Heat Transfer Augmentation Techniques in Circular Tube Fitted With Swirl Flow Generator: A Review

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Abstract—Heat transfer enhancement is an important matter of concern for energy conservation and also beneficial from economic point of view. Passive techniques, where swirl inserts are used in the flow passage to enhance the heat transfer rate, are advantageous compared with active techniques, because the swirl flow inserts are simple to manufacture and these techniques can be easily employed in an existing heat exchanger. This paper is a review of works dealing with swirl flow devices such as twisted tape, screw tape insert, wire coil, conical ring turbulators etc. because according to the recent studies, these are known to be economic tool in the field of heat transfer enhancement. Also the effect of Perforation Index on friction factor is discussed in this paper.

Keywords— Circular Tube, Twisted Tape, Helical Screw Tape Inserts, Perforation Index, Heat Transfer Enhancement

I. INTRODUCTION

A. Importance of heat exchangers

Energy and materials saving considerations, as well as economic incentives, have led to efforts to produce more efficient heat exchange equipment. Common thermal-hydraulic goals are to reduce the size of a heat exchanger required for a specified heat duty, to upgrade the capacity of an existing heat exchanger, to reduce the approach temperature difference for the process streams, or to reduce the pumping power.

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. In the design of compact heat exchangers, passive techniques of heat transfer augmentation can play an important role if a proper passive insert configuration can be selected according to the heat exchanger working condition (both flow and heat transfer conditions). The major challenge in designing a heat exchanger is to make the equipment compact and achieve a high heat transfer rate using minimum pumping power. Furthermore, as a heat exchanger becomes older, the resistance to heat transfer increases owing to fouli ng 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, several techniques have been proposed in recent years and are discussed in the following sections of this paper.

B. Important Definitions

In this section a few important terms commonly used in heat transfer augmentation work are defined.

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

2) Overall enhancement ratio: The overall enhancement ratio is defined as the ratio of the heat transfer enhancement ratio to the friction factor ratio. This parameter is also used to compare different passive techniques and enables a comparison of two different methods for the same pressure drop. The overall enhancement ratio is defined as

\[ x = \frac{\left( \frac{Nu}{Nu_0} \right)}{f/f_0} \]

Where Nu, f, Nu0 and f0 are the Nusselt numbers and friction factors for a duct configuration with and without inserts respectively. The friction factor is a measure of head loss or pumping power.

3) Nusselt number: The Nusselt number is a measure of the convective heat transfer occurring at the surface and is defined as \( h d/k \), where \( h \) is the convective heat transfer coefficient, \( d \) is the Diameter of the tube and \( k \) is the thermal conductivity.

4) Prandtl number: The Prandtl number is defined as the ratio of the molecular diffusivity of momentum to the molecular diffusivity of heat

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

II. LAMINAR AND TURBULENT FLOW THROUGH A CIRCULAR TUBE

For fully developed laminar flow in a circular tube without any insert, the Nusselt number has a constant value under the condition of constant wall temperature, \( Nu = 3.657 \), and the friction factor for this flow is given as

\[ f = 16/Re \]

For fully developed turbulent flow in a smooth circular tube, the Nusselt number can be predicted by the Dittus–Boelter correlation,

\[ Nu = 0.023Re^{0.8}Pr^{0.4} \]

And the friction factor can be obtained by the relation

\[ f = 0.079Re^{-0.25} \]
III. AUGMENTATION TECHNIQUES IN CIRCULAR PIPE

Generally, heat transfer augmentation techniques are classified in three broad categories:

a) Active Method
b) Passive Method
c) Compound Method

Active method involves some external power input for the enhancement of heat transfer and has not shown much potential owing to complexity in design. Furthermore, external power is not easy to provide in several applications. Some examples of active methods are induced pulsation by cams and reciprocating plungers, the use of a magnetic field to disturb the seeded light particles in a flowing stream, etc. Passive method does not need any external power input and the additional power needed to enhance the heat transfer is taken from the available power in the system, which ultimately leads to a fluid pressure drop. These methods generally use surface or geometrical modifications to the flow channel by incorporating inserts or additional devices. For example, use of inserts, use of rough surfaces etc.

