Heat Transfer Augmentation in a Circular tube and Square duct Fitted with Swirl Flow Generators: A Review

Suhas V. Patil and P. V.Vijay Babu

Abstract—**The present paper is a review of research work in last decade on heat transfer enhancement in a circular tube and square duct. In the present paper emphasis is given to works dealing with twisted tape ,screw tape inserts because according to the recent studies, these are known to be economic tool in the field of heat transfer enhancement. Passive techniques, where inserts are used in the flow passage to increase the heat transfer rate, are advantageous compared with active techniques, because the insert manufacturing process is simple and cheap and these techniques can be easily employed in an existing heat exchanger. The thermohydraulic performance of above inserts depends on the various factors such as flow conditions, geometry of pipe and insert configurations. The present review is organized separately according to type of insets, pipe geometry, for laminar and turbulent flow respectively.**

Index Terms—**Twisted tape, screw tape , circular tube, square duct,heat transfer enha ncement**

I. Introduction

The process of improving the performance of a heat transfer system or increase in heat transfer coefficient is referred to as heat transfer augmentation or enhancement. This leads to reduce size and cost of heat exchanger. An increase in heat transfer coefficient generally leads to additional advantage of reducing temperature driving force, which increases second law efficiency and decreases entropy generation. General techniques for enhancing heat transfer can be divided in three categories. One is passive method such as twisted tapes, helical screw tape inserts, rough surfaces, extended surfaces, additives for liquid and gases. The second is active method, which requires extra external power, for example mechanical aids, surface fluid vibration, use of electrostatic fields. Passive methods are found more inexpensive as compared to other group. Twisted tape is one of the most important members useful in laminar flow from this group.

The third category includes combined application of active and passive techniqes to obtain enhancement in heat transfer that is greater than that produced by either of them when used individually, is termed as compound enhancement. This technique involves complex design and hence has limited applications.

Heat transfer augmentation techniques (passive, active or a combination of passive and active methods) are commonly used in areas such as process industries, heating and cooling in evaporators, thermal power plants, air-conditioning equipment, refrigerators, radiators for space vehicles, automobiles, etc.Passive techniques, where inserts are used in the flow passage to increase the heat transfer rate, are advantageous compared with active techniques, because the insert manufacturing process is simple and cheap and these techniques can be easily employed in an existing heat exchanger.

Furthermore, as a heat exchanger becomes older, the resistance to heat transfer increases owing to fouling or scaling. These problems are more common for heat exchangers used in marine applications and in chemical industries. In some specific applications, such as heat exchangers dealing with fluids of low thermal conductivity (gases and oils) and desalination plants, there is a need to increase the heat transfer rate. 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 an existing heat exchanger at an economic pumping power.

In general, swirl flow generators are placed in the flow passage to augment the heat transfer rate, and this reduces the hydraulic diameter of the flow passage. Heat transfer enhancement in a tube flow by inserts such as twisted tapes, screw tape is mainly due to flow blockage, partitioning of the flow and secondary flow. 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 in some situations leads to a significant secondary flow. Secondary flow further provides a better thermal contact between the surface and the fluid because secondary flow creates swirl and the resulting mixing of fluid improves the temperature gradient, which ultimately leads to a high heat transfer coefficient.

In present paper, a review of heat transfer augmentation tool i.e. twisted tape and screw tape swirl flow generators are discussed, for laminar and turbulent flow. Since they are most commonly used as enhancement tool. This paper also gives performance evaluation criteria for a swirl flow generator. Finally it is expected to be the pioneer source as an intensive literature review for a swirl flow generator.

A. Circular Tube Fitted with Twisted Tape in Laminar Flow

Many studies were conducted previously to analyze heat transfer and pressure drop with twisted tape (as shown in figure 1) as swirl generators in a circular tubes.

Manuscript received July 06, 2011; revised September 22, 2011.This is partial research of P.hD. work.

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Hong and Bergles [1] reported heat transfer enhancement in laminar viscous liquid flows in a tube with uniform heat flux boundary conditions, but their correlation has limited applicability as it is valid for a high Prandtl number (approximately 730).They reported that as much as threefold improvement in heat transfer rate using twisted tape insert in a tube.

