EXPERIMENTAL INVESTIGATION OF THERMAL CHARACTERISTICS WITH MULTIPLE TWISTED TAPE INSERTS IN TUBULAR HEAT EXCHANGER

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ABSTRACT

The aim of this present work is to enhance thermal performance characteristics in a tubular heat exchanger by studying multiple twisted tapes in different arrangements. The tube inserted the multiple twisted tapes showed superior thermal performance factor when compared with plain tube or the tube inserted a single twisted tape, due to continuous multiple swirling flow and multi-longitudinal vortices flow along the test tube. The higher number of twisted tape inserts led to an enhancement of thermal performance that resulted from increasing contact surface area, residence time, swirl intensity and fluid mixing with multi-longitudinal vortices flow. Moreover, arrangement of twisted tapes in counter current was superior energy saving devices for the practical use, particularly at low Reynolds number. This was especially the case for quadruple counter tapes in the cross directions (CC-QTs) where heat transfer enhancement with relatively low friction loss penalty was deserved. The use of CC-QTs led to the highest thermal performance factor up to 1.33. The Nusselt number and friction factor increased to 2.28 times and 9.8 times of those in the plain tube.

Keywords: Heat Transfer Enhancement, Dual/Triple/Quadruple Twisted Tapes, Multiple Swirl Flows, Heat Exchanger.

I INTRODUCTION

Several heat transfer enhancement (HTE) techniques have been used in many engineering applications such as nuclear reactor, chemical reactor, chemical process, automotive cooling, refrigeration, and heat exchanger, *etc*. HTE techniques are powerful tools to increase heat transfer rate and thermal performance as well as to reduce of the size of heat transfer system in installing and operating costs. HTE techniques can be classified into 2 categories; (1) active method: by supplying external power source to the fluid or the equipment; (2) passive method: by turbulence promoter (such as special surface geometries, twisted tape, propeller, tangential inlet nozzle, snail entry, axial/radial guide vane, spiral fin) or fluid additives (such as nanofluid), without using any direct external power source. Due to its easy installation/operation and cost saving, passive method has drawn great attention.

One important group of devices used in passive method is swirl flow devices which produce secondary recirculation on the axial flow leading to an increase of tangential and radial turbulent fluctuation. This allows a greater mixing of fluid inside a heat exchanger tube and subsequently reduces a thickness of the boundary layer [1]. Among the swirl generators of tube inserts, twisted tapes have gained great attention and widely used for producing compact heat exchangers and upgrading the heat transfer rate of the existing heat exchanger due to its low cost, acceptable thermal performance and ease of manufacture installation [2]. Twisted tapes are generally equipped along the core tube to generate swirl causing the fluid transfer between the core tube and near wall tube. This leads to several mechanisms for heat transfer

augmentation by improving flow velocities caused by partial blockage of the tube flow, which directs toward reducing the hydrodynamic or thermal boundary layer thickness. The hydraulic diameter reduction results in greater heat transfer coefficient, lengthening flow path in consequence of a helically twisting fluid motion, improving fluid mixing and thinning thermal boundary layer. However, more pumping power is required when twisted tapes are equipped inside the tube. Therefore, economic consideration has to be taken into account by using twisted tape with a proper geometry.

Nomenclature:

A	heat transfer surface area, m2		**Greek Symbol**
D	inside diameter of test tube, m	δ	Tape thickness, m
f	friction factor	η	Thermal performance factor
h	heat transfer coefficient, W m-2K-1		
L	length of test section, m		**Abbreviations**
Nu	Nusselt number		
ΔP	pressure drop, Pa	ST	single tape as single swirl flow generator
Pr	Prandtl number	Co-DTs	dual co-tapes as co-dual swirl flow generators
Q	Heat transfer rate, W	C-DTs	dual counter tapes as counter-dual swirl flow generators
T	Temperature, OC		
W	Tape width, m	Co-TTs	triple co-tapes as co-triple swirl flow generators
y	Pitch length of twisted tape, m	C-TTs	triple co-tapes as counter -triple swirl flow generators
y/W	Twist ratio		
		Co-QTs	quadruple co-tapes as co-quadruple swirl flow generators
Subscripts		CC-QTs	quadruple counter tapes as counter-quadruple swirl flow generators
b	bulk	PC-QTs	quadruple counter tapes as parallel-quadruple swirl flow generators
i	inlet		
o	outlet		
p	plain tube		
t	twisted tape		
w	wall		

