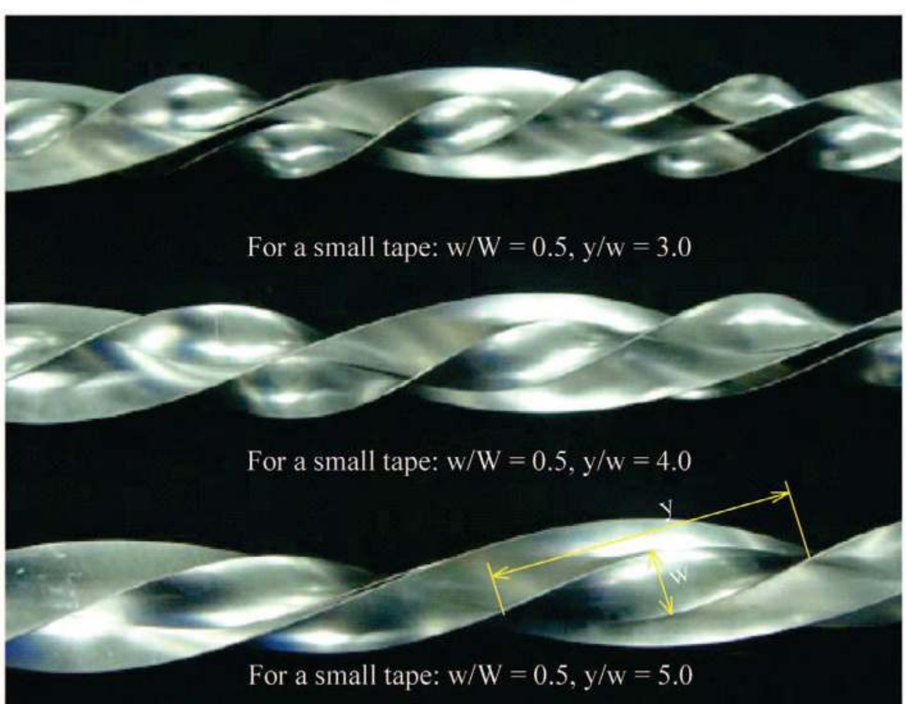

Fig. 9. Concentric double twisted tape (S. Eiamsa-ard et al., 2013a).

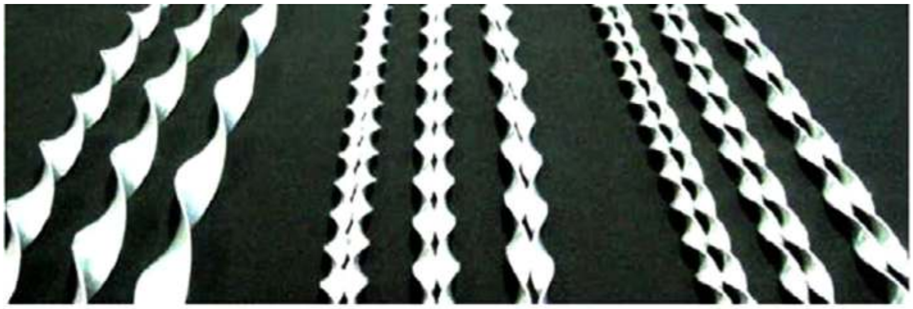

Fig. 10. Single and double twisted tape with counter-swirl and co-swirl arrangement (Eiamsa-Ard and Wongcharee, 2013).

tape performed better than the simple twisted tape. An experimental study of quadruple V-finned twisted tape (Fig. 12) was conducted by Promvonge (2015). He also conducted experiments for V-finned counter twisted tape and found that the counter twisted tape performed better than the quadruple twisted tape. Maximum TPF of 1.75 was found by using counter twisted tape.

2.1.7. Effect of wire coil insert

Gunes et al. (2010a,b, 2011) performed experiments with wire coiled inserts as a heat transfer enhancement technique. The cross section of coiled wire insert was triangular, placed eccentrically and 1 mm away from the tube wall. Coiled wire improved Nu, friction factor and TPF. Highest TPF of 1.36 was achieved at Re = 3858 (Gunes et al., 2010a). To check the effect of the distance of the coil from the tube wall, experiments were performed for 1 mm and 2 mm distance from tube wall with pitch ratios 1, 2 and 3. Their results revealed that TPF increased with decrease in pitch ratio and the distance of wire from the wall of tube (Gunes et al., 2010b). Effect of parameters such as ratio of distance between the coil wire and tube wall to tube diameter, pitch ratio, ratio of the side length of the equilateral triangle to tube diameter and Re on heat transfer and pressure drop in wire coiled inserts were studied. To optimize the design parameters in the tube with coiled wire inserts, a Taguchi approach was applied. Each goal was optimized separately and then combined together. The optimized results were found at the ratio of distance between the coil wire and tube wall to tube diameter = 0.0357, pitch ratio = 1, ratio of the side length of equilateral triangle to tube diameter = 0.0714 and Re = 19800 (Gunes et al., 2011).

San et al. (2015) conducted experiments to analyze the effect of wire diameter to tube diameter ratio and coil pitch to tube inner diameter ratio. They observed that Nu increased with increase of wire diameter to tube diameter ratio where as it increased with decrease in coil pitch to inner diameter ratio. Chang et al. (2015) determined the effects of ribbed and grooved wire coils on thermal performance experimentally. Unsteady separated flow generated due to the ribs flowed through the grooves resulting in enhanced thermal performance. TPF of 90° rib, 45° groove and 45° rib and 45° groove was more than one and the 45° groove had the best performance for different coil pitch to inner diameter ratio.

Martinez et al. (2014) determined the thermal performance of wire coil inserts for Newtonian and non-Newtonian fluids. Results revealed that up to Re = 500, effect of the wire coil insert was negligible. Normally, non- Newtonian fluid moves at low Re. Therefore, the wire coil insert is not a good option to enhance the heat transfer of non-Newtonian fluid. Selvam et al. (2012) used the wire coiled coil-matrix turbulator as an insert in the concentric tube heat exchanger. They analyzed the effect of bonding and without bonding of wire coiled coil-matrix turbulator on heat transfer and friction factor characteristics. Tests were performed for three pitches of 5 mm, 10 mm and 15 mm with bonding and without bonding to the tube wall. They concluded that the heat transfer rate enhanced with decrease in the pitch. Selvam et al. (2013) also conducted experiments for different arrangement of wire coiled coil-matrix turbulator. They used wire coiled coil-matrix with and without center core rod as an insert in the concentric tube heat exchanger. Better result was obtained for pitch to diameter ratio of 0.23 and center core rod with bonding and TPF for this combination was 1.42. Eiamsa-ard et al. (2012a) used the tandem wire coil element insert in a square duct to determine its heat transfer behavior. They also performed experiments for full length inserts and concluded that the TPF of full length wire coiled insert was higher than regularly spaced coil.

Garcia et al. (2012) compared the influence of corrugated tubes, dimpled tubes and wire coil insert on heat transfer enhancement. Saha (2010) conducted experiments to analyze the effect of transverse rib and wire coil inserts. He concluded that the use of transverse rib with wire coil was a better option for enhancement of thermal performance. Numerical investigation was carried out by Feng et al. (2017) to study the effect of wire coil inserts on laminar flow in rectangular microchannel heat sink using ANSYS CFX. From the results, they concluded that the wire coil insert performed best only in case of the low Re flow. Eiamsa et al. (2010b) performed experiments to understand the influence of combined non-uniform wire coil and twisted tape inserts on thermal performance characteristics. Wire coil was arranged in two different forms: (1) decreasing the coil pitch ratio and (2) increasing–decreasing the coil pitch ratio. TPF of 1.25 was found with increasing–decreasing coil with low twist ratio. Roy and Saha (2015) suggested a combination of helical screw tape with wire coil inserts to improve the thermal performance parameters of heat exchangers. Saha et al. (2014) affixed a uniform full length wire coil on the inner surface of the duct and placed eccentric center cleared twisted tape to enhance the thermal performance. Rout and Saha (2013) used the helical screw-tape inserts instead of twisted tape to enhance the heat transfer performance with wire coil inserts. Nanan et al. (2013b) determined heat transfer by using helically twisted tapes to generate co and counter swirl flow (Fig. 13). They conducted experiment for different parameters and found that co-swirl helically twisted tape having higher TPF than counter-swirl tape. Also they concluded that TPF of the combined enhancement technique was better compared to the individual enhancement techniques. Following correlation of TPF for co-swirl and counter-swirl has been proposed:

$$Forco-swirl\eta = 3.72Re^{-0.149}(p/D)^{0.299}$$

$$Forcounter-swirl\eta = 3.80Re^{-0.147}(p/D)^{0.303}$$

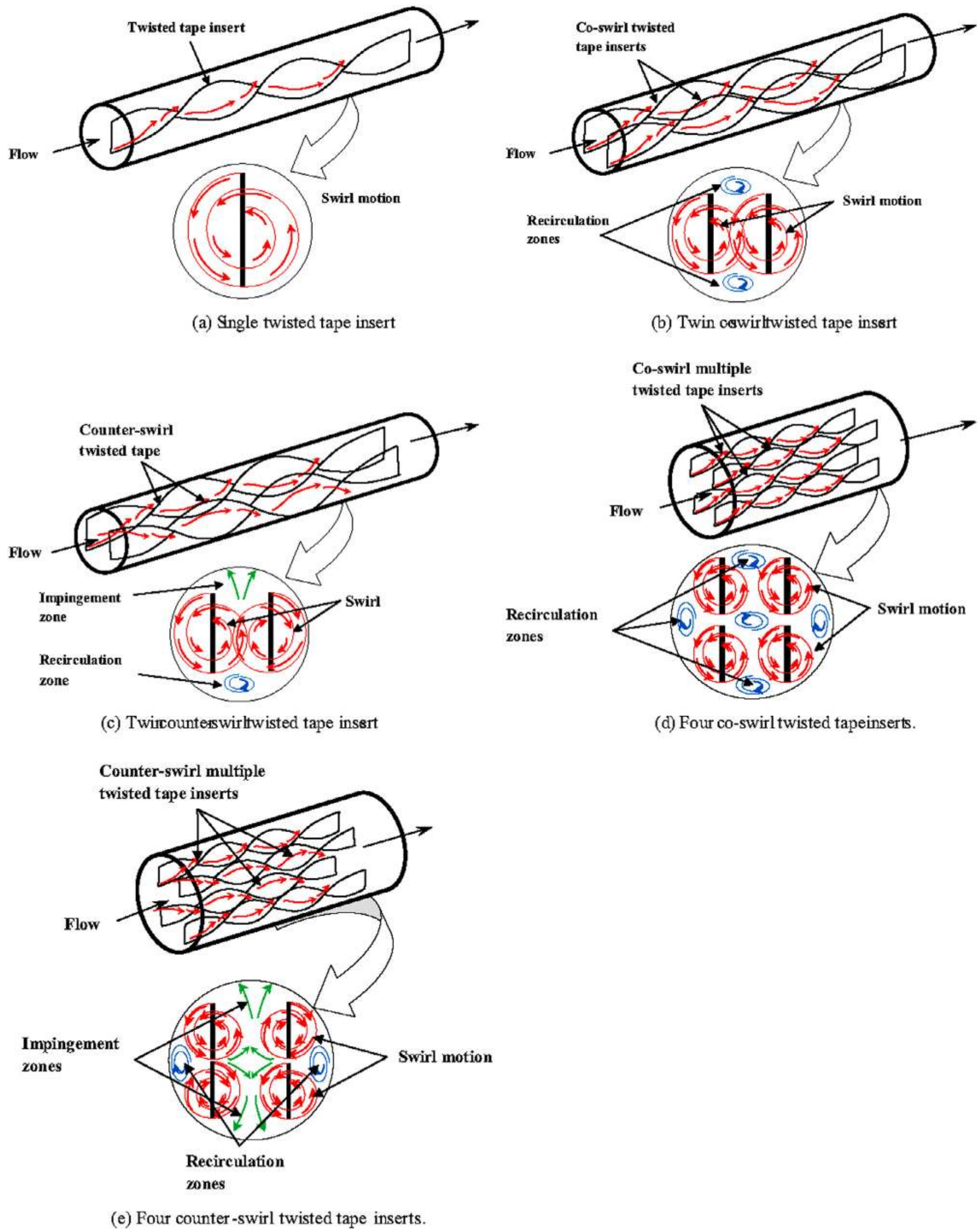

Fig. 11. Theorized flow pattern of different twisted tape arrangement (Vashistha et al., 2016).

2.1.8. Effect of perforation

Heat transfer rate increases considerably (Ahamed et al., 2011; Thianpong et al., 2012; Bhuiya et al., 2013b); Nanan et al., 2014) when perforation is used with twisted tape insert. Ahmed et al. (2011) investigated experimentally the effects of perforated twisted tape with different perforation ratio. Maximum performance was obtained at 4.5% perforation, the heat transfer rate was 1.8 times higher than that of a simple twisted tape. Thianpong et al. (2012) performed experiments on perforated twisted tape with different twist ratio, pitch ratio and diameter

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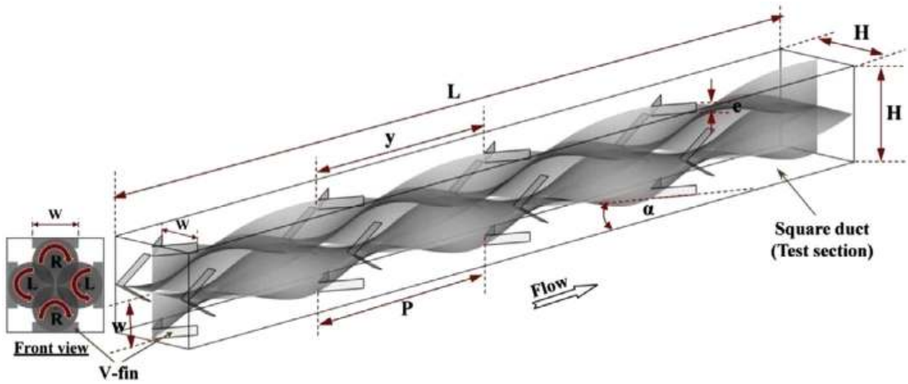

Fig. 12. Combined V-fins and quadruple counter-twisted tape (Promvonge, 2015).

ratio (Fig. 14). Their results revealed that at lower diameter ratio, TPF is high and TPF decreases with increase in the tape twist ratio and pitch ratio. But at high Re TPF of perforated twisted tape is less than unity which is not desirable. They suggested the following correlation of TPF: $\eta = 1.764Re^{-0.059}(y/w)^{-0.114}(s/w)^{-0.065}(d/w)^{-0.028}$

Bhuiya et al. (2013b) investigated the effect of porosity and hole diameter of the perforated twisted tape insert on heat transfer. Nanan et al. (2014) used the helical perforated twisted tape (Fig. 15) and concluded that TPF of perforated helical twisted tape is lower than that of simple helical twisted tape. TPF of perforated twisted tape was higher compared to the simple twisted tape for the same twist and pitch ratio because of lower pressure drop due to perforation. Heat transfer and flow resistance characteristics in tubular heat exchanger with staggered-winglet perforated tape were analyzed by Skullong et al. (2016a) (Fig. 16). Winglet perforated tape was used to generate longitudinal vortex flow for the purpose to disrupt the thermal boundary layer near the wall, which provided stronger fluid mixing. They used winglets with different winglet blockage ratio and fixed angle of 30°. TPF of 1.71 was achieved with less blockage and high pitch ratio. The small pipe insert was used by Wenbin et al. (2014) to enhance heat transfer characteristics in a circular pipe. They used pipe inserts of different configuration (Fig. 17) using tap water as a working fluid. Pipe inserts improved the heat transfer considerably with low flow resistance. TPF of 2.7 was obtained at Re = 4000 and it decreased with increase in Re. Tu et al. (2015) numerically studied the heat transfer with pipe insert (Fig. 18) for low Re for different dimensionless spacer length. The result revealed that Nu increased with decrease in spacer length. With the same pumping power, heat transfer was higher in pipe insert because its special structure made it possible for the fluid to flow from the central region to the wall region, which helped in regenerating the velocity profile and the temperature profile at the wall.

Khoshvaght-aliabadi (2016) investigated the combined and separate effect of nanofluid and vortex generator. Results revealed that vortex generator is more effective than nanofluid. It has been observed that the combination of nanofluid and vortex generator has TPF of 1.67. Water-propylene glycol based CuO nanofluid was used for heat transfer enhancement by Naik et al. (2013). They observed that the increment in pressure drop due to nanofluid was negligible compared to the base fluid, but convective heat transfer coefficient increased considerably.