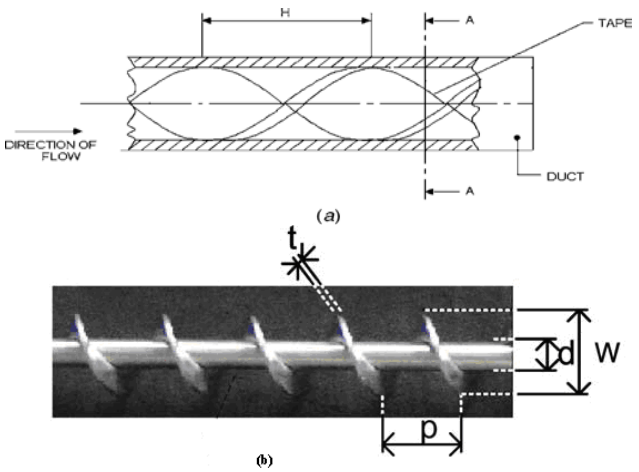

Fig. 1 Schematic diagram of different inserts, (a) for twisted tape , (b) for Screw tape insert

Marner and Bergles [2] were the first investigators to recognize the importance of uniform wall temperature (UWT) boundary condition to a major group of heat exchanger used in chemical industry. They studied UWT heating and cooling of ethylene glycol(Pr = 24-85, Re_a=380-3470) using single twisted tape insert of y = 5.4 in a tube and internally finned tubes, and observed that both heat transfer and friction factor increased substantially beyond particular Reynolds number, at which secondary swirl flow and turbulence were induced in the flowing fluid.Manglik and Bergles[3] correlated heat transfer and pressure drop for twisted tape inserts for uniform wall temperature conditions using water and ethylene glycol as working fluid, for laminar flow condition and explained physical description of enhancement mechanism. Depending upon the flow rate and tape geometry, the enhancement in heat transfer is due to the tube partitioning and flow blockage, the large flow path and secondary fluid circulation. They proposed laminar flow correlations for the friction factor and Nusselt number, including the swirl parameter, which defines the interaction between viscous, convective inertia and centrifugal forces.

Shivkumar and Raja Rao [4] studied compound laminar flow heat transfer augmentation laminar flow heat transfer to power law fluid in spirally corrugated tubes with twisted tape inserts. But they did not observe any better results compared to the case twisted tape insert in the plain circular tube.Saha *et al.*[5]studied pressure drop and heat transfer characteristics in a circular tube fitted with regularly spaced twisted–tape elements under constant wall heat flux boundary condition They concluded that pinching of place rather than connecting elements by rods is a better proposition from the thermohydraulic performance point of view. Reducing tape width yields poor results. Vijay Babu and Raja Rao [6] studied pseudo-plastic type power law fluid for laminar flow in a circular pipe under constant wall temperature condition and proposed a predictive correlation to fit well all available data.

Agarwal and Raja Rao[7] reported experimental investigations of isothermal and nonisothermal friction factor and mean Nusselt number for uniform wall temperature (UWT) heating and cooling of servotherm oil(Pr = 195-375) in a circular tube(Re_a = 70-4000) with twisted tape inserts (y = 2.41-4.84). Isothermal friction factor were found to be 3.13-9.71 times the plain tube values. The Nusselt were found to be 2.28 -5.35 and 1.21-3.7 times the plain tube forced convection values based on constant flow rate and constant pumping power respectively. They proposed correlation representing effect of heat transfer on friction factor for practical application.Loknath [8] studied pressure drop and heat transfer on laminar flow of water though horizontal tube under constant wall heat flux conditions, tube fitted with half length and full length twisted tapes. He found that that half length twisted tapes were more effective than full length tapes.Al-Fahed *et al.* [9] reported pressure drop and heat transfer results for a plain, microfin, and twisted-tape insert-tubes in shell and tube heat exchanger with oil as working fluid under constant wall temperature. The twisted-tape used in the experiments includes three different twist ratios each with two different widths. The twist ratio and the width of the tape seem to have a large effect on the performance of the twisted-tape insert.

Saha *et al.*[10] studied laminar flow of viscous fluid though horizontal tube under constant wall heat flux conditions, tube fitted with regularly spaced twisted tapes. They found that pinching (placing of a twisted tape exactly at the centre of the tube) of twisted tape in a tube performs better than a twisted tape inserted by a loose fit. Patil [11]reported the friction factor and heat transfer characteristics of laminar swirl flow of pseudo plastic type power law fluid in a circular tube using varying width full length twisted tapes under uniform wall temperature conditions. He found that, from the considerations of enhanced heat transfer and savings in heat transfer and savings in pumping power and in tape material cost, reduced width twisted tapes are better for enhancing laminar swirl flow heat transfer. He has observed that 17-60% reduction in friction factor and 5-24 % reduction in Nusselt number for 15-50%reduction in tape-width.