II LITERATURE REVIEW

Since Whitham et al. [1] reported the success of using twisted tapes in improving heat transfer in heat exchanger, heat transfer enhancement using the devices have been extensively studied. In particular, the modifications of twisted tape have been continually released. Recently, many research groups modified various types of twisted tapes. They found that the geometries of twisted tapes have significant influences on fluid mixing and heat transfer rate [3-6]. The modified edges or centre of twisted tapes have been proposed to induce stronger turbulence intensity in the vicinity of tube wall or the core of tube. Rahimi et al. [7] numerically evaluated heat transfer enhancement by modified twisted tapes including jagged perforated and notch twisted tapes. Their results revealed that among the studied twisted tapes, jagged twisted tape possessed the best performance with 31% higher heat transfer rate and 22% higher thermal performance factor compared to those of typical twisted tape. Sivashanmugam and Suresh [8-11] compared the heat performance and pressure drop of full length helical twisted and the helical twisted with spacer length in laminar and turbulent flow region, and found that the tape with spacer length within 10% of the entire length could preserve heat transfer augmentation and decrease pressure drop simultaneously. Krishna et al. [12] reported that the twisted tape with twist ratio of 4 and width of 1 inch provided an appreciable heat transfer enhancement when space length was kept below 2 inches. The experimental results reported by Sivashanmugam et al. [13-14] showed that right-left helical screw inserts exhibited a

superior heat transfer enhancement to straight helical twist at the same twist ratio. Later, the helical and left-right twisted tapes were used in thermosyphon solar water heating system to enhance heat transfer and thermal performance [15]. Moreover, Nagarajan et al. [16] reported that the geometries of left-right twisted tapes played an important role in governing heat transfer, friction factor and thermal performance. Jaisankar et al. [17] employed typical twisted tapes with different twist ratios (3.0–5.0) in a solar water heater, and found that the tape with a smaller twist ratio provided higher heat transfer enhancement as well as friction factor due to a stronger swirl flow intensity.

Eiamsa-ard et al. [18] investigated the effect of coupling twisted tapes on heat transfer enhancement in a heat exchanger. The studied parameters were: (i) twisted tape orientation; co twisted tapes (co-CTTs) and counter twisted tapes (counter-CTTs); (ii) width ratio; (iii) twist ratio. The experimental results revealed that heat transfer, friction loss and thermal performance factor increased with decreasing twist ratio and increasing width ratio. Three different arrangements were determined: (1) the wing-tips pointing upstream of the flow (TTW-up, twin delta-winged twisted tape in counter-flow arrangement) (2) the wing-tips pointing downstream of the flow (TTW-down, twin delta-winged twisted tape in co-flow arrangement) and (3) the wing-tips pointing opposite direction (TTW-o, opposite winged twisted tape). At similar conditions, TTW-up gave the highest Nusselt number, friction factor and thermal performance factor, followed by TTW-o and TTW-down. The TTW-up with wing-tip angle of 20° gave the maximum thermal performance factor of 1.26 along with the Nusselt number and friction factor of 2.57 and 8.55 times compared to those of the plain tube.

According to the above review, it has been proven that the heat transfer enhancement by using twisted tape is a promising approach. However, the influences of the geometries of twisted tape on heat transfer enhancement, friction factor and thermal performance characteristics and nanoparticles are limited explored. To extend the study in the field of heat transfer enhancement by compound technique, this work introduces the use of modified twisted tapes (dual, triple, quadruple twisted tapes) with water as base fluid. The study encompasses Reynolds number from 5000 to 25,000.

