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A COMPREHENSIVE STUDY OF PASSIVE TECHNIQUES FOR HEAT TRANSFER ENHANCEMENT IN TUBES

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ABSTRACT

Techniques have been investigated on enhancement of heat transfer rate and decrease the size and cost of the involving equipment especially in heat exchangers. One of the most important techniques used are passive heat transfer technique. These techniques when adopted in Heat exchanger improved the overall thermal performance significantly. This paper is a review of such techniques keeping focus on passive augmentation techniques used in heat exchangers. This paper reviews experimental and numerical works taken by Researchers on this technique such as twisted tape, wire coil, swirl flow generator etc. to enhance the thermal efficiency in heat exchangers and useful to designers implementing passive augmentation techniques in heat exchanger. The authors found that variously developed twisted tape inserts are popular researched and used to strengthen the heat transfer efficiency for heat exchangers. The other techniques used for specific work environments are studied in this paper.

KEYWORDS: *Heat transfer enhancement, Spiral tapes, pressure drop, turbulence*

I. INTRODUCTION

Effective utilization of available energy becomes need of hour today. This obviously requires effective devising. When it concerns heat energy the devices are heat exchangers. Heat exchangers are used in variety of applications. Some of the applications of heat exchangers are in process industries, thermal Power plants, air-conditioning equipments, refrigerators, radiators for space vehicles, automobiles etc. Increase in Heat exchanger performance can lead to more economical design of heat exchanger which can help to make energy, material & cost savings related to a heat exchange process. To increase the thermal performance of heat exchangers Heat transfer augmentation techniques are used.

Heat transfer augmentation techniques refer to different methods used to increase rate of heat transfer without affecting much the overall performance of the system. In the last decades, significant effort has been made to develop heat transfer enhancement techniques in order to improve the overall performance of heat exchangers. The design procedure of heat exchangers is quite complicated, as it needs exact analysis of heat transfer rate, efficiency and pressure drop apart from issues such as long-term performance and the economic aspect of the equipment.

The interest in these techniques is closely tied to energy prices and, with the present increase in energy cost, it is expected that the heat transfer enhancement field will go through a new growth phase. Although there is need to develop novel technologies, experimental work on the older ones is still necessary. The knowledge of its performance shows a large degree of uncertainty which makes their industrial implementation difficult. The efficiency of heat transfer equipment is essential in energy conservation. Furthermore, a more efficient heat exchanger design can reduce the size of the heat exchanger, thus reducing the costs associated with both material and manufacturing of the heat exchanger. There have been numerous attempts to reduce the size and cost of heat exchangers. Hence, there have been continuous attempts to improve the efficiency of heat exchangers by various methods. The literature survey in this area shows that a lot of research work has been carried out on passive techniques, specially wire coil inserts and twisted tapes. A number of experimental investigations are carried on wire coil inserts and twisted tapes acting alone and combining, by varying thickness, pitch, separation from tube wall, cross section and have developed correlations for Nusselt number with different variables listed. The comparison of the heat transfer rate, pressure drop behaviour and thermal performance between wire coil inserts of varying pitch ratios, twisted tape and their combination inserted in a test tube and also developed correlations of the Nusselt number and friction factor for all parameters studied. The main aim of this paper is to study the heat transfer enhancement of air flowing through a horizontal circular tube with wire coil, strip tape inserts.

II. METHODS OF HEAT TRANSFER ENHANCEMENT

In order to augment heat transfer and to increase thermal performance of the heat exchangers heat transfer enhancement techniques are widely used. These techniques are classified in two groups, passive and active techniques.

2.1 Passive techniques

These techniques generally use surface or geometrical modifications to the flow channel by incorporating inserts or additional devices. They promote higher heat transfer coefficients by disturbing or altering the existing flow behaviour (except for extended surfaces) which also leads to increase in the pressure drop. In case of extended surfaces, effective heat transfer area on the side of the extended surface is increased. Passive techniques hold the advantage over the active techniques as they do not require any direct input of external power. Use of this technique causes the swirl in the bulk of the fluids and disturbs the actual boundary layer so as to increase effective surface area, residence time and consequently heat transfer coefficient in existing system.