A compound method is a hybrid method in which both active and passive methods are used in combination. The compound method involves complex design and hence has limited applications.

IV. REVIEW OF ENHANCEMENT TECHNIQUES

An extensive literature review of heat transfer augmentation technique with swirl flow inserts has been discussed in this section. These devices produce secondary recirculation on the axial flow for single phase or two-phase flows heat exchanger. In this part we investigate the previous work in which authors used twisted tape and screw tape kind of turbulators.

A. Wire coil

The effects of wires with square cross section forming a coil used as a tubular on the heat transfer and turbulent flow friction characteristics in a uniform heat flux, circular tube are experimentally investigated by Pongjet Promvonge. The experiments are performed for flows with Reynolds numbers ranging from 5000 to 25,000. Two different spring coiled wire pitches are introduced. The results are also compared with those obtained from using a typical coiled circular wire, apart from the smooth tube. The experimental results reveal that the use of coiled square wire turbulators leads to a considerable increase in heat transfer and friction loss over those of a smooth wall tube.

The use of coiled square wire causes a high-pressure drop increase, which depends mainly on spring pitches and wire thickness, and also provides considerable heat transfer augmentations. However, the Nusselt number augmentation tends to decrease rapidly with the rise of Reynolds number. If wire coils are compared with a smooth tube at constant pumping power, an increase in heat transfer is obtained, especially at low Reynolds number. The coiled square wire should be applied instead of the round one to obtain higher heat transfer and performance, leading to the more compact heat exchanger. The best operating regime for the coiled square wire turbulator is found at lower Reynolds number where the heat transfer enhancement is about 1.2–1.3 times.

B. Twisted tape

Twisted tape increases the heat transfer coefficient at a cost of a rise in pressure drop. Several researchers have studied various configurations of twisted tape, such as full-length twisted tape, short-length twisted tape, full-length twisted tape with varying pitch and regularly spaced twisted tape. This section discusses which configuration of twisted tape is suitable for laminar flow.

I. Typical twisted tape

These tapes have length equal to the length of exchanger tube. An experimental investigation for a solar water heater with twisted tape inserts having twist pitch to tube was studied by Kumar and Prasad [1]. They found that twisted-tapes generate turbulence superimposed with swirlness inside the flow tube and consequently result in enhanced heat transfer. Decreasing the values of twist ratio leads to increasing values of heat transfer rate and the pressure drop. Esmaeilzadeh et al. [2] investigated heat transfer and friction factor characteristics of γ-Al2O3-water nanofluid through circular tube with twisted tape inserts with various thicknesses at constant heat flux (Fig. 1). They showed that the use of twisted tapes increase friction factor due to larger contact surface and reduction of fluid free flow area which causes high speed swirl flow. Finally, the convective heat transfer enhancement outweighs the effect of friction factor increase, leading enhanced thermal performance. An experimental study of fully developed turbulent flow in a dimpled tube in conjunction with a twisted tape has been performed by Thianpong et al. [3] (Fig. 2). They found that the heat transfer and friction factor are increase with decreasing both of pitch ratio and twist ratio.

Figure 1. Schematic layout of inserts

Figure 2. Dimpled tube and twisted tape

2. Varying length, alternate-axes and pitches twisted tape

Sarada et al. [4] studied the enhancement of heat transfer using varying width twisted tape inserts. They showed that the enhancement of heat transfer with twisted tape inserts as compared to plain tube varied from 36% to 48% for full width and 33% to 39% for reduced width inserts. This enhancement is mainly due to the centrifugal forces resulting from the spiral motion of the fluid. The thermo hydraulic characteristics of the circular tubes equipped with alternate clockwise and
counterclockwise twisted-tapes (TA) for the Reynolds number ranging from 830 to 1990, were reported by Wongcharee and Eiamsa-ard [5] (Fig. 3). They found that thermal performance increases with increase of Reynolds number and decrease of pitch ratio. An experimental study on Nusselt number, friction factor and enhancement efficiency characteristics in a round tube with short-length twisted tape insert under uniform wall heat flux boundary conditions was investigated by Eiamsa-ard and Thianpong [6]. The heat transfer enhancement efficiency (η) is higher than unity only for the full-length tape insert at low Reynolds number.