III DUAL/TRIPLE/QUADRUPLE TWISTED TAPES

The schematic view and details of the single, dual, triple and quadruple twisted tapes with different arrangements are shown in Fig. 1(a &b) and Table 1. All twisted tapes were made of aluminium strip with a thickness of 0.8 mm, which is a minimum twisting operation, and a length of 1000 mm. To fabricate a twisted tape, one end of a straight tape was clamped while another end was carefully twisted to achieve a desired twist length. Single twisted tape was 19 mm in width while dual, triple and quadruple twisted tapes were 8 mm in width. The tapes were formulated at constant twist ratio (y/W) of 3 where twist ratio is defined as twist length (180°/twist length) to tape width (W). For dual, triple and quadruple twisted tapes, each tape was individually twisted and subsequently welded together. In the experiment, the swirl direction corresponding to tape arrangement was designed as: (i) co-swirl flow; all tapes were aligned to be twisted in the same direction. In this case, dual, triple and quadruple twisted tapes were assigned as Co-DTs/Co-TTs/Co-QTs, respectively, (ii) counter-swirl flow; this arrangement was designed for dual and quadruple twisted tapes. In the case of dual twisted tapes, two tapes were aligned to be twisted in opposite directions and assigned as C-DTs. In the case of quadruple twisted tapes, two tapes were aligned to be twisted in the same direction which was opposite to that of other two tapes. In addition, the quadruple counter tapes consisting of two pairs of tapes were in two different arrangements, to produce (1) parallel counter-swirl flow and (2) cross counter-swirl flow. For parallel counter-swirl flow, the tapes in each pair produced swirl flow in the same direction; in this case the quadruple counter tapes were

assigned as PC-QTs. For cross counter-swirl flow, the tapes in each pair produced swirl flow in the opposite directions. The quadruple counter tapes were assigned as CC-QTs.
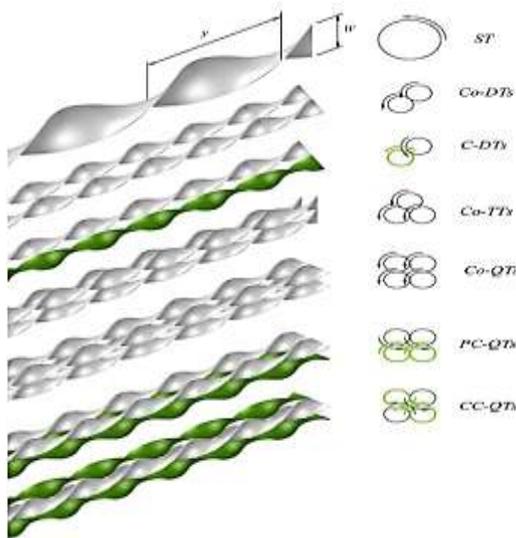

| Fig.1(a) | Fig.1(b) |

Table 1 Details of twisted tape inserts

Twisted tape	ST	Co-DTs	C-DTs	Co-TTs	C-TTs	Co-QTs	PC-QTs	CC-QTs
(a) Number of tape	1	2	2	3	3	4	4	4
(b) Tape width (W)	19 mm	8 mm	8 mm	7.5 mm	7.5 mm	7 mm	7 mm	7 mm
(c) Tape pitch length (y)	90 mm	40 mm	40 mm	37.5 mm	37.5 mm	35 mm	35 mm	35 mm
(d) Twist ratio (y/W)	5	5	5	5	5	5	5	5
(e) Tape thickness (δ)	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm
(f) Material	Al	Al	Al	Al	Al	Al	Al	Al
(g) Swirl type	S–S	Co D-Ss	Counter D-Ss	Co T-Ss	Counter D-Ss	Co Q-Ss	Counter Q-Ss in P-A	Counter Q-Ss in C-A

IV EXPERIMENTAL STRATEGY

For this research work, the experimental setup fabricated is totally unique setup build for the investigation of performance of multiple twisted tape inserts. The different component of experimental setup are selected cautiously so that the component give the accurate performance. A specification of the present experimental setup is given in following table 2

Table 2 Specification of the Experimental Setup

Sr No	Equipment Name	Dimension Range / Capacity	Remark
1	Test Section(Copper Tube)	Length= 1m, ID= 18mm , OD= 23mm	
2	Nichrome Wire Heater	3 kW, 20 Gauge, 240V, 5A	Surface Temp=550^{0}C
3	Insulation (Ceramic wool)	Thickness=20mm	K=0.12 W/mk
4	Differential Manometer	0 to 500 mm	Least Count= 1 mm
5	Pump	0.5HP	
6	Thermocouple(K Type)	0^{0}C to 1260^{0}C	Least Count= 0.1^{0}C
7	Rotameter	2 L/min to 20 L/min	Least Count= 0.5 l/min
8	Storage Tank	25Litre	