2.2. Effect of surface characteristics on heat transfer

The baffles are used as an artificial roughness to create turbulence in the air channel so as to improve the heat transfer rate. Secondary flow is developed due to baffle which creates turbulence or swirl. Baffles with different shapes and geometrical configurations are used e.g. winglets, rectangular-shaped winglets, delta shaped wings, V-shaped wings and perforated baffles that can be attached and bent away from the plate to create turbulence in the flow field, which results in enhanced heat transfer in various engineering applications including heat exchangers, vortex combustors, and solar air channels among others. Various investigators have studied the heat transfer and pressure drop characteristics generated by baffle elements of various shapes, sizes, and orientations as an artificial roughness on a heated plate as discussed below.

2.2.1. Effect of fin

Zhang et al. (2012) performed experiments to investigate the effect of helical fin and vortex generator on the heat transfer and pressure drop characteristics on shell side of a double tube heat exchanger. They attached only the helical fin, helical fin with delta wing and rectangular wing along with winglet on the inner tube. They observed that the heat transfer due to helical fins with wings increases by 35–46% than helical fins at the cost of rise in pressure drop by 51–122%. The results showed that the heat transfer enhancement per vortex generator is highest for delta wing followed by a delta winglet pair, rectangular winglets and rectangular wing. TPF is more than one only in case of a delta wing and a delta winglet pair at low Re. For other attachments, it is less than one. Delta winglet vortex generator has been used by Zdanski et al. (2015) to determinethe effect on an in-line tube bank. They concluded that the delta winglet VG improve the heat transfer rate in an in-line tube bank. Geometric shape of vortex generators, angle of attack of vortex generators, placement of the vortex generators pair and wavy fin height are the important parameters which considerably improve the thermal performance of compact heat exchangers (Lotfi et al., 2014). Performance of fin and tube heat exchanger with wavy rectangular winglet type vortex generator was determined by Gholami et al. (2014). They numerically analyzed the effect of flat rectangular, wavy down rectangular and wavy up rectangular winglet. Wavy rectangular winglet considerably improved the heat transfer rate and wavy up rectangular winglet performed better than the wavy down rectangular winglet. Sangtarash and Shokuhmand (2015) performed experiments and analyzed numerically an in-line and staggered arrangement of dimples and perforated dimples to multi-louvers fins as a heat transfer augmentation technique. Single row of louvers was arranged on the heated wall as shown in (Fig. 19). Simulations showed that due to circulation generated by the dimples, heat transfer rate increased. It was observed that compared to in-line arrangement, staggered arrangement performed much better. Louvers with simple and staggered dimples arrangement had TPF of 1.23 and 1.29 respectively, whereas the TPF of simple and staggered perforated dimples was 1.28 and 1.40 respectively. Their

Fig. 13. Isometric, front and top view of helical twisted tape (Nanan et al., 2013b).

results revealed that the louvers with perforated dimples perform better than the simple dimples.

Two novel heat transfer surfaces were developed by Tiruselvam and Raghavan (2012) named as Turbo C and EXTEK. Turbo C could be an external low fin tube with three dimensional cuts and EXTEK is a spiral fluted tube as shown in (Fig. 20). In Turbo C, modified cuts increase the surface area and sharp tip helps in reduction of the condensate film thickness. In EXTEK tube, swirl flow is developed due to spiral fluted design that leads to high vapour shear for condensate film removal. The experiments indicate that the flow appears to develop faster in Turbo C, while the annulus flow in EXTEK does not develop since it breaks up continuously. Thus, the friction factor is high in EXTEK compared to Turbo C. Ribbed

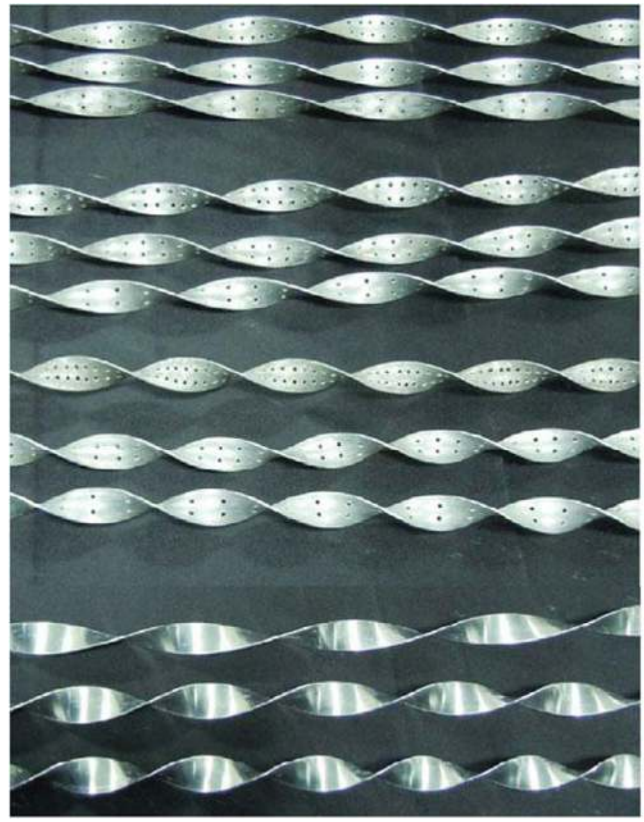

Fig. 14. Perforated twisted tapes with different pitch and twist ratio (Thianpong et al., 2012).

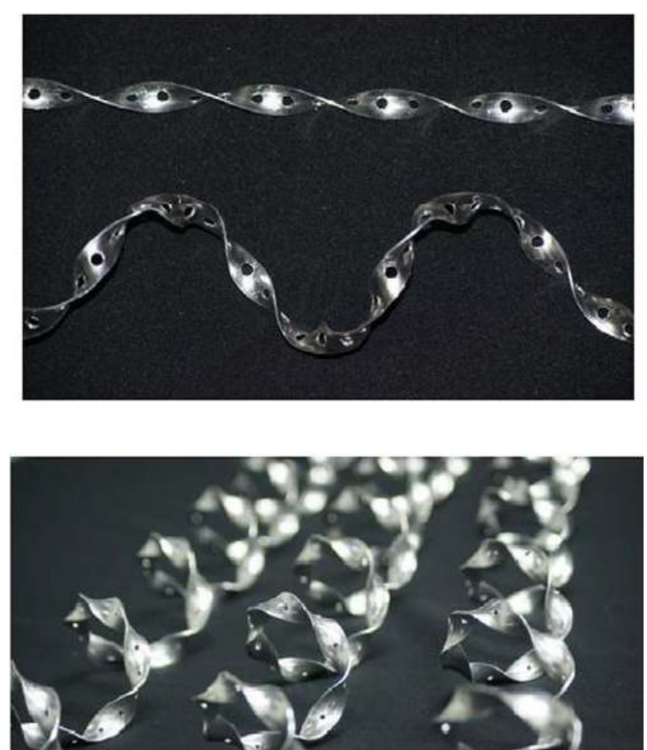

Fig. 15. Perforated helical twisted tapes(Nanan et al., 2014).

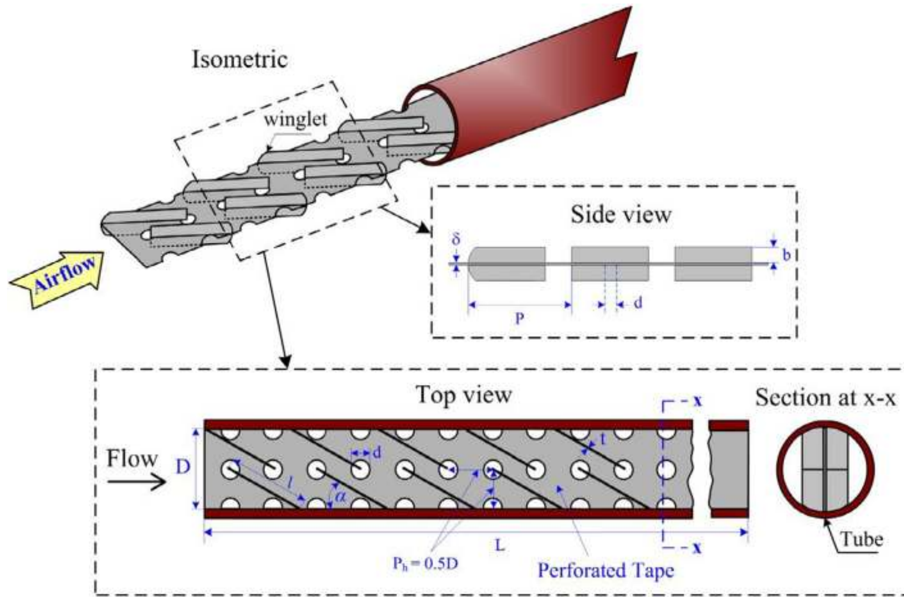

Fig. 16. Staggered winglet perforated tapes (Skullong et al., 2016a).