3. Multiple twisted tapes

Bhuiya et al. [7] presented study explored the effects of the double counter twisted tapes on heat transfer and fluid friction characteristics in a heat exchanger tube. Their experimental results demonstrated that the Nusselt number, friction factor and thermal enhancement efficiency were increased with decreasing twist ratio. Their results also revealed that the heat transfer rate in the tube fitted with double counter twisted tape was significantly increased with corresponding increase in pressure drop. The maximum thermal enhancement efficiency of 1.34 was achieved by the use of double counter twisted tapes at constant blower power. Turbulent convective heat transfer characteristics in a helical-ribbed tube fitted with twin twisted tapes have been investigated experimentally by Promvonge et al. [8] (Fig. 4). Their experimental results revealed that the co-swirling inserted tube operates much better than the ribbed/ smooth tube alone at a similar operating condition. The co-swirl tube at Y E8 yields the highest thermal performance at lower Reynolds number (Re). The influences of triple twisted tapes on heat transfer rate, friction factor and thermal enhancement efficiency were experimentally investigated by Bhuiya et al. [9]. They showed that the thermal enhancement efficiency for all the cases was more than one, which indicated that the effect of heat transfer enhancement due to the enhancing tool was more dominant than the effect of the rising friction factor and vice versa.

4. Helically twisted tapes.

Eiamsa-ard et al. [10] studied the heat transfer enhancement attributed to helically twisted tapes (HTTs) (Fig. 5). They observed that heat transfer rate and friction factor increase as the tape twist ratio and helical pitch ratio decrease, while the thermal performance shows opposite trend. Experimental investigation of heat transfer, friction factor and thermal performance of solar water heater system fitted with helical and Left–Right twist has been performed by Jaisankar et al. [11]. They showed that the helical twisted tape induces swirl flow inside the riser tubes unidirectional over the length. But, in Left–Right system the swirl flow is bidirectional which increases the heat transfer and pressure drop when compared to the helical system.

5. Perforated Twisted Tape

Thianpong et al. [12] studied the effect of perforated twisted-tapes with parallel wings on heat transfer enhancement in a heat exchanger tube (Fig. 6). Their results showed that heat transfer and friction factors were significantly influenced by the presences of wings and holes on PTTs. Both heat transfer and friction increased with the increase of wing depth ratio and the decrease of perforation hole diameter ratio. Due to the dominant effect of increased heat transfer over that of increased friction factor, the thermal performance factor was found to be increased as wing depth ratio increased and hole diameter ratio decreased.

6. Twisted tape and wire coil turbulators

Influences of insertion of wire coils in conjunction with twisted tapes on heat transfer and turbulent flow friction characteristics in a uniform heat-flux, circular tube using air as the test fluid are experimentally investigated by Pongjet Promvonge [13]. The wire coil used as a turbulator is placed inside the test tube while the twisted tape is inserted into the
wire coil to create a continuous impinging swirl flow along the tube wall. The effects of insertion of the two turbulators with different coil pitch and twist ratios on heat transfer and friction loss in the tube are examined for Reynolds number ranging from 3000 to 18,000. The use of the wire coil and the twisted tape inserts causes a high-pressure drop increase and also provides considerable heat transfer augmentations, $N_{Ua}/N_{U0} = 3–6$. However, Nusselt number augmentation tends to decrease with the rise of Reynolds number. If the combined wire coil and twisted tape turbulators are compared with a smooth tube at a constant pumping power, a double increase in heat transfer performance is obtained especially at low Reynolds number. Therefore, the combined wire coil and twisted tape should be applied instead of using a single one only to obtain the highest heat transfer performance of about 200–350%, leading to more compact heat exchanger. The best operating regime for combined both the turbulators is found at lower Reynolds number values for the lowest values of the coil spring pitch and twist ratio.