The experimental setup consists of a test section, a chiller, a storage tank, and a variable displacement pump with a by-pass valve arrangement, temperature indicator, flow meter and a differential manometer. The Schematic diagram of the proposed experimental setup is shown in Fig2.
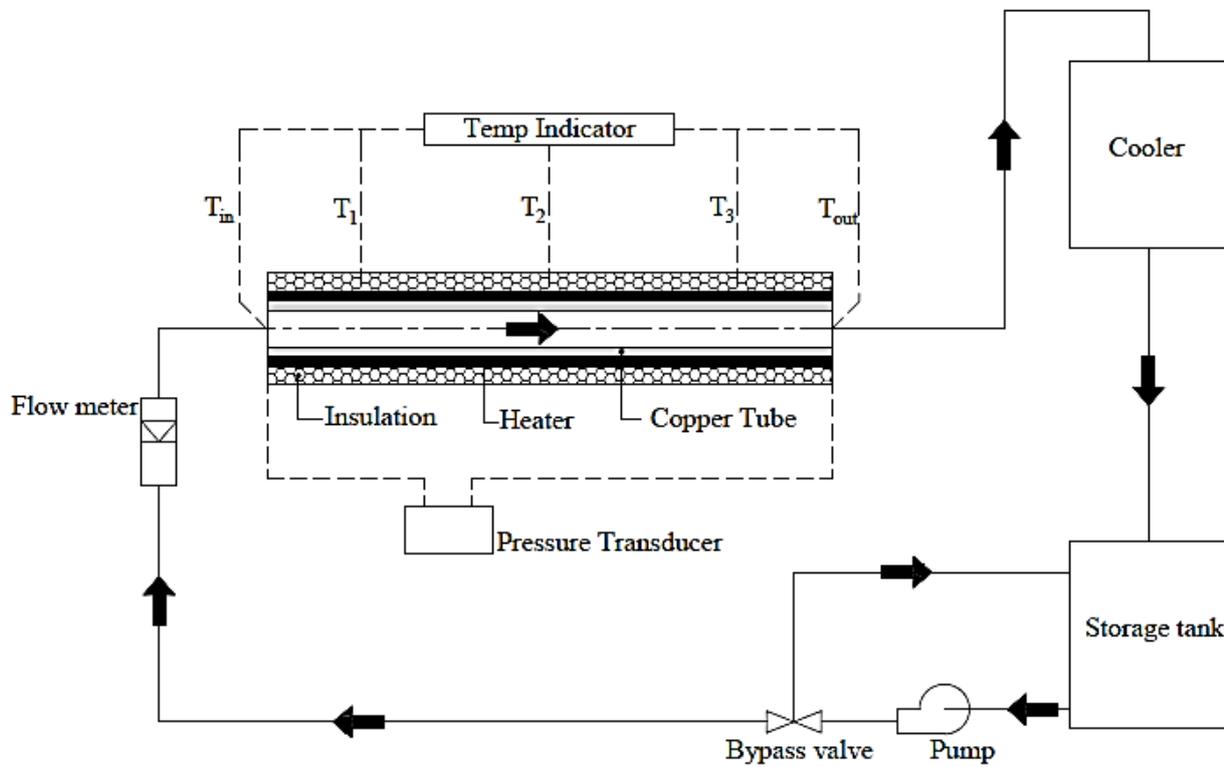
Fig2. Experimental Set-Up

Fig 2. Shows the photographic image of experimental setup fabricated for this dissertation. Test section consist of copper tube of 1m length having 20mm and 23mm inside and outside diameter respectively. Nichrome wire is wound on outer periphery of copper tube. Nichrome wire is properly insulated so that current will not pass to the copper tube and other components. Several thermocouples are provided, in which two are used to record the inlet, outlet temperatures of the working fluids and the remaining thermocouples are brazed on the outer periphery of the test section of the tube, to measure the average surface temperature of the tube. Pressure drop across the test section is measured by providing differential manometer. Copper tube along with Nichrome heater is thermally insulated to avoid heat loss to the environment. Test section is covered with metallic sheet to protect it from physical damage. The aspect ratio of the test section is sufficiently large for the flow to be hydro-dynamically developed.

The working fluid under investigation is forced through the test section with pump connected to the sufficient capacity of storage tank. The fluid is heated by receiving heat from the test section and is allowed to cool by passing it through an evaporative cooler. By recirculation, the chiller in the flow loop helps in achieving steady state condition faster. PUC pipes are used to transfer of fluid. Flow meter is incorporated in order to measure flow rate of working fluid.