Heat transfer augmentation by these techniques can be achieved by:

1. Treated Surfaces
2. Rough surfaces
3. Extended surfaces
4. Swirl flow devices
5. Coiled tubes
6. Use of additives

The turbulators are of different types like wire coil inserts, twisted tapes and their combination. Out of all, inserts are most popular devices used for improving heat transfer performance of heat exchangers used in industries.

2.2 Active techniques

These techniques are more complex from the use and design point of view as the method requires some external power input to cause the desired flow modification and improvement in the rate of heat transfer. It finds limited application because of the need of external power in many practical applications. In comparison to the passive techniques, these techniques have not shown much potential as it is difficult to provide external power input in many cases.

Various active techniques are as follows:

1. Mechanical Aids
2. Surface vibration
3. Fluid vibration
4. Electrostatic fields
5. Injection
6. Suction

2.3 Compound techniques

A compound augmentation technique is the one where more than one of the above mentioned techniques is used in combination with the purpose of further improving the thermo-hydraulic performance of a heat exchanger.

III. VARIOUS PASSIVE TECHNIQUES

3.1 Tubes with various Inserts

The Heat transfer enhancement in tube flow by inserts such as twisted tape, coil inserts/spirals, ribs and dimples is mainly due to flow blockages, partitioning of the flow and secondary flow. The flow blockages increase the pressure drop and leads to increased viscous effect because of reduced fluid flow area. The blockages also increase flow velocity and in some situations it leads to a significant secondary flow. The secondary flow further provides a better thermal contact between surface and fluid as secondary flow creates swirl and this results in mixing of fluid that enhances the thermal gradient which ultimately enhances the heat transfer coefficient.
In turbulent flow, the dominant thermal resistance is limited to thin viscous sub layers. The wire /spiral coil inserts are more efficient in turbulent flow compared with twisted tape inserts because wire coil mixes the flow in viscous sub layers near the wall quite effectively whereas twisted tape cannot properly mix the flow near the viscous sub layers. For a laminar flow, the dominant thermal resistance is limited to thicker region compared with turbulent flow. Thus wire coil inserts are not effective for laminar flow because it cannot mix the bulk flow well and reverse is true for twisted tape inserts. Thus twisted tape inserts are efficient in laminar or transition flow. Cost and performance are important factors that play important role in selection of any passive technique for enhancement of heat transfer.