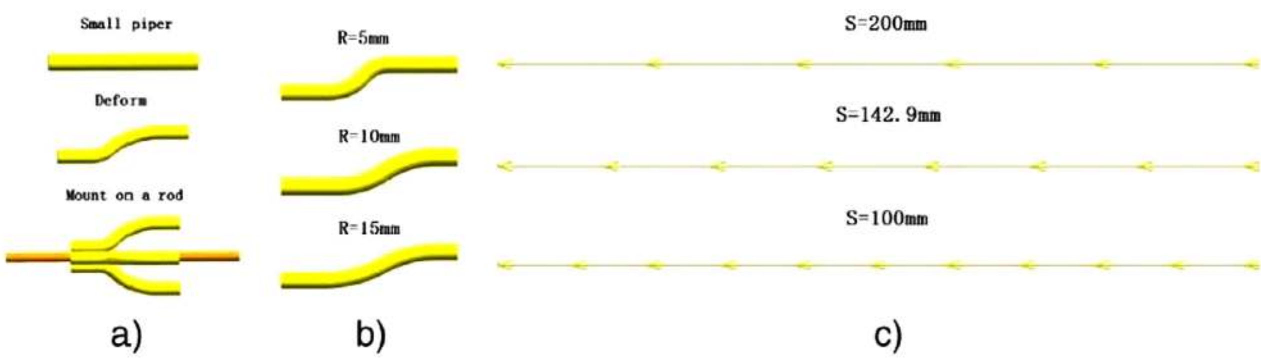

Fig. 17. Fabrication, shape and pipe inserts with various spacer length (Tu et al., 2014).

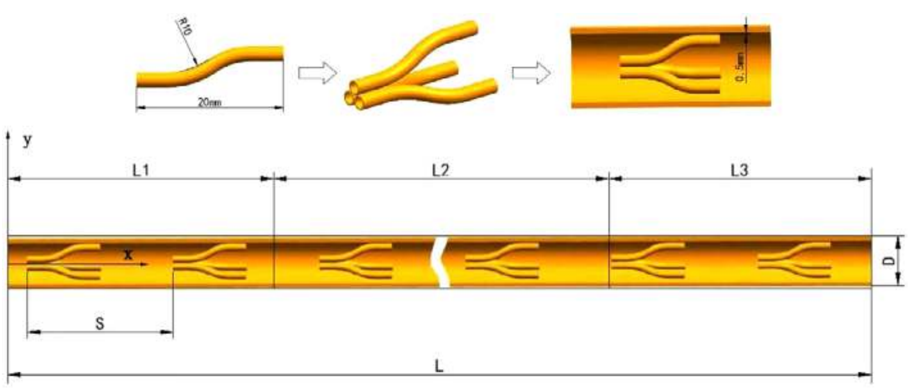

Fig. 18. Schematic of pipe inert (Tu et al., 2015).

pipe increases heat transfer compared to smooth pipe. At low Re, performance of ribbed pipe is good but its effect is reduced with an increase in Re (Xu et al., 2016). The combined effect of integral spiral rib and twisted tape with oblique teeth was investigated by Pal and Saha (2015). Experiments were conducted for laminar viscous oil flowing through a circular duct. The combination of several heat transfer techniques performed significantly better than an individual enhancement technique acting alone. Internally scattered grooves were employed by Zheng et al. (2016b) for the purpose of improving the thermal performance. Due to this modification, heat transfer rate increased considerably without increase in pressure drop. They concluded that the entropy generation was minimum and thermal performance was maximum at 30°.

2.2.2. Effect of rib and groove

Due to desire to replace conventional fossil fuel, the use of solar energy has increased dramatically in recent years. Researchers focusing on increasing the effectiveness of the solar air heater.

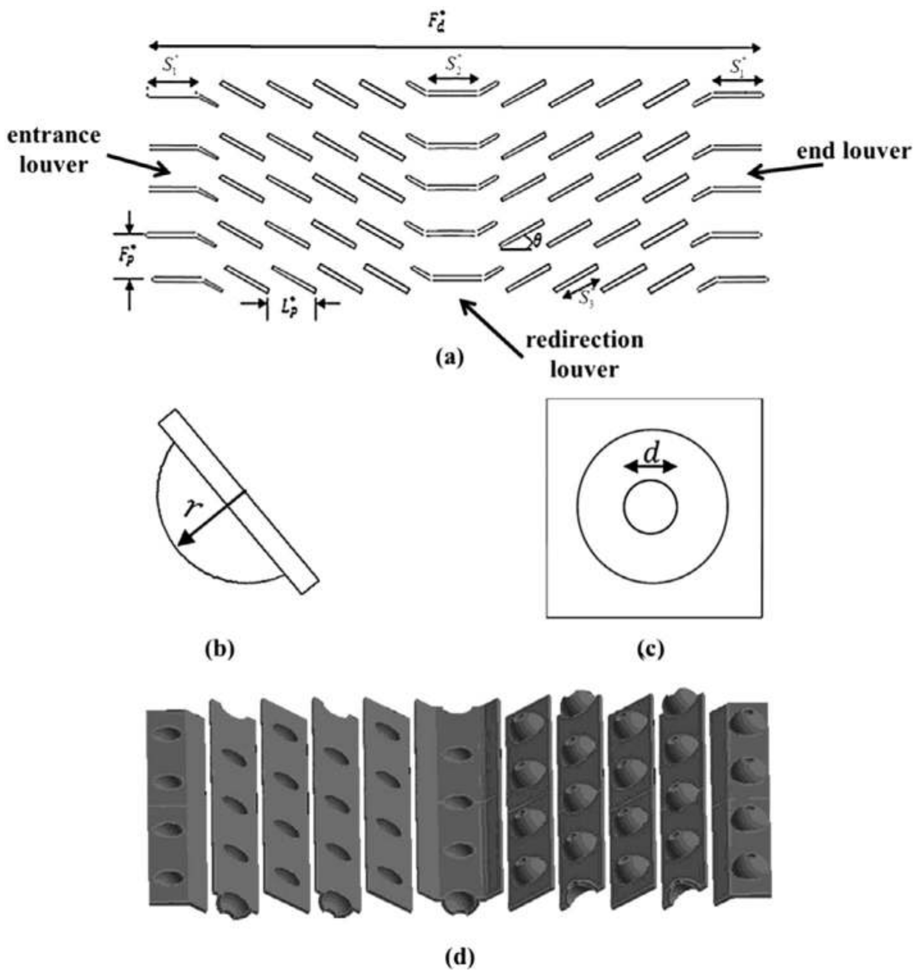

Fig. 19. Simple multi-louvered fin array, dimple louver, perforated dimpled louver and perforated dimpled louvers with staggered arrangement (Sangtarash & Shokuhmand, 2015).

Fig. 20. Turbo C and EXTEK tubes (Tiruselvam & Raghavan, 2012).

Effectiveness of solar air heater is reduced due to the development of viscous sub-layer on the absorber plate. Therefore, the turbulence can be introduced to counter the effect of viscous sub layer. To generate turbulence, artificial roughness can be constructed on one (absorber) or two sides of the plate.