Temperature indicator with 0.1^0C least count is used to indicate temperature readings of various thermocouples provided at different positions of test section. The physical properties of fluid flowing inside the tube of test section is assumed to be constant along the length and evaluated at the average bulk temperature for each run.

V RESULTS AND DISCUSSION

The experimental and numerical results of heat transfer enhancement by using dual, triple and quadruple twisted tapes as tube inserts and water as the working fluids, are reported in this section. The results of the plain tube and the tube with the single twisted tapes are also presented.

5.1 Verification of the plain tube with/without typical twisted tape

To gain confidence on experimental data throughout the research, the experimental data of the plain tube with water as the working fluid were firstly compared with those from the open literatures [19] which are Dittus–Boelter and Gnielinski correlations for Nusselt number and Blasius and Petukhov correlations for the friction factor.
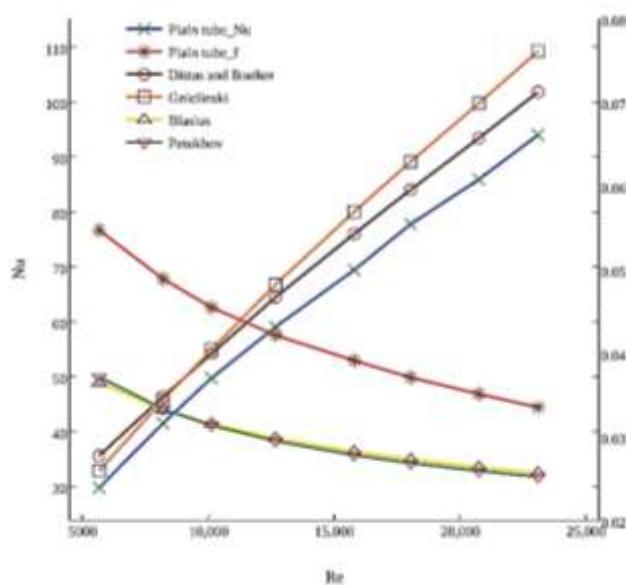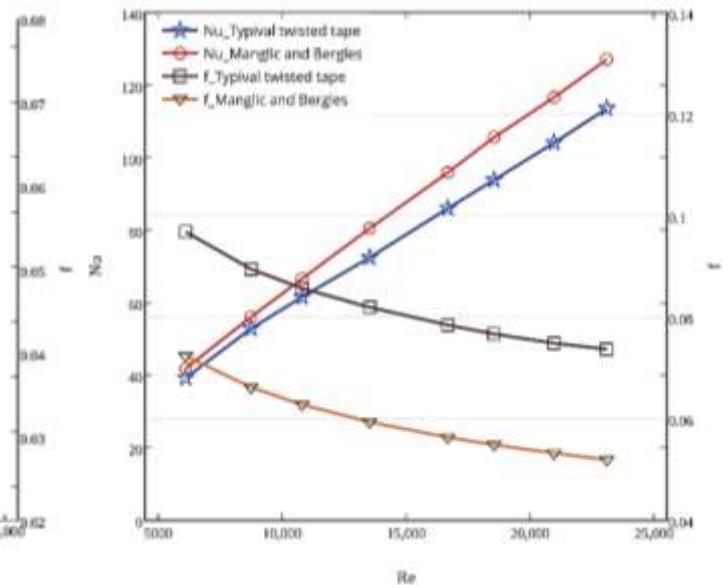
Fig. 3 (a)   Fig. 3 (b)

Verification of the heat transfer and friction in the plain tube is shown in Fig. 3(a). The experimental Nusselt number was in satisfactory agreement, the mean experimental Nusselt number of plain tube were respectively 9% and 12% lower than that of the Dittus-Boelter and Gnielinski correlations. Experimental meanfriction factors of plain tube were respectively 42% and 43% higher than that of the Blasius and Petukhov correlations. Fig. 3(b) shows the comparison between the experimental data of the present plain tube equipped with the typical/single twisted tape and those from the correlations of Manglik and Bergles[20]. Evidently, mean Nusselt number and friction factor of the tube with the typical/single twisted tape (ST) were respectively 9.65% lower and 37.9% higher than those of Manglik and Bergles equation. According to the comparative results mentioned above, it can be concluded that the present facility was reliable and experimental data was accurate enough. These provide a strong confidence in the present investigation of the heat transfer and flow friction in the tube equipped with dual/triple/quadruple twisted tapes.