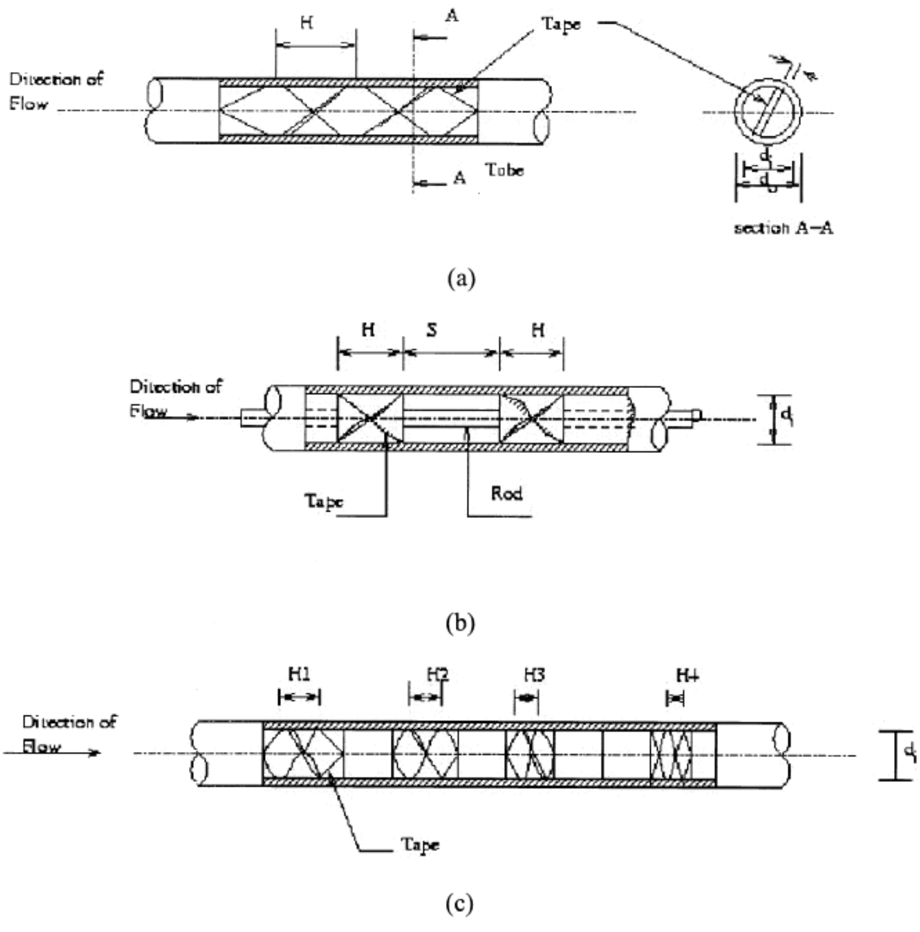

Figure 1: (a) Full length twisted tape (b) Regularly spaced twisted tape and (c) Smoothly varying (gradually decreasing) pitch full length twisted tape

Figure 2: Various Twisted tapes

3.2 Dimpled Tube

The Dimple Tube Heat Exchangers incorporate smooth interruptions on the internal surface to gently agitate product with minimal abrasion and shearing.

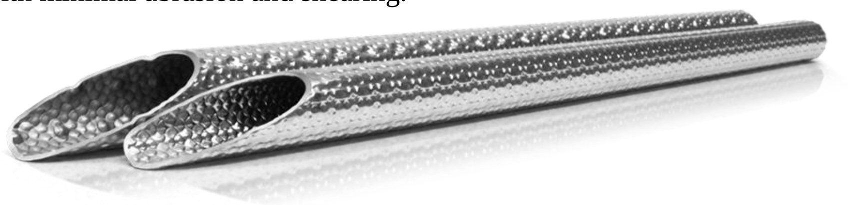

Figure 3: Dimpled tube

Benefits:

Dimple Tube Heat Exchangers are efficient in heating and cooling. Turbulating design facilitates excellent heat transfer with lower product velocity and reduced pressure drop.

- Conforming design insures no residual product or chemicals will remain after cleanup
- Stable temperature control, energy conservation, prolonged operation, and easy to clean.
- Turbulating design enhances heat transfer at reduced velocity.
- Dimple Tube design offers enhanced drainage advancements

3.3 Extended Surfaces

Extended or finned surfaces increase the heat transfer area which could be very effective in case of fluids with low heat transfer coefficients. This technique includes finned tube for shell & tube exchangers, plate fins for compact heat exchanger and finned heat sinks for electronic cooling.

Figure 4: Extended Surfaces

3.4 Displaced Enhancement devices

Displaced enhancement devices displace the fluid elements from the core of the channel to heated or cooled surfaces and vice versa .Displaced enhancement devices include inserts like static mixer elements (e.g. Kenics, Sulzer), metallic mesh, and discs, wire matrix inserts, rings or balls. Heatex wire matrix tube insert is one of the commercially available new displaced enhancement devices

Figure 5: Wire matrix

3.5 Tubes with annular or screw knurling

Tubes with annular or screw knurling are widely used in heat exchangers. Owing to the flow movement along in the helical trajectories in the near-wall layer in tubes with screw knurling, the pressure drop in such tubes in a certain range of parameters is lower than that in tubes with annular knurling, while heat transfer intensity in such tubes increases due to twisting of the flow. Screw knurling can be performed with different numbers of threads, which is determined by the requirements of the heat-transfer and pressure drop growth rates.

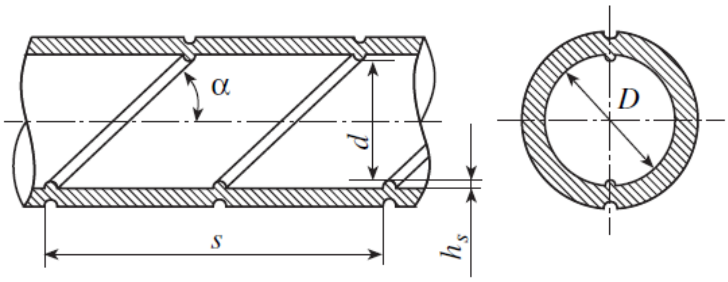

Figure 6: Annular knurling

3.6 Use of Nanofluids

Nanofluids are suspension of nanoparticles (less than 100 nm) in the conventional base fluids. The dispersed solid metallic or non-metallic nanoparticles change the thermal properties like thermal conductivity, viscosity, specific heat, and density of the base fluid. Past studies focused on measuring the thermal properties of nanofluids. These suspended nanoparticles effectively improve the transport properties and heat transfer characteristics of the base fluids. Recently, heat transfer augmentation using suspensions of nanometre-sized solid particles in base liquids have been investigated by various research groups across the world.