For enhancing the heat transfer in a rectangular duct, experiments were performed by Promvonge and Thianpong (2008). They used ribs having cross section area of isosceles triangular wedge and rectangular shape on both sides as shown in (Fig. 21). Heat was supplied from the upper face of the duct. Maximum TPF for triangular rib was 1.1 followed by the wedge rib upstream, wedge rib downstream and rectangular rib. Eiamsa-ard and Promvonge (2008) numerically studied the effect of periodic grooves on heat transfer in rectangular duct. They determined the TPF for different width to height ratio of rectangular duct. Maximum TPF 1.34 was found for a B/H ratio of 0.75 for the range of Re studied. At a particular Re, TPF of the bottom groove was larger compared to that obtained in an analysis by Promvonge and Thianpong (2008) for both sides. Lanjewar et al. (2011), Yadav and Bhagoria (2014) and Gawande et al. (2015) performed an analysis of the thermal

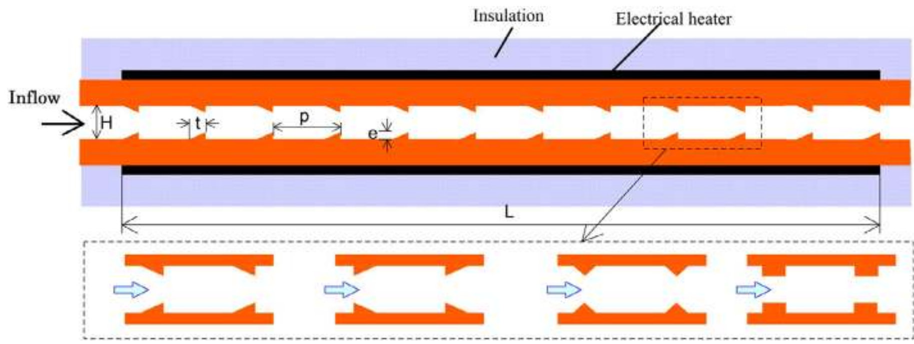

Fig. 21. In-line rib arrangements with wedge pointing upward, wedge pointing downward, triangular and rectangular (Promvonge & Thianpong, 2008).

performance of a solar air heater by using W rib, equilateral triangular sectioned rib and right angle triangular rib as artificial roughness on the absorber plate side. Lanjewar et al. (2011) used the W-up, W-down and V type ribs and concluded that the maximum TPF was obtained in W-down ribs followed by W-up and V-ribs at all values of Re. CFD base numerical analysis was performed by Yadav and Bhagoria (2014) for equilateral triangular ribs and they found that TPF varied from 1.36 to 2.11 for the range of parameters analyzed. By analysis, Gawande et al. (2015) concluded that at the maximum relative roughness height and 7.14 relative roughness pitch, TPF obtained was more than 2. V-down rib with gap was used by Singh et al. (2012) in a rectangular duct of solar air heater. Five plates were tested with flow angle of attack from 30° to 75°. They concluded that 60° was the optimum angle of attack for ribs with gap and it also performed better than the continuous rib. Cylindrical grooves were used by Liu et al. (2015a) to enhance the heat transfer rate in a rectangular channel. Five cylindrical groove shapes were analyzed numerically. The new geometries were conventional cylindrical geometries with rounded transition to flat surface. From the results, it was found that the velocity magnitude near the wall surface was higher than that of a conventional ribbed surface which led to high heat transfer rate. Sethi et al. (2012) generated dimples on the absorber side of the solar air heater to increase the heat transfer rate. They found maximum TPF of 1.4 for relative roughness height of 0.036, relative roughness pitch of 10 and arc angle of 60°. Effect of spherical dimples and teardrop dimples on heat transfer characteristics was experimentally and numerically investigated by Rao et al. (2015). Teardrop dimples performed better than the spherical dimples and TPF with teardrop dimples was 1.5 for wide range of Re. Wang et al. (2014) conducted experiments on a semi-dimple vortex generator attached to a flat surface. A heat transfer enhancement of 17% was achieved with the cost of 30% rise in pressure drop.

Combination of different duct shapes and ribs affects the heat transfer considerably compared to ribs only. Experimental investigations were conducted by Salameh et al. (2016) about the effect of various shaped ribs on heat transfer in U- channel solar air heater. Four rectangular ribs with different configurations [plain, perforated, U-grooved and dimple] were considered for the analysis. TPF decreased with increasing Re. The perforated rib case and the grooved rib case gave highest TPF of 2.6. This can be explained for the perforated rib case since it has the smallest pressure drop among all the tested rib cases. Grooved rib case and the dimpled rib case yielded the highest TPF 2 and 1.95 respectively at high Re. Heat transfer performance of rib-roughed rectangular channel decreased with increase in aspect ratio. Thermal boundary layer developed as flow progressed in case of ordinary rib. A longitudinal rib was installed at the center to intersect the ordinary rib. This technique improved the thermal performance of the channel (Chung et al., 2015). Kumar et al. (2012) worked on the multi V-shaped rib with gap as an artificial roughness in a rectangular duct. They analyzed the effect of relative gap distance and relative gap width on the heat transfer characteristics. Their results revealed that the best TPF was obtained for the relative gap distance of 0.69 and the relative gap width of 1 for the studied range of Re. Park et al. (1992) investigated the combined effect of aspect ratio and rib angle of attack on heat transfer characteristics in rectangle channels with opposite ribbed walls. Authors suggested that for lower aspect ratio channels ribs with 45° /60° angle performed better and for high aspect ratio channels ribs with 30° /45° angle performed better. Alam et al. (2014) determined the effect of geometrical parameters of V shaped perforated block (Fig. 22) on heat transfer in a rectangular duct. They conducted experiments for different relative blockage height, relative pitch ratio and open area ratio with a fixed angle of attack. TPF of 2–3 was obtained for different combinations of parameters.

2.2.3. Effect of roughness

Roughness improves the heat transfer characteristics in a solar air heater duct. To determine the effect of roughness on small diameter pipe, experiments were performed by Kandlikar et al. (2003). They generated roughness by acid treatment. Their results revealed that roughness increases Nu and pressure drop simultaneously and transition to turbulence starts below Re = 2300. Li et al. (2011) examined the effect of surface roughness heights on heat transfer characteristics at various Re. They concluded that the Nu ratio did not always increase with increase in roughness height and Re. If roughness height was less than the thickness of viscous sublayer, it was difficult to enhance the heat transfer and if roughness height was more than five times the viscous sublayer thickness then the friction factor increased sharply compared to increase in the heat transfer rate. Maximum heat transfer occured at constant pumping power when roughness height was about three times the viscous sub layer thickness. For large Pr, roughness height is a suitable technique to enhance turbulence and heat transfer. Influence of structured roughness on heat transfer characteristics was investigated by Lin and Kandlikar (2012). They ana-

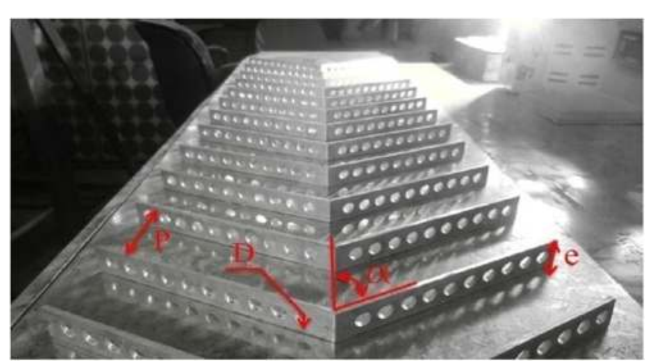

Fig. 22. V shaped perforated block (Alam et al., 2014).

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lyzed the effect of water passing through a mini-channel. Eight roughness elements were employed having lateral grooves of sinusoidal profile. It was found that all surface roughness heights improved the heat transfer rate, but roughness element pitch had no significant effect. Aligned and offset roughness patterns were used by Koopaee and Zare (2015). They studied numerically the impact of roughness patterns in a rectangular cross-section micro-channel and found that the offset pattern provided lower pressure drop compared to aligned pattern. Effects of macro and micro roughness were analyzed by Nine et al. (2014). They fabricated ribs of different heights as macro roughness and copper porous layer height as the roughness height. Their results revealed that the porous layer provided TPF of 1.42. Also porous layer less than 5 μm was found to increase the heat transfer surface area and the dynamic behavior of the working fluid. (Y. Liu et al., 2015).