Nusselt number correlations for the plain tube:

Correlation of Dittus-Boelter:

$$Nu = 0.023 Re^{0.8} Pr^{0.4}$$

Correlation of Gnielinski:

$$Nu = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)}$$

Friction factor correlation for the plain tube:

Correlation of Petukhov:

$$f = (0.79 \ln Re - 1.64)^{-2}$$

Correlation of Blasius

$$f = 0.318 \, Re^{-0.25}$$

Nusselt number correlations for the typical twisted tape of Manglic and Bergles

$$Nu = \left[1 + \frac{0.769}{\left(\frac{y}{w}\right)}\right]\left[0.023 Re^{0.8} Pr^{0.4}\left(\frac{\pi}{\pi - \frac{4\delta}{D}}\right)^{0.8}\left(\frac{\pi + 2 - \frac{2\delta}{D}}{\pi - \frac{4\delta}{D}}\right)^{0.2}\right]\left(\frac{T_b}{T_w}\right)^{0.45}$$

Friction factor correlation for the typical twisted tape of Manglic and Borgles:

$$f = \left[1 + 2.06\left(1 + \left(\frac{2\left(\frac{y}{w}\right)}{\pi}\right)^2\right)^{-0.74}\right]\left[0.079 Re^{-0.25}\left(\frac{\pi}{\pi - \frac{4\delta}{D}}\right)^{1.75}\left(\frac{\pi + 2 - \frac{2\delta}{D}}{\pi - \frac{4\delta}{D}}\right)^{1.25}\right]$$

5.2 Effect of multiple twisted tapes

5.2.1 Heat transfer

The heat transfer of tubes equipped with tape insert(s) presented in terms of Nusselt number (Nu_t) and Nusselt number ratio (Nu_t/Nu_p), where Nu_p is Nusselt number for the plain tube, is shown in Fig. 4 (a) and (b). For the present work, the Reynolds number is available over the range 5000–25,000 and water was used as the working fluid. Fig. 4(a) shows that Nusselt number considerably increased with increasing Reynolds number. This was attributed to a stronger turbulent intensity and thus a better fluid mixing. At a given Reynolds number, Nusselt number in the tube with single/dual/triple/quadruple twisted tapes was significantly higher than those in the plain tube. This is responsible by the induction of multiple swirl flows, resulting in thinner boundary layer. Fig. 4(b) shows that Nusselt number ratio (Nu_t/Nu_p) slightly decreased with increasing Reynolds number. This can be explained that at lower Reynolds number, a thermal boundary becomes thicker; therefore the swirl flows induced by twisted tapes possess more significant effect on disruption of thermal boundary. Moreover, a higher number of tape inserted in the tube consistently possessed higher Nusselt number. The tube with quadruple twisted tapes (QTs) provided the highest Nusselt number over the entire Reynolds number range. That is, Nusselt number of QTs was 24–29%, 49–54%, 71–74%, 106–129%, higher than those of the tubes with triple twisted tapes, dual twisted tapes, single twisted tape and the plain tube alone, respectively. This can be explained by the fact that more tapes induce higher