The nanoparticles used to prepare the nanofluids are basically metals (e.g. Cu, Ni, Al), oxides (e.g. Al2O3, TiO2, CuO, SiO2, Fe2O3, Fe3O4, BaTiO3) and some other compounds (e.g. CNT, TNT, AlN, SiC, CaCO3, graphene) with a size of 1 to 100 nm.

Various researchers studied heat transfer and flow behaviour of aqueous suspensions of given nanoparticles (nanofluids) flowing upward through a vertical pipe. They observed that addition of nanoparticles into the base liquid increases the thermal conduction and the enhancement improves with increasing particle concentration and decreasing particle (agglomerate) size.

The literature review reveal that nanofluids considerably enhance the heat transfer ability of conventional heat transfer liquids including oil or water or ethylene glycol or propylene glycol by dispersing nanoparticles in these fluids. It is understood that following mechanisms are responsible for enhancement of heat transfer coefficient in nanofluids,

- Increasing particle volume concentration and decreasing particle (agglomerate) size.
- Dispersion of dispersed nanoparticles.

- Non-uniform distribution of thermal conductivity and viscosity field due to influence of particle migration.
- Thermal boundary layer thickness reduction.
- Particle migration results in flattened velocity profile induced by Brownian diffusion and thermophoresis.
- Particle re-arrangement under shear, enhanced wettability and particle shape effect and structuring.
- Rise in value of thermal conductivity and Reynolds number of nanofluids.

IV. REVIEW OF HEAT TRANSFER ENHANCEMENT USING TWISTED TAPE

Twisted tapes are the metallic strips twisted with some suitable techniques with desired shape and dimension, inserted in the flow. Following are the main categories of twisted tape which are analyzed.
Full length twisted tape: These tapes have length equal to length of test section.

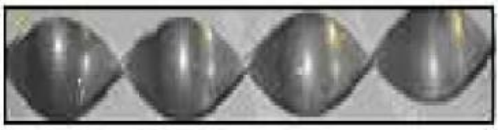

Figure 7: Full length twisted tape

Varying length twisted tape: These are distinguished from first category with regards that they are not having the length equal to length of test section, but half length, ¾ th length, ¼ th length of section etc.

Figure 8: Varying length twisted tape

Regularly spaced twisted tapes: These are short length tapes of different pitches spaced by connecting together.
Tape with attached baffles: Baffles are attached to the twisted tape at some intervals so as to achieve more augmentation.

Figure 9 Tape with attached baffles

Slotted tapes and tapes with holes: Slots and holes of suitable dimensions made in the twisted tape so as to create more turbulence.

Figure 10: Holes twisted tape

Tapes with different surface modifications: Some insulating material is provided to tapes so that fin effect can be avoided. In some cases dimpled surfaced material used for tape fabrication. Some of the common tape formats are shown in following figure.

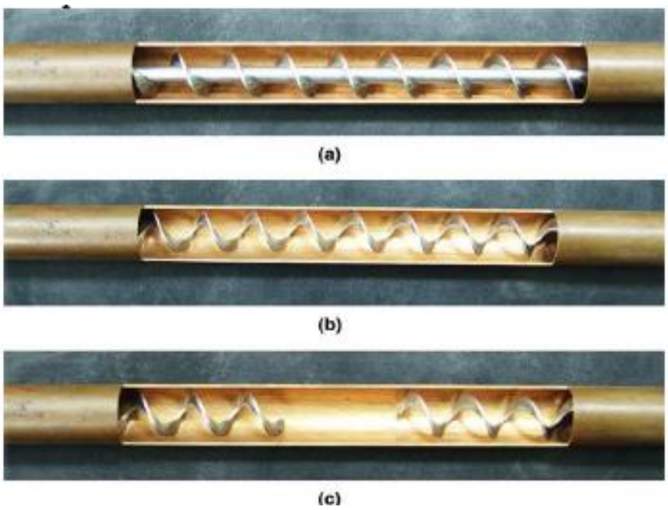

Figure 11: The inner tube fitted with various helical geometries insert:

(a) Full-length helical tape with a rod;

(b) Full-length helical tape without a rod;

(c) Regularly-spaced helical tape without a rod.