Sarma *et al.*[12] new method was postulated to predict heat transfer coefficients with twisted tape inserts in a tube, in which the wall shear and the temperature gradients are properly modified through friction coefficient correlation leading to heat transfer augmentation from the tube wall. The eddy diffusivity expression of van Driest is modified to respond to the case of the internal flows in a tube with twisted tapes for ranges of Reynolds number corresponding to the laminar flow in tubes. The predictions from the present theory are compared with some correlations available in literature for twisted tape inserts.

Yadav [13] studied influences of the half length twisted tape insertion on heat transfer and pressure drop characteristics in a U-bend double pipe heat exchanger using oil as working fluid. The experimental results revealed that the increase in heat transfer rate of the twisted tape inserts was found to be strongly influenced by tape – induced swirl. The heat transfer coefficient is found to increase by

40%with half-length twisted tape inserts when compared with plain heat exchanger. On the basis of equal mass flow rate the heat transfer performance of half length twisted tape is better than the plain heat exchanger, and on the basis of unit pressure drop the heat transfer performance of smooth tube is better than half-length twisted tape. It was also observed that the thermal performance of plain heat exchanger was found better than half length twisted tape by 1.3-1.5 times.

B. Circular Tube Fitted with Twisted Tape in Turbulent Flow

The important investigations of twisted tape for turbulent flow in a circular pipe are represented in following section. Twisted tape in turbulent flow is effective up to a certain Reynolds number range but a not over a wide Reynolds number range.

Lopina and Bergles [14] observed that the difference between isothermal and heated flow friction factors for the swirl flow of liquids is substantially less than the corresponding difference for a plain tube. In turbulent flow, insertion of a twisted tape increases the heat transfer, but the pressure drop also increases significantly.

Manglik and Bergles [15] developed correlations for both turbulent flow and laminar flow. For an isothermal friction factor, the correlation describes most available data for laminar, transitional and turbulent flows within 10 per cent. Date [16] formulated and solved numerically the problem of fully developed, uniform property flow in a tube containing a twisted tape. Presented comparision between existing experimental data with numerical prediction. Saha *et al.* [17] found that, for a constant heat flux boundary condition, regularly spaced twisted tape elements do not perform better than full-length twisted tape because the swirl breaks down in-between the spacing of a regularly twisted tape.Sivashanmugam and Sunduram [18] studied the thermohydraulic characteristics of tape-generated swirl flow under constant heat flux in circular tube using water as working fluid.

Noothong *et al.*[19] studied influences of the twisted tape insertion on heat transfer and flow friction characteristics in a concentric double pipe heat exchanger using air as working fluid. In the experiments, the swirling flow was introduced by using twisted tape placed inside the inner test tube of the heat exchanger with different twist ratios, y = 5.0 and 7.0. The experimental results revealed that the increase in heat transfer rate of the twisted-tape inserts is found to be strongly influenced by tape-induced swirl or vortex motion. Over the range investigated, the maximum Nusselt numbers for using the enhancement devices with y = 5.0 and 7.0 are 188% and 159%, respectively, higher than that for the plain tube. In addition, the effects of the twisted tape on the heat transfer enhancement efficiency were also investigated.Murugesan *et al.* [20] reported experimental investigations of heat transfer and friction factor studies of turbulent flow in a tube fitted with trapezoidal –cut twisted tape with twist ratios 6 and 4 for water as working fluid. They found that Heat transfer coefficient and friction factor increases with the decreases in twist ratio. The trapezoidal –cut twisted tape with twist ratios 6 and 4 augment the heat transfer rate 27 and 41.8 % higher than plain tube.

C. Circular Tube Fitted with Screw Tape Insert in Laminar Flow

The tape twisted in the form of screw-tape with similar geometry of the helical-tape is a modified form of the twisted-tape wounded on a core-rod as shown in figure1(b). However, both the helical screw-tape and the twisted-tape generate a similar swirling flow in the circular tube and both of them possess different characteristics of flow. For the helical screw-tape, the swirling flow rotates in single way smooth direction of flow like a screw motion, while the twisted-tape shows the swirling flow in two way directions of parallel flows simultaneously (two parallel flows separated by the twisted-tape). Important investigations in the area of heat transfer augmentation in circular tube with screw tape inserts are summarized in this section.