number of swirl flows imparted to an axial flow, resulting in more uniform fluid mixing between the core and the tube wall regions, throughout the tube.
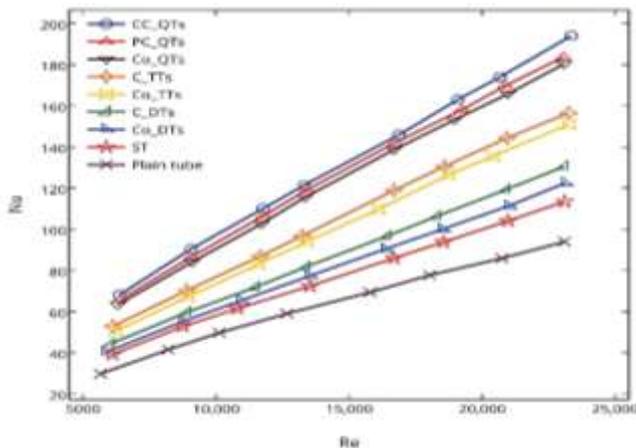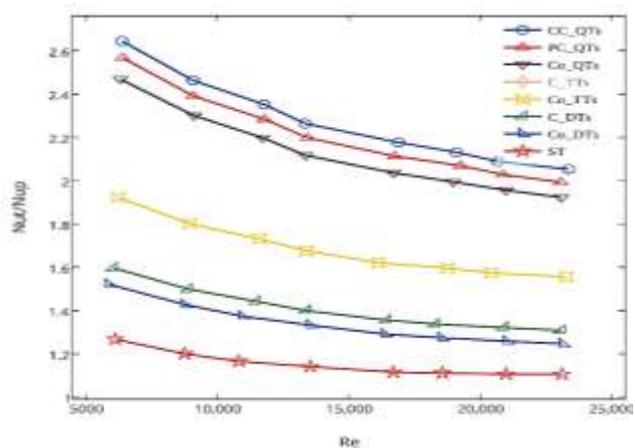

Fig. 4 (a)

Fig. 4 (b)

5.2.2. Friction loss

The friction loss of tubes equipped with tape inserts presented in terms of friction factor (f_t) and friction factor ratio (f_t/f_p), where f_p is friction factor for the plain tube, is shown in 5. For all the cases, friction factor slightly decreased Fig. 5(a) while friction factor ratio (f_t/f_p) slightly increased Fig 5 (b) with increasing Reynolds number. The effect of twisted tape on friction factor was found that friction factors generated in the tube with tape insert(s) were considerably higher than those in the plain tube. In addition, multiple-tapes inserts (dual/triple/quadruple twisted tapes) consistently caused higher friction factor than the single one. This is directly responsible by the larger surface area of the inserts which perturbed the flows within the tubes. Moreover, an increase of swirl flow number boosted the interaction of the pressure forces with inertial forces in the boundary layer. Therefore, the highest mean friction factors were observed in quadruple twisted tapes. For co-swirl arrangement, friction factors over Co-QTs were 2.0 and 1.33 times higher than for Co-DTs (co-dual twisted tapes) and triple twisted tapes, respectively. For counter-swirl arrangement, CC-QTs generated 1.96 and 1.34 times more friction factors than C-DTs (counter-dual twisted tapes) and C-TTs respectively. The influence of multiple-tape inserts on friction factor ratio (f_t/f_p) was similar to that on friction factor (f_t). The CC-QTs gave the highest friction factor with the maximum friction factor ratio (f_t/f_p) of about 9.83.
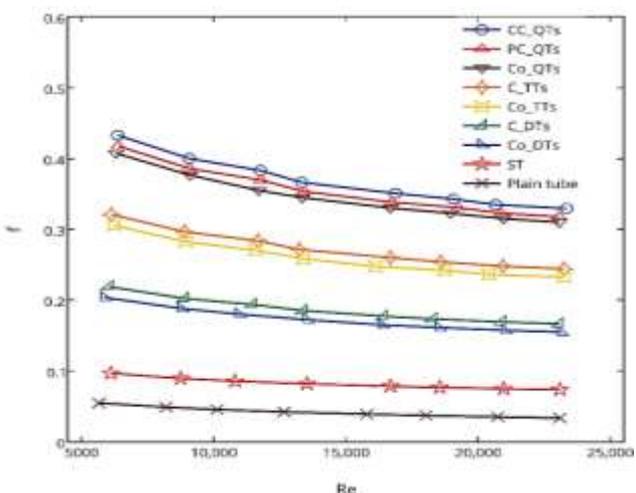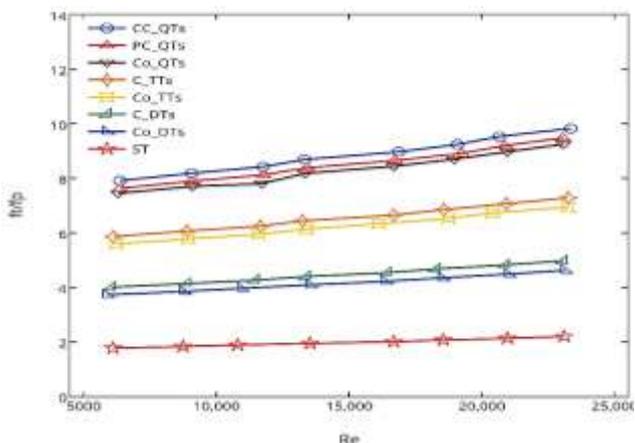