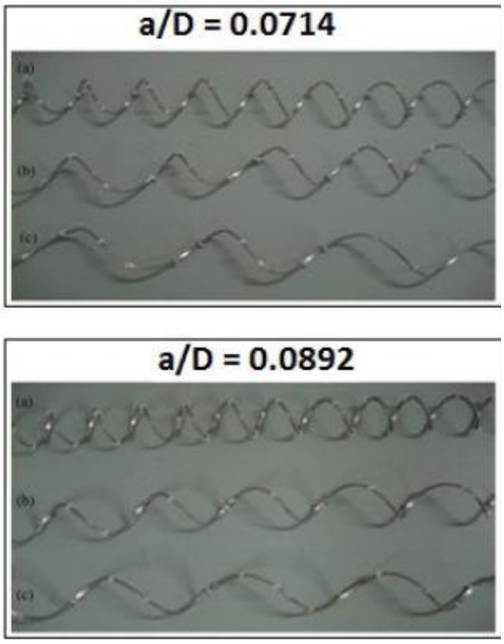

Figure 12: The coiled wire inserts with Teflon rings (a) P/D = 1, (b) P/D = 2, and (c) P/D = 3.

Common attributes of tape:

i. Width: Small width tapes are preferred to minimize pressure drop.
ii. Thickness: Thickness of the tape plays important role in its fabrication and also has contribution in fin effect
iii. Pitch: It is the distance between two consecutive twists measured axially.
iv. Twist ratio: It is the ratio of pitch of tape to tape width. So, if width of the tape considered as a constant (as found generally) twist ratio depends on pitch only. Under this condition if pitch is more it means less number of turns.
v. Fin effect: If the tape material is conductive then during the flow some heat will be absorbed by the tape material itself till its saturation. This is simply the loss of available heat energy.