2.2.4. Effect of corrugation and vortex generator

A numerical study was conducted by Yang and Chen (2008) using V corrugated plates of angle 20°, 40° and 60° to determine the effect of angle on heat transfer. Conclusion obtained from the results was that increasing the angle of the plate makes the heat transfer performance better. Sakr (2015) numerically analyze the V-corrugated channel with different phase shift as shown in (Fig. 23).The V corrugated channel had significant impact on heat transfer enhancement with increase in pressure drop due to breaking and destabilizing of the thermal boundary layer at corrugated surface. Phase shift performed better in narrow channels. 180° phase shift performed better than 0° and 90°. Ramgadia and Saha (2012) presented numerical simulations of heat transfer in sinusoidal wavy channels. They simulated geometries with minimum to maximum height ratio from 0.1 to 0.5 and found maximum TPF obtained at a ratio of 0.2 for studied range of Re. Punched triangular and rectangular edges were used by Caliskan (2014) as a vortex generator (Fig. 24). He punched longitudinally at angles of attack of 15°, 45° and 75°. TPF of the triangular vortex generator was found to be 2.92 with angle of attack of 45° and for the rectangular vortex generator TPF was 2.85. Modified rectangular longitudinal vortex generator obtained by cutting off the four corners of a rectangular wing was used by Min et al. (2010). Fluid flow and heat transfer characteristics of original rectangular and modified rectangular vortex generators were investigated experimentally. Results revealed that the modified vortex generator had better flow and heat transfer characteristics than the original rectangular vortex generator. Combined wavy grooved and perforated delta wing vortex generators were used by Skullong et al. (2016b) in solar air heater duct to enhance thermal performance. They used forward and backward type vortex generator at angles of 30°, 45° and 60°. They found that the forward type vortex generator performed well and the vortex generator at 45° angle gave the highest TPF in both cases (1.80–2.10). Han et al. (2015) investigated the performance of outward convex asymmetrical corrugated tubes and found that the performance improved by large corrugation trough radii (rl) located at upstream side. The effect of various rl on heat transfer characteristics was investigated for the purpose of determination of the optimum performance. The results showed that rl/D = 0.6 gave the optimum performance. Thermal characteristics of periodic cross-corrugated channel were numerically investigated by Liu and Niu (2015). They investigated the effect of the apex angle and aspect ratio on heat transfer, pressure drop and Thermal Performance Factor. Numerical analysis showed that the apex angle strongly influenced the heat transfer and pressure drop. Apex angle of 90° and 120° apex gave the highest heat transfer. Mean Nu for 30° apex angle is 0.5 time the minimum value of Nu at 90° and 120°. Thus 90° and 120° apex angles are recommended for the purpose of heat transfer enhancement in cross-corrugated triangular channel.

Turbine blades operate at high temperature. To improve the heat transfer rate from the turbine blade V-rib and broken V-rib were used by Kumar and Amano (2014) in cooling passage of gas turbine blade. They used two pass square channel with four combinations of 60° V-rib and 60° broken V-rib. They concluded that the maximum overall performance of broken V-rib was 50% higher than that of V-rib. Zheng et al. (2016a) numerically investigated the effects of the rib arrangement on heat transfer characteristics in an internally ribbed heat exchanger tube. They used parallel and the V-type arrangement of ribs. Their results showed that both rib arrangements considerably affected the heat transfer rate, turbulence intensity and flow pattern (Fig. 25 & Fig. 26). V-type arrangement performed better than the parallel type arrangement. TPF of V type arrangement and parallel type arrangement is 1.55 and 1.15 at Re = 10000 respectively. Dizaji et al. (2015) studied the effects of corrugation on heat transfer characteristics in a double pipe heat exchanger. They tried different combinations of corrugation in the inner tube as well as in the outer tube. Akhavan-behabadi and Esmailpour (2014) conducted experiments on corrugated pipe at different inclination angle to determine the effect of the inclination on the evaporation rate of R-134a. They found that the performance increased with increase in inclination angle and became maximum at 90°.

2.3. Effect of duct shape

Bhadouriya et al. (2015a) used the twisted square duct and the twisted elliptical pipe as a heat transfer enhancement technique. They investigated the heat transfer characteristics for the broad range of Re and Pr. Uniform wall temperature was considered as a boundary condition. Due to twist, swirl and secondary flow are produced at the corner which lead to enhancement in heat transfer coefficient. The results showed that the heat transfer rate and pressure drop increased considerably in laminar as well as turbulent flow for Re up to 9300. Bhadouriya et al. (2015b) studied the heat transfer properties in an annulus of inner twisted square duct and outer circular pipe. They observed that the friction factor and Nu increased considerably for smaller annulus parameters. Aliabadi and Lahtari (2016) numerically analyzed heat transfer characteristics in twisted mini-channels with different tube cross sections (Fig. 27). They investigated the effect of pitch twist to channel length ratio for different cross section of the twisted channel. They concluded that all twisted channels performed better than the smooth circular pipe. Semi circular twisted mini channel had the

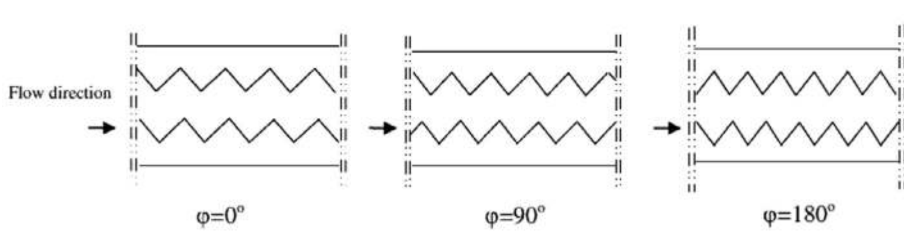

Fig. 23. Typical configuration of the corrugated channel representation (Sakr, 2015).

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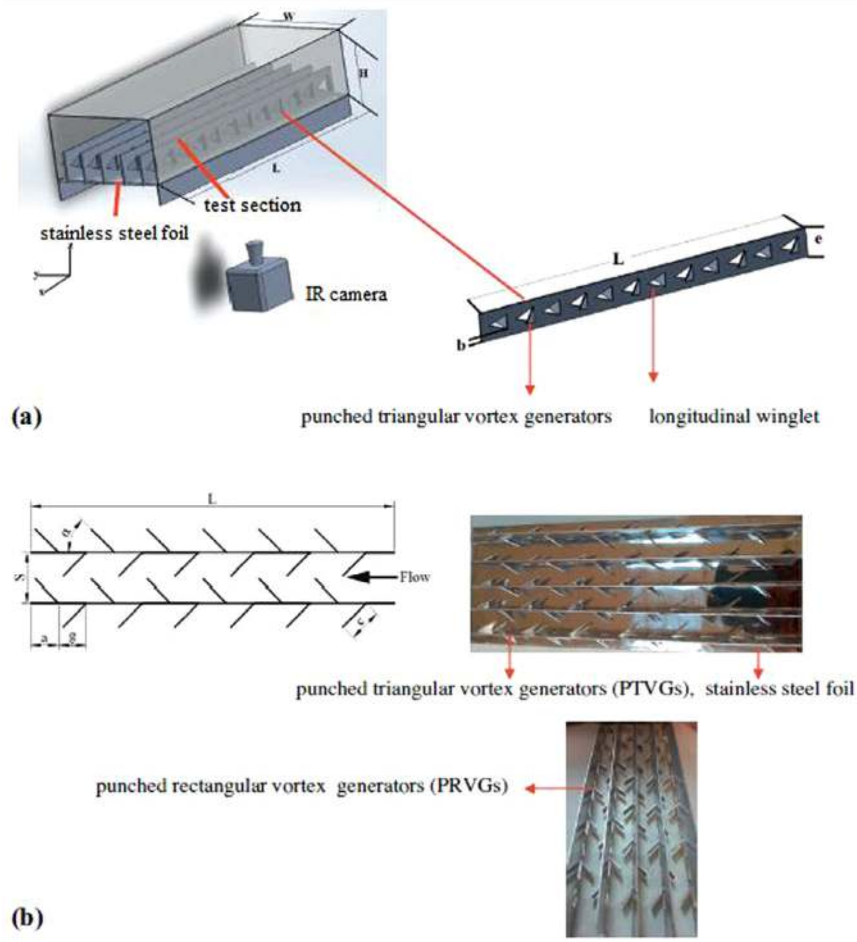


Fig. 24. Schematic view of triangular and rectangular vortex generator (Caliskan, 2014).

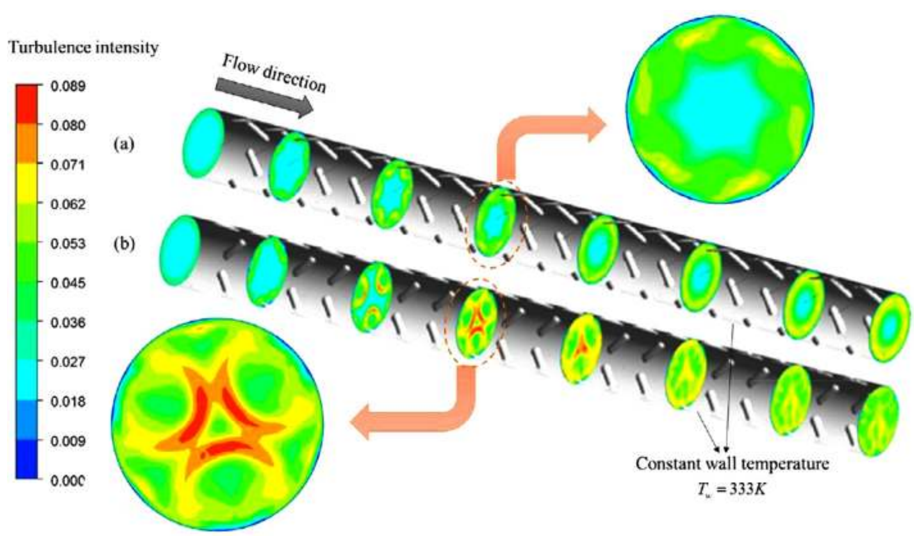


Fig. 25. Turbulence intensity contours in transverse plane (Zheng et al., 2016a).

highest TPF in air flow and the square twisted mini channel performed better for water flow.