Fig. 5 (a)

Fig. 5 (b)

5.2.3. Thermal performance factor

Fig. 6demonstrates the thermal performance factors (η) of tubes with tape inserts, which compromises between the heat transfer and friction loss. For a net energy gain, the value of the thermal performance factor is greater than unity. The results revealed that thermal performance factor decreased when Reynolds number increased. This implies the benefit of using tape inserts at lower Reynolds number rather than at higher Reynolds number. For a given Reynolds number, thermal performance factor increased as the number of tape inserts increased. It can be mentioned that the heat transfer enhancement by tape inserted reflects an overwhelming of increased friction loss. The thermal performance factors of the tubes with quadruple, triple and dual twisted tapes varied between 0.96-1.33, 0.82-1.13, and 0.77-1.01, respectively. In other words, quadruple and triple twisted tapes respectively gave 13-27%, (-3)-8% higher thermal performance factors than the single tape, whereas dual twisted tapes gave 4-10% lower thermal performance factors than the single tape.
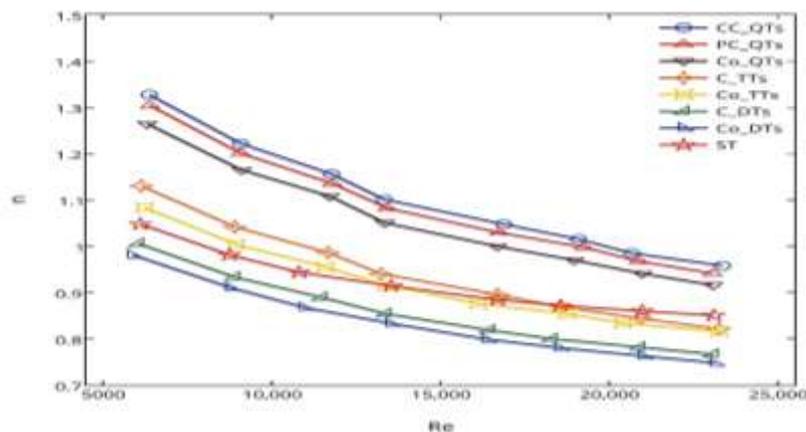

Fig 6

5.3. Effect of co-/counter tape arrangement

5.3.1. Heat transfer

The effect of co-/counter tape arrangement on heat transfer enhancement can be observed from Fig. 4 (a) and (b). The tapes in counter arrangement consistently yielded higher Nusselt number than that in co-arrangement (Nu of C-DTs > Nu of Co-DTs and Nu of CC-QTs and PC-QTs > Nu of Co-QTs). Nusselt number of C-DTs was 6.5-10.1% higher than those of Co-DTs. For quadruple twisted tapes, Nusselt number of CC-QTs and PC-QTs was respectively 5.1-7.6% and 1.9–3.8% higher than those of Co-QTs. Comparing the heat transfer enhancement in counter arrangement of QTs indicated that Nusselt number of CC-QTs was 5.6–3.7% higher than that of PC-QTs.

5.3.2. Friction loss

The effect of co-/counter tape arrangement on friction loss is shown Fig 5 (a) and (b). For dual twisted tapes, C-DTs consistently caused higher friction factor than Co-DTs due to a higher Nusselt number reflecting to the pressure forces, as similarly explained in Section 6.2.2. The friction factors of C-DTs were 7.5% higher than those of Co-DTs. That is, the friction loss increased in the order CC-QTs > PC-QTs > Co-QTs. The friction factors of CC-QTs were 2.5% and 6.3% higher than those of PC-QTs and Co-QTs, respectively. In other words, friction factors of CC-QTs were 3.7% higher than those of PC-QTs.

5.3.3. Thermal performance factor

The effect of co-/counter tape arrangement on thermal performance factor at the same pumping power is shown in Fig. 6. Apparently, the tapes in counter arrangement possessed higher thermal performance factors than that in co-arrangement. Therefore, it can be mentioned that in a case of DTs the heat transfer enhancement by C-DTs reflects an overwhelming of increased friction loss