V. General Arrangement For Experimental Set-Up

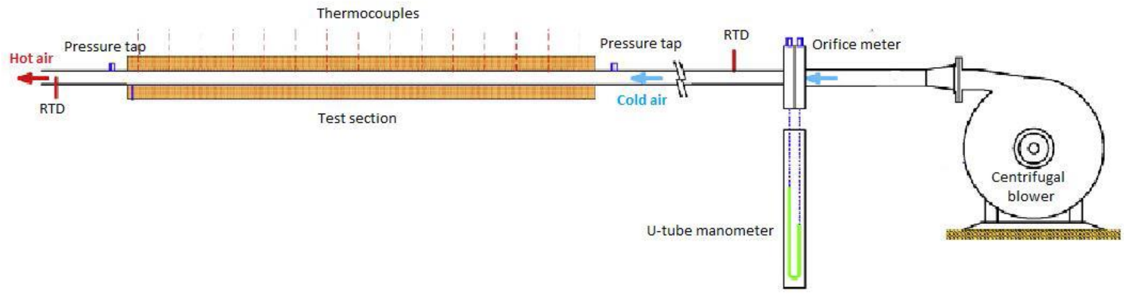

Figure 13: Typical Experimental set-up

The experimental setup consists of following main components:
1. Blower: The facility includes a blower to provide air velocity, coupled with inverter to vary air velocity. A 3 KW capacity blower is generally used. The delivery side of the blower is usually avoided as it creates eddies and suction side of the blower is generally used to avoid these eddies. A nozzle may be used to allow the air enter in the tube uniformly.
2. Venturimeter & Pressure Transmitter: It is used to measure the mass flow rate of air, and thereby velocity of air. Generally Venturimeter is fitted across the delivery side of the blower to avoid the effect of its back pressure on test section. The Venturimeter should be calibrated as per calibration process available in literature. The volumetric air flow rates from the blower can be adjusted by varying motor speed through an inverter. The pressure drop across the test tube is measured by using a differential pressure transmitter.
3. Test Section: The test section is length of tube in which wire coil inserts are to be placed and is heated from outside. The test tube length selected is 3100 mm with a coiled wire insert. The material used for test tube is SS304 seamless steel test tube and has 56 mm inner diameter (D), 60 mm outer diameter (Do), and 2 mm thickness (t).
4. Calming Tube: The Calming tube section is provided to allow the flow to be hydro-dynamically fully developed. The air vacuumed through the calming tube and then it is directed to test section. Its length as per [1] is 6000 mm. Generally its length is 10 times the hydraulic diameter of the tube.
5. Heater and Insulation: Uniform heat flux is applied to the test tube by heating it with electrical cable. The electrical output power can be controlled by a variac transformer to provide constant heat flux along the entire length of the test section. The outer surface of the test tube is well insulated with glass wool to reduce the convective heat loss to the surroundings.
6. Thermocouples and Data logging System: The surface temperatures of the tube wall is measured by many K-type thermocouples, which are placed on the local wall of the tube and should calibrated within ±0.2 °C deviation by thermostat before being used. The inner and outer temperatures of the bulk air were also measured by K-type thermocouples at certain points. The heated air in the test tube should be removed from the experimental field to the atmosphere by a piping system during the experiments. Therefore, the temperature of experimental field should not change considerably, it is negligible.

VI. Experimentation

A series of experimentation is carried out with the heat exchanger set-up. Initially the experiment is conducted without utilizing any heat transfer augmentation method (case I). Case I is set as benchmark for the analysis of other augmentation methods.
The flow rate for both hot and cold water is varied within limits, considering the capacity of the electric appliances used, and at a time both the mass flow rates are kept almost constant. Four

temperatures (cold water inlet and outlet, hot water inlet and outlet) are measured with the digital temperature indicator. The mass flow rate is measured manually with help of measuring jar and stopwatch. The same procedure is repeated for all cases by varying Inserts type and twist ratios.
Process Variables:

- Inlet temperature of Cold water
- Outlet temperature of cold water
- Inlet temperature of hot water
- Outlet temperature of hot water
- Mass flow rate

VII. DATA REDUCTION

In the experiments, the heat transfer rate in the tube is taken into account under a uniform heat flux (UHF) condition by using air as the test fluid.
The heat transfer given by the hot surface to fluid (i.e. air) at any Reynolds number is Rate at which air is heated.

$Qa = mCp (To - Ti)$

The convection heat transfer from the test section is given as

$Qc = hAs(Ts - Tm)$

At steady state condition, the heat transfer is assumed to be equal to the heat loss from the test section that can be drawn as , $Qa = Qc$
The mean temperature of the fluid in the test tube is given by

$Tm = (To + Ti) / 2$

Ts is the mean temperature of surface wall temperature of the test tube. The average wall temperature is calculated from 4 points of local wall temperatures lined between the inlet and the exit of the test tube. The average heat transfer coefficient (h) and the mean Nusselt number (Nu) are estimated by

$h = mCp (To - Ti) / hA(Ts - Tm)$

The Nusselt number in terms of average heat transfer coefficient is defined as

$Nu = hD / k$

Also, $Nu_{the} = 0.023\, Re^{0.8}\, Pr^{0.4}$
The Reynolds number is written as

$Re = \rho UD / \mu$

The experiment pressure losses, Δp across the test tube are arranged in non-dimensional form by using the following equation:

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

Also, $f_{the} = 0.25\,(1.82 * \log10\, Re_D - 1.64)^{-2}$
in which U is mean velocity in the test tube and L is the test tube length. All of thermo-physical properties of the air are determined at the overall mean air temperature (Tm).

VIII. EXPERIMENTAL RESULTS AND DISCUSSIONS

In this section, the pressure drop, friction factor characteristics, heat transfer and thermal enhancement index in a tube fitted with twisted tapes, double twisted tape and wire coil (counter/co-swirl tape) are presented.
The experiments are performed in the range of Reynolds number between 5000 and 18,000. The results obtained for the tube fitted with the single twisted tapes (ST) with three different twist ratios and the empty tube are used as the reference data for the performance evaluation of the modified tubes.