Figure 7. Test tube with wire coil and twisted tape inserts

C. Conical-Ring Turbulators

To increase convection heat transfer in a uniform heat flux tube by a passive method, several conical rings used as turbulators were mounted over the test tube by Promvonge [14]. They reported an augmentation of up to 197%, 333%, and 237% in Nusselt number is obtained in the turbulent flow for the CR, DR and CDR arrays, respectively, although the effect of using the conical ring causes a substantial increase in friction factor. Their results were correlated in the form of Nusselt number as a function of Reynolds number, Prandtl number and diameter ratio.

Flow-induced vibration characteristics of conical-ring turbulators used for heat transfer enhancement in heat exchangers are investigated experimentally by Kenan Yakut, Bayram Sahin. The conical- rings, having 10, 20 and 30 mm pitches, are inserted in a model pipe-line through which air is passed as the working fluid. It is observed that as the pitch increases, vortex shedding frequencies also increase and the maximum amplitudes of the vortices produced by conical-ring turbulators occur with small pitches. In addition, the effects of the promoters on the heat transfer and friction factor are investigated experimentally for all the arrangements. It is found that the Nusselt number increases with the increasing Reynolds number and the maximum heat transfer are obtained for the smallest pitch arrangement. The turbulator with 10 mm pitches was found to improve the rate of heat transfer by 250% under the condition of a constant pumping power. The vortices having maximum amplitude values were produced by turbulators with 10 mm pitch. The maximum amplitude values were increased by almost 4.5-fold compared with those for an empty smooth tube. On the other hand, the vortices with the maximum shedding frequencies were generated by the turbulators having 30 mm pitch. In the case of the flow-acoustic coupling condition, vortex shedding frequencies are in a frequency band of 200–220 Hz for all arrangements. The vortices with maximum amplitudes were produced by 10 mm pitches between Reynolds numbers of 8000 and 18000.

Figure 8. Conical-Ring Turbulators

D. Screw Helical Tape

Eiamsaard and Promvonge [15] carried out an experimental investigation to study heat transfer enhancement in double pipe heat exchanger tube equipped with helical tapes; inserted to obtain swirl flow which leads to enhancement of heat transfer rate. The range of Reynolds number considered was 2300–8800. The inner tube was equipped with different helical geometries viz. full length helical tape with centered rod, full length helical tape without centered rod and regularly spaced helical tapes without centered rod (shown in fig. 9(a)–(c)). Hot air was allowed to pass through the inner tube while cold water through the annulus. Experimental results were compared with plain tubes data and it was found that heat transfer rate in tubes with helical tapes was higher than that of plain tube. Also, the highest heat transfer rate was obtained for full length helical tapes with centered rod but with increase in pressure drop. However, different free spacing ratio (space to tape ratio) was analysed to minimise this problem. Flow patterns inside the tube equipped with helical tapes were studied using visualisation technique.

Figure 9. (a) Full length helical tape with a centred rod, (b) full length helical tape without centred rod, (c) regularly spaced helical tapes