Ribbed triangular duct was used by Ahmed et al. (2015) to investigate the combined effect of vortex generator and nanofluid on heat transfer and fluid flow characteristics. Triangular section having low pressure drop as well as heat transfer rate was compared to other duct configurations. Triangular section was used to reduce the pressure drop and nanofluid was used to improve the heat transfer rate. Combination of the two led to improved TPF. Experiments were conducted by Petkov et al. (2014) to understand the effect of non-circular duct shapes on heat transfer characteristics. They used isosceles triangular, rectangular, trapezoidal, hexagonal and elliptical shapes. Constant surface temperature and hydraulic diameter were considered as common constraints. They

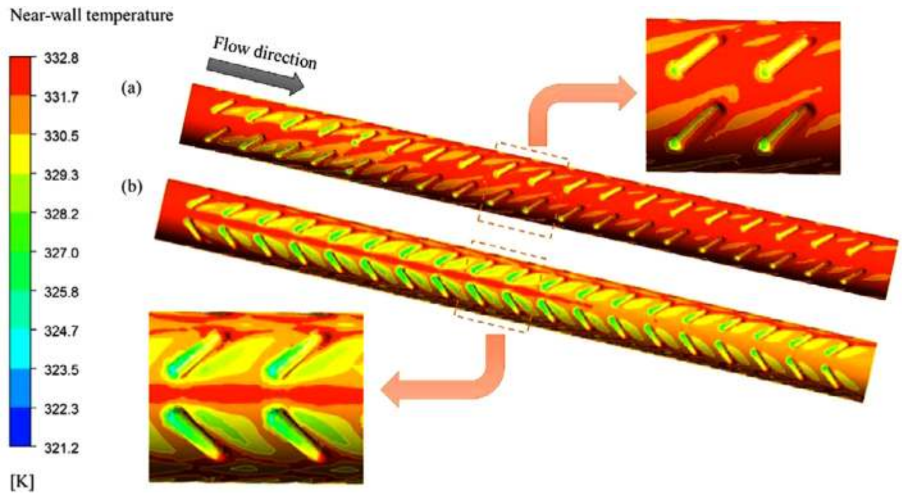


Fig. 26. Near wall fluid temperature contours in transverse plane (Zheng et al., 2016a).

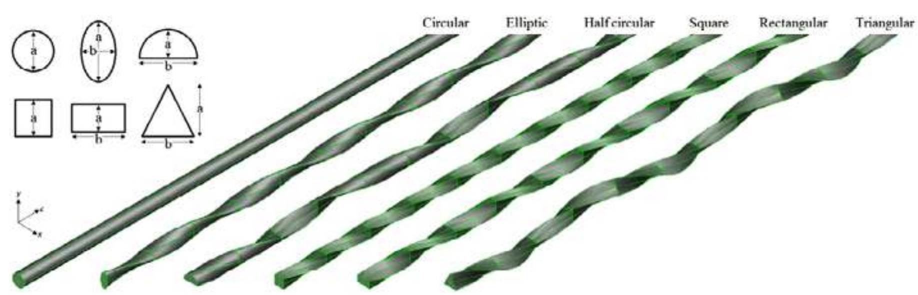


Fig. 27. Twisted mini-channel with different cross section shapes (Khoshvaght-Aliabadi & Arani-Lahtari,2016).

concluded that the hexagonal duct performed best among all shapes selected for analysis.

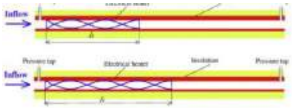
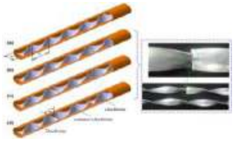
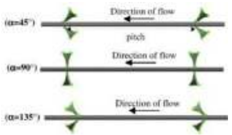
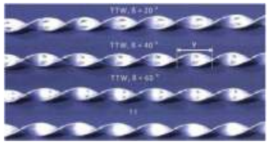
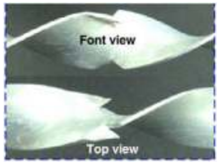
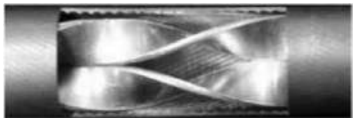
2.4. Effect of tube shape

Aliabadi et al. (2015) conducted numerical analysis of TPF of curved tubes namely the helical, spiral and serpentine. They used water, engine-oil and ethylene–glycol as a working fluid to check the effect of geometric parameters on TPF. The results showed that for the same geometrical and operating conditions better performance was obtained for helical tube followed by the spiral and serpentine tube. Tang et al. (2015) experimentally and numerically investigated the heat transfer characteristic in a twisted oval tube and twisted tri-lobed tube. Heat transfer rate and friction factor increased with reduction in twisted pitch length. Twisted tube with right and left rotation performed better than the single side rotation. Increase in pitch ratio in oval tube and the number of lobes in lobed tube decreased the TPF. TPF was more than unity for the configurations investigated.

2.5. Effect of nanofluid

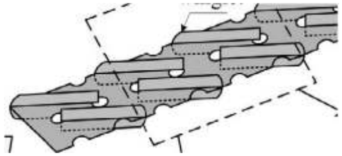
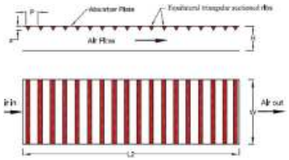
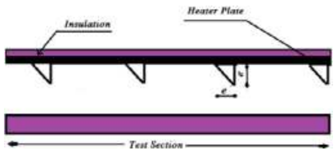
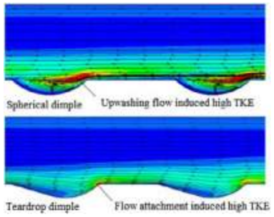
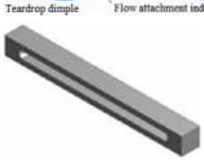
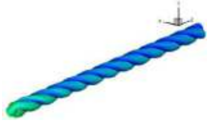
Sarafraz and Hormozi (2015) used the biological nanofluid to intensify the forced convection in a double-pipe heat exchanger. Ethylene-glycol/water (50:50 by volume) was used as a base fluid and volume fraction of nanomaterial was 0.1%, 0.5% and 1%. Results showed that at volume fraction of 1%, heat transfer coefficient increased by 67%. Kumar et al. (2017) used Fe_3O_4/Water as nanofluid with different volume fraction of Fe_3O_4. They showed that the heat transfer rate enhanced with higher volume fraction but with the penalty of pressure drop. Prasad et al. (2014) used Al_2O_3 nanofluid along with helical tape inserts. They concluded that the helical tape inserts with nanofluid gave better performance compared to inserts only or nanofluids only. Ahmed et al. (2014) numerically investigate the effect of corrugation profile and CuO-Water nanofluid on the TPF. Results showed that the TPF increased with increased nanoparticles volume fraction and Re. Arani and Amani (2013) performed experiments to investigate the effects of TiO_2 nanoparticle size on heat transfer characteristics. Their results showed that the nanoparticles with 20 mm diameter had the highest TPF for studied range of Re and volume fractions of nanoparticles. Eiamsa-ard et al. (2015) used the TiO_2/Water nanofluid and overlapped dual twisted tape to improve the heat transfer characteristics. Higher volume fraction and lower overlapped twist ratio enhanced the TPF up to 1.13. Copper-Water nanofluid was used by Khoshvaght-Aliabadi et al. (2014) to analyze TPF of plate-fin channels. They used five weight fractions of nanoparticles (0%, 0.1%, 0.2%, 0.3% & 0.4%). Their results showed that the TPF improved with decrease in weight fraction and increase in flow rate. Kumar et al. (2017) numerically analyzed the effects of Al_2O_3-H_2O nanofluid on TPF when fluid was flowing through a protrusion obstacle in a square mini-channel. From results, it has been observed that TPF of more than 2 was obtained by combined use of the obstacle and the Al_2O_3-H_2O nanofluid. Sarafraz et al. (2016) used COOH-CNT/Water nanofluids in a double tube heat exchanger. Influence of different operating parameters was studied for the Re ranging from 900 to 10,500. It was observed that the carbon nanotube nanofluids could enhance the TPF up to 1.44 at maximum mass concentration of 0.3. Hormozi et al. (2016) investigated the effects of surfactants on the thermal performance of the hybrid nanofluid. The use of Alumina-Silver nanofluid and Sodium Delecyl Sulfate (SDS) anionic surfactant gave 16% higher Thermal Performance Factor compared to that for the pure distilled water. Heat transfer rate increased with nanofluid as nanoparticles volume concentration increased due to increase in contact surface area and thermal conductivity of the fluid.