Sivashanmugam and Suresh [21] studied the laminar heat transfer and friction factor characteristics in a circular tube fitted with full-length helical screw-tapes with different twist ratios under constant heat flux conditions, including the increasing and decreasing order of twist ratio sets. They reported on a significant improvement of the heat transfer rate for using the tape inserts and also found that there is not much change in the magnitude of heat transfer coefficient enhancement between using the increasing and decreasing twist ratio sets.

Sivashanmugam and Nagarajan [22] reported experimental investigation on heat transfer and friction factor characteristics of laminar flow in a circular tube fitted with right-left helical screw inserts of equal length, and unequal length of different twist ratio under constant heat flux condition. The heat transfer coefficient enhancement for right-left helical screw inserts is higher than that for straight helical twist for a given twist ratio. Performance evaluation analysis has been made and the maximum performance ratio of 2.85 and 2.97, respectively were obtained for 300 R and 300 L, and 400 R and 200 L type inserts.

D. Circular Tube Fitted with Screw Tape Insert in Turbulent Flow

Several researchers have studied various configurations of screw tape, such as full-length screw tape, increasing and decreasing order of twist, regularly spaced screw tape insert and right and left helical screw tape inserts.

Eiamsa-ard and Promvonge [23] reported effects of insertion of a helical screw-tape with or without core-rod in a concentric double tube heat exchanger on turbulent heat transfer and flow friction characteristics with cold and hot waters as the test fluids. The Reynolds number in a range of 2000 to 12,000. An effect of the loose-fit, helical screw tape inserts with/without core-rod were experimentally studied The experimental results show that the increases in average Nusselt number of using the loose-fit, helical tape with and without core-rod are found to be 230% and 340%, respectively, over the corresponding plain tube.Furthermore, the enhancement efficiency of the helical screw-tapes varies between 1.00 and 1.17, 1.98 and 2.14, for the tapes with and without core-rod, respectively. Sivashanmugam and Suresh [24] reported experimental investigation of heat transfer and friction factor characteristics of circular tube fitted with full-length helical screw element of different twist ratio and

increasing and decreasing order of twist ratio set have been studied with uniform heat flux under turbulent flow conditions. The Reynolds number was varied from 2700 to 13500. The maximum Nusselt number for the twist of 1.95 was obtained. The performance of the helical twist insert was compared with the twisted tape performance reported in the literature and found that it is better than twisted tape performance.

Sivashanmugam and suresh[25] investigated heat transfer and friction factor characteristics of circular tube fitted with full length helical screw elements of different twist ratio and helical screw inserts with spacer length 100,200,300,400 mm with uniform heat flux under turbulent flow conditions. They found that regularly spaced helical screw elements can safely be used for heat transfer augmentation with less reduction in pressure drop than full length helical screw inserts.

E. Laminar Heat transfer in Square /Rectangular Duct

Square duct offers more surface to volume ratio than circular tube therefore more heat transfer enhancement was observed in square and rectangular duct. Important investigations in square and rectangular duct using various geometrics of swirl generators have discussed in this section.

Ray and Date [26] numerically predicted characteristics of laminar flow and heat transfer through square duct with twisted tape insert under constant heat flux condition. The transport equations were solved on a non-staggered non-orthogonal grid using the curvilinear version of the complete pressure correction algorithm. They found that, Square duct containing twisted tape offers better thermo hydraulic performance than plain duct for all *Re,Pr,y.* Heat transfer of square tubes was found considerably higher (up to a maximum 350%) than the circular tube. Ray and Date [27] derived a correlation for the friction factor and Nusselt number for a square duct from the predicted data. They compared the correlation for the friction factor with experimental data and the agreement was found to be within +10 per cent.

Saha and Mallik [28] reported an experimental investigation of the heat transfer and pressure drop characteristics of laminar flow of viscous oil through horizontal rectangular and square plain ducts and ducts inserted with full-length twisted tapes, short length twisted tapes, and regularly spaced twisted-tape elements, under constant heat flux boundary conditions. They proposed empirical correlations and found that the short-length twisted tape in square and rectangular ducts performs worse than the full-length twisted tape. However, regularly spaced twisted-tape elements perform significantly better than the full-length twisted tapes.