Sivashanmugam and Suresh [16] carried out an experimental study to determine heat transfer characteristics and friction factor of circular tube equipped with full length helical screw tape inserts. The study was performed with helical screw tapes of different twist ratios 1.95, 2.93, 3.91 and 4.89 and for increasing and decreasing order of twist ratio set. The different helical screws with different twist ratios were shown in fig. 11 (a), (b), (c) and (d). Turbulent flow conditions with Reynolds number from 2700 to 13,500 were selected for the study. The results showed that maximum value of Nusselt number is obtained with 1.95 twist ratio and both heat transfer coefficient and friction factor increases with the twist ratio. No appreciable change in the magnitude of heat transfer coefficient enhancement was found with decreasing and increasing twist ratio, due to the same amount of swirl generated at inlet and outlet in both the cases. Also, the maximum performance ratio was found 2.05 with twist ratio of 1.95.
Sivashanmugam and Suresh [17] carried out an experimental study to investigate heat transfer characteristics and friction factor of circular tube equipped with full length helical screw tapes inserts with spacer length 100, 200, 300 and 400 mm (shown in Fig. 5(a), (b), (c) and (d)). Four different twist ratios 1.95, 2.93, 3.91 and 4.89 of helical screws were selected as shown in figure 12, (a)-(d). The study was carried out for turbulent flow condition with uniform heat flux. From the experimental results it was found that Nusselt number decreases within 10% with spacer length for each 100 mm successive increase in spacer length. Also, the friction factor decreases by 5% for each 100 mm successive increase in spacer length. In addition to this, value of friction factor for helical screws with 100 mm spacer length was found much closer to the value of full length helical screws for all Reynolds numbers. The study concluded that helical screws are useful for the enhancement of heat transfer in turbulent flow only with less decrement in pumping power. The decrease in Nusselt number and friction factor was found to be 30–40% and 40–45% respectively for all Reynolds number from twist ratio 1.95 to 4.89.

Figure 11. (a) Helical screw inserts of twist ratio 1.95. (b) Helical screw inserts of twist ratio 2.93. (c) Helical screw inserts of twist ratio 3.91. (d) Helical screw inserts of twist ratio 4.89.

Figure 12. (a) Helical screw having twist ratio 1.95 with 100 mm spacer length. (b) Helical screw having twist ratio 1.95 with 200 mm spacer length. (c) Helical screw having twist ratio 1.95 with 300 mm spacer length. (d) Helical screw having twist ratio 1.95 with 400 mm spacer length.

V. RESEARCH Gap

Past literature shows 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 long residence time. Because of lower pressure drop, twisted tape insert is, in general, more popular than the helical tape despite higher heat transfer rate. Researchers are working on reducing the flow blockage in helical screw inserts. Up to date researchers tried to increase or decrease twist ratio, spacing in helical tube and also by using helical tube with and without rod. But none of researchers work in the direction of reducing pressure drop by doing perforation in helical screw tape. As the value of perforation index increases there is huge decrease in the amount of friction factor, as the flow blockages decreases. But the thermal performance factor shows significant increase with increase in the value of perforation index. This improvement in the thermal performance factor is because of fluid stream detachment and reattachment, and less flow blockages because of perforation.

Therefore Perforation Index could be important Parameter in reducing pressure drop in future study of heat transfer enhancement using helical screw tape.

CONCLUSION

This review paper has considered different methods which can be used to enhance the heat transfer enhancement in a circular tube such as twisted tape, wire coil, screw helical tape, conical ring turbulators and various combinations and parameters in the literature such as heat transfer coefficient and friction factor according to different geometry.

- The use of different inserts in a circular tube results in a significant increase in the heat transfer enhancement because of increase in the turbulence.
- The heat transfer coefficients of the coiled tubes with larger pitches are less than those of the ones with smaller pitches; and the effect of pitch on Nusselt number is more visible in high temperatures.
- In turbulent flow twisted tape is effective up to a certain Reynolds number range. Also as twisted tape blocks the flow and therefore pressure drop increase, it is not effective in turbulent flow.
- Swirl flow heat transfer is higher than non-swirling flow.
- 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.
- With the increase of perforation rate there is huge decrease in the amount of friction factor, as the flow blockages decreases. Heat transfer also decreases with increases in the amount of perforation index because of lesser eddy and vortex formation.
- Thermal performance factor shows significant increase with increase in the value of perforation index.

References