8.1 Heat transfer result

Experimental results of the Nusselt number (Nu) in plain tubes combined with a twisted tape (y/w = 3.5, 2.66, 2.25), double twisted tape (y/w = 3.5, 2.66) and wire coil (p/d = 1.17, 0.88) are presented in

Figure 14. The Nusselt numbers for the plain tube acting alone are also plotted for comparison. The data show that the Nusselt number (therefore, the heat transfer coefficient) increases with increasing Reynolds number for the conventional turbulent tube flow. This is the most likely caused by a stronger turbulence and better contact between fluid and heating wall. It is noted that the increasing Nusselt number in the plain tube in common with a twisted tapes and wire coil is caused by the generating of pressure gradient along the radial direction, and this leads to redeveloping of thermal/hydrodynamic boundary layer.

The higher increase of the Nusselt number in this style of both turbulence and swirl flows is a consequence of the higher reduction of boundary layer thickness and increase of resultant velocity.

The variations of Nusselt number with Reynolds number for three different twist ratios (y/w = 3.5, 2.66, 2.25) with wire coil of pitch ratio (p/d = 0.88) shown in figure 14. Nusselt number increases with the decrease of twist ratio and the increase of Reynolds number. The highest Nusselt number is achieved for twist ratio (y/w = 2.25) and pitch ratio (p/d=0.88).

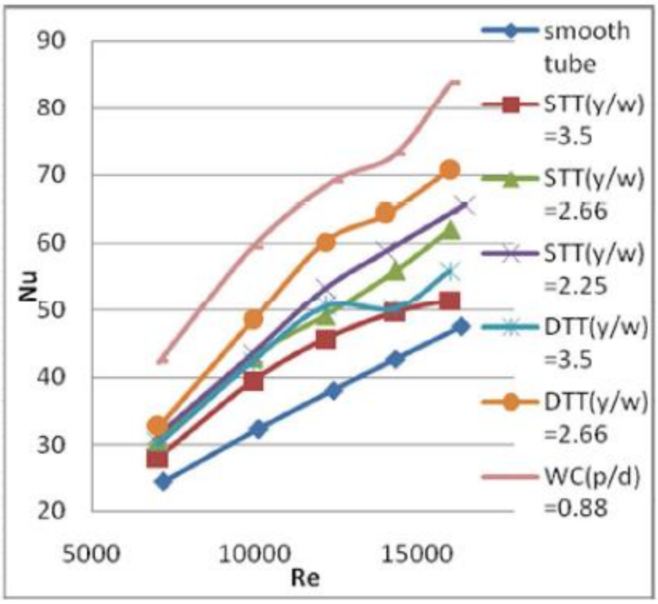

Figure 14: Variation of Nu for different inserts

8.2 Friction factor results

Experimental results of the friction factor (f) characteristics in plain tubes combined with a twisted tape (y/w = 3.5, 2.66, 2.25), double twisted tape (y/w = 3.5, 2.66) and wire coil (p/d = 1.17, 0.88) are presented in Figure 15. The friction factors of the plain tube acting alone are also plotted for comparison. Figure shows the influence of a plain tube combined with a twisted tape and wire coil on pressure loss, which indicates the friction in a heat exchanger.

The relationship between pressure loss in terms of friction factor and Reynolds number for the tube with twisted tape (STT & DTT) and wire coil inserted and also for the plain tube is presented in Figure 15. It is found that using twisted tape and wire coil gives higher friction factor values than those from the plain tube as expected. The friction factor decreases with the increase of twist ratio and Reynolds number.