Pramanik and Saha [29] studied heat transfer and the pressure drop characteristics of laminar flow of viscous oil through rectangular and square ducts with internal transverse rib tabulators on two opposite surfaces of the ducts and fitted with twisted tapes under constant heat flux conditions. The combined use of full-length twisted-tape and transverse ribs enhances the thermohydraulic performance of the square and rectangular ducts compared to the use of only twisted-tape or only transverse ribs for laminar flow. However, the performance evaluation shows that the short-length twisted tape in square and rectangular ducts with rib turbulators, through which laminar flow occurs under constant wall heat flux boundary condition performs worse than the full-length twisted tape.

II. Conclusion

A twisted tape insert mixes the bulk flow well and therefore performs better in laminar flow, because in laminar flow the thermal resistant is not limited to a thin region. The result also shows twisted tape insert is more effective, if no pressure drop penalty is considered.

Twisted tape in turbulent flow is effective up to a certain Reynolds number range. It is also concluded that twisted tape insert is not effective in turbulent flow, because it blocks the flow and therefore pressure drop increases. Hence the thermohydraulic performance of a twisted tape is not good in turbulent flow. These conclusions are very useful for the application of heat transfer enhancement in heat exchanger networks.

This helical screw tape can help to promote higher heat transfer exchange rate than the use of twisted-tape because of shorter pitch length which leads to stronger swirling flow and longer residence time in the tube.

Because of lower pressure drop and ease of manufacturing, the twisted-tape is, in general, more popular than the helical screw-tape having a higher heat transfer rate at the same mass flow rate. However, at low values of Reynolds number the pressure drops for using both tapes are not much different.

Heat transfer of square tubes was found considerably higher than the circular tube. This is mainly because of square duct has high surface to volume ratio.

The combined use of full-length twisted-tape and transverse ribs enhances the thermohydraulic performance of the square and rectangular ducts compared to the use of only twisted-tape or only transverse ribs for laminar flow.

The short-length twisted tape in square and rectangular ducts performs worse than the full-length twisted tape. However, regularly spaced twisted-tapes perform significantly better than the full-length twisted tapes.

III. Appendix

Ao plain duct flow cross sectional area, (W.D),m2
Cp specific heat at constant pressure, KJ/Kg.K
d iameter of screw tape rod, m
De equivalent diameter of t = 4Ao / 2 (W+D) ,m
H average convective heat transfer coefficient,W/m2 K
H axial distance for 180o rotation of twisted tape, m
K thermal conductivity of the test liquid, W/m.k
Nu Nusselt number (defined on equivalent diameter)
P pitch of screw tape,m
Pr prandlt number, Pr=Cp μ / K , dimensionless
Re Reynolds number (based on equivalent diameter), Re= Devρ/ μ , dimensionless
t thickness of screw tape,m
v average velocity of test liquid, m/s
y wist ratio of the twisted tape, y = H/De ,dimensionless

w width of duct, as well as insert , m Greek symbols
ρ density of test of liquid, Kg/m3
μ viscosity of test liquid, Kg/m.s
Subscripts
a augmented condition
Ao plain duct flow cross sectional area, (W.D),m2
Cp specific heat at constant pressure, KJ/Kg.K
d iameter of screw tape rod, m
De equivalent diameter of t = 4Ao / 2 (W+D) ,m
H average convective heat transfer coefficient,W/m2 K
H axial distance for 180o rotation of twisted tape, m
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Re Reynolds number (based on equivalent diameter), Re= Devρ/ μ , dimensionless
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v average velocity of test liquid, m/s
y wist ratio of the twisted tape, y = H/De ,dimensionless
w width of duct, as well as insert , m Greek symbols
ρ density of test of liquid, Kg/m3
μ viscosity of test liquid, Kg/m.s
Subscripts
a augmented condition

ACKNOWLEDGEMENT

This work was done by Mr. S.V.Patil (Research Scholar) as a part of his doctoral programme during July 2007 to July 2010,at the department of Chemical Engineering, Dr.Babasaheb Ambedkar Technological University, Lonere, under the guidance of Professor P.V.Vijay Babu. We are thankful to the authorities at Dr.BATU; for providing all facilities for completing this work.

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