3. Summary of important techniques and their TPF

Author	Modification	Parameter	Re	TPF	Nu/Nu_0	f/f_0	Fluid type	Image
Eiamsa-ard et al. (2009)	Short length twisted tape	Twist ratio -4,Tape length ratio – 0.39–1	5000	0.98	1.30	2.31	Air	
	Short length twisted tape		10000	0.95	1.24	2.23		
	Short length twisted tape		20000	0.91	1.16	2.1		
Eiamsa and Promvonge (2010)	Alternate clockwise and counterclockwise	Twist ratio – 3–5,Twist angle - 30°-90°	5000	1.35	2.52	6.62	Water	
	Alternate clockwise and counterclockwise		10000	1.26	2.18	5.26		
	Alternate clockwise and counterclockwise		20000	1.18	1.8	3.58		
Rahimi et al. (2009)	Jagged twisted tape	Width – 15 mm, Pitch length- 5 cm, Twist ratio – 2.94, Thickness-1mm	5000	1.17	2.22	6.86	Water	
	Jagged twisted tape		10000	1.09	1.93	5.61		
Shabanian et al. (2011)	Butterfly twisted tape	Thickness- 0.5 mm, Holding rod diameter- 1.9 mm, Angle-45°-135°, Pitch length-6cm	5000	1.60	4.74	26.6	Water	
	Butterfly twisted tape		10000	1.53	3.73	14.8		
Eiamsa-ard et al. (2013a)	Twin Delta winged tape	Twist ratio-3,Wing tip angle-20°-60°,Wing declination angle-15°	5000	1.24	2.54	8.78	Water	
	Twin Delta winged tape		10000	1.12	2.10	6.64		
Eiamsa-ard et al. (2010a)	Delta winglet twisted tape	Twist rati-3–5, Depth of wing cut ratio-0.11–0.32	5000	1.22	2.24	6.3	Water	
	Delta winglet twisted tape		10000	1.18	2.08	5.65		
	Delta winglet twisted tape		20000	1.15	1.94	4.83		
Promvonge et al. (2014)	Twisted tape with winglet vortex generator	Twist ratio-4&5, Attack angle of winglet-30°,R_B-0.1–0.2,R_P-2–5	5000	1.56	3.16	8.47	Air	
	Twisted tape with winglet vortex generator		10000	1.48	2.95	9.33		
	Twisted tape with winglet vortex generator		20000	1.38	2.83	9.85		
Wongcharee and Eiamsa-ard (2011)	Twisted tapes with alternate axes and triangular wing	Twist ratio-4,Wing cord ratio-0.1–0.3	5000	1.42	2.87	8.4	Water	
	Twisted tapes with alternate axes and triangular wing		10000	1.25	2.34	6.7		
	Twisted tapes with alternate axes and triangular wing		20000	1.13	1.96	5.6		
Eiamsa and Wongcharee (2013)	Counter double twisted tape	Twist ratio-3–5, Width-4mm	5000	2.02	4.7	12.7	Water	
	Counter double twisted tape		10000	1.76	4.05	12.5		
	Counter double twisted tape		20000	1.50	3.45	12.5		

(*continued on next page*)

Summary of important techniques and their TPF (*continued*)

Author	Modification	Parameter	Re	TPF	Nu/Nu_0	f/f_0	Fluid type	Image
Bhuiya et al. (2013b)	Triple twisted tape	Twist ratio-1.92–6.79	5000	1.44	2.85	7.5	Air	
	Triple twisted tape		10000	1.40	2.51	5.83		
	Triple twisted tape		20000	1.33	2.2	4.6		
Skullong et al. (2016a)	Staggered winglet perforated tape	Winglet inclination angle-30°,Winglet blockage ratio-0.1–0.3, Winglet pitch ratio-0.5–1.5	5000	1.7	4.2	15	Air	
	Staggered winglet perforated tape		10000	1.58	4.1	18		
	Staggered winglet perforated tape		20000	1.48	4.0	20.5		
Yadav and Bhagoria (2014)	Triangular sectioned rib as roughness on absorber plate	Relative roughness pitch-7.14–35.71, Relative roughness height-0.021–0.042	5000	2.05	3.05	3.36	Air	
	Triangular sectioned rib as roughness on absorber plate		10000	2.07	3.2	3.69		
	Triangular sectioned rib as roughness on absorber plate		20000	1.98	3.08	3.83		
Gawande et al. (2015)	Right angle triangular rib as roughness on absorber surface	Relative roughness pitch-7.14–35.71, Relative roughness height-0.021–0.042	5000	1.99	3.07	3.68	Air	
	Right angle triangular rib as roughness on absorber surface		10000	2.01	2.96	3.23		
	Right angle triangular rib as roughness on absorber surface		20000	1.98	2.93	3.38		
Rao et al. (2015)	Surfaces with spherical and tear drop dimples	Depth to diameter ratio-0.2	5000	1.48	1.65	1.4	Air	
	Surfaces with spherical and tear drop dimples		10000	1.51	1.8	1.68		
	Surfaces with spherical and tear drop dimples		20000	1.53	1.9	1.92		
Salameh et al. (2016)	Perforated rib	Pitch ratio-10,Rib height to hydraulic diameter ratio-0.1	5000	2.8	4.8	5	Air	
	Perforated rib		10000	2.45	4.4	5.9		
	Perforated rib		20000	1.9	3.6	6.8		
Caliskan (2014)	Punched triangular vortex generator	Attack angle-15°-75°, Winglet height to channel height ratio-0.6	5000	2.7	1.95	0.38	Air	
	Punched triangular vortex generator		10000	2.48	2.1	0.6		
	Punched triangular vortex generator		20000	2.2	2.21	1		
Tang et al. (2015)	Twisted tri-lobed inner tube	Twist pitch length-200	10000	1.11	1.19	1.22	Water	
	Twisted tri-lobed inner tube		20000	1.04	1.09	1.15		

4. Conclusions

From the present review, it can be concluded that the heat transfer enhancement occurs in all cases due to reduction in the flow cross section area, an increase in turbulence intensity and an increase in tangential flow established by various types of inserts. Geometrical parameters of inserts like width, length, twist ratio, etc. affect the heat transfer enhancement considerably. Twist direction is also an important parameter in case of multiple twisted tapes since the counter-swirl performs better than the co-swirl. The role of inserts in increasing the turbulence intensity is more significant in laminar regime than in turbulent regime. Therefore to enhance the heat transfer in turbulent flow, wire coil inserts are used. In recent years, second generation enhancement techniques that combine the twisted tape inserts and wire coil have been used to get better heat transfer performance in laminar as well as turbulent flows. Some researchers have also used regularly spaced and perforated twisted tape for the purpose of material saving; the results have shown that the perforation can lead to TPF of more than one. Since perforation results in less obstruction.

The regularly spaced twisted tape does not generate turbulence in non twisted tape area. Therefore, it is better to use full length twisted tape instead of regularly spaced twisted tape. In large Prandtl number flow, roughness performs better than the twisted tape and the maximum heat transfer occurs due to roughness when the roughness height is three times the viscous sublayer thickness. The artificially corrugated rough surface can be developed to significantly improve the heat transfer characteristics by breaking and destabilizing the thermal boundary layer on the surface. Passive techniques are widely used in various industries for their cost saving, low maintenance requirements and easy set up.

The TPF reduces with increase in Reynolds Number. Twisted tape does not perform well where air is used as a working fluid. It performs well where water and nanofluid are used as working fluid because of larger density of liquid. Therefore for air heating applications vortex generators, ribs or deflectors are more helpful in increasing the TPF. In case of liquids swirl producing devices are more helpful in increasing the TPF.

Exhaustive research has been done by many investigators on the use of twisted tape, artificial roughness or vortex generators to enhance the heat transfer characteristics in tube heat exchangers as discussed in this review; however the areas related to outer tube geometries like conical, parabolic, frustum, etc have not yet been explored and could be the focus of new research.

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