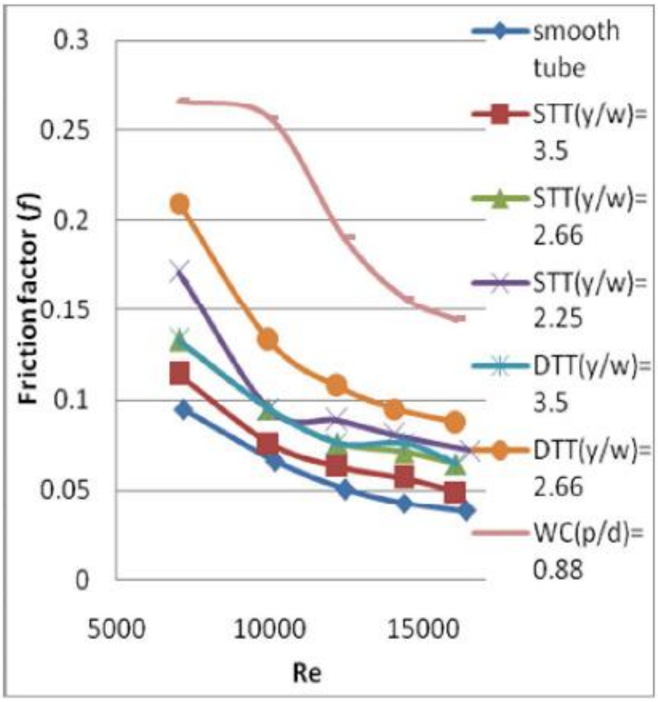

Figure 15: Variation of f for different inserts

8.3 Performance factor results

$$Overall\ Enhancement\ ratio = (Nu)/(Nu0)/(f/f0)^{\frac{1}{3}}$$

The performance analysis was made by equation and the results are shown in Figure 16. It is observed from above Fig. that the thermal enhancement index decreases with increasing Reynolds number.
The thermal evaluation is considered under constant pumping power for each twisted tape with respect to the case without twisted tape (plain tube).
The thermal performance factors for single twisted tape, double twisted tape and wire coil are presented in Figure 16. Apparently, a thermal performance factor decreases with increasing Reynolds number for all tape inserts. A larger pressure loss at a higher Reynolds number is responsible for the mentioned result. This suggests that the geometry of wire coil is more appropriate for practical use than the others in the view point of energy as well as operating cost savings.

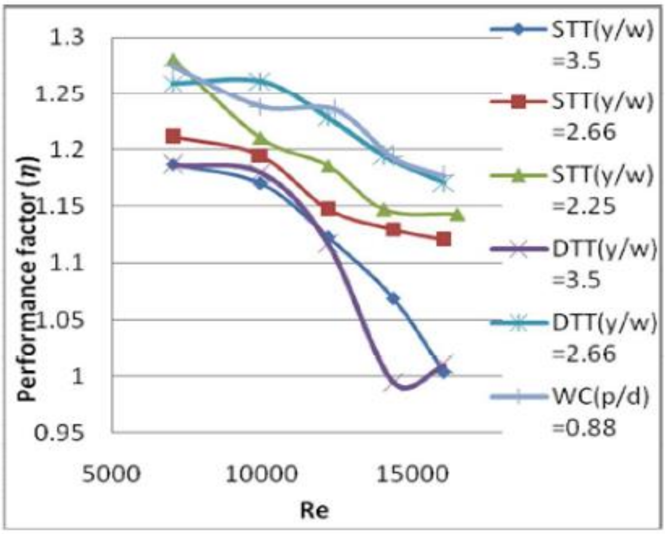

Figure 16: Variation of η for different inserts

IX. CONCLUSION

Twisted tapes mixes with bulk flow and are better for laminar flow than any other inserts. However twisted tape inserts performance also depends fluid properties such as Prandtle number .If the Prandtle number is high (Pr>30) twisted tape will not provide good thermo hydrodynamic performance compared with other inserts such as wire coil inserts. In general, twisted tape inserts and wire coil inserts are more widely applied and have been preferred in recent past than other technique probably because methods such as extended surface

Thermal characteristics in a tube fitted with twisted-tapes in co-swirl arrangement with wire coil are presented in the present study. Results shows that wire coil of pitch ratio 0.88 is more superior to all twisted tapes. In twisted tape double twisted tape act as counter swirl generator, which shows better performance than single twisted tape. The work has been conducted in the turbulent flow regime, Reynolds number from 5000 to 18,000 using air as the test fluid. The findings of the work can be drawn as follows:

1. For the inserted tube, the pressure drop tends to increase with the rise in mass flow rate while the friction factor and performance factor give the opposite trends.
2. The compound enhancement devices of the tube and the counter/co-swirl show a considerable improvement of heat transfer rate and thermal performance relative to the smooth tube acting alone, depending on twist ratios.
3. The counter/co-swirl tube yields higher friction factor and performance factor than the smooth tube at low Reynolds number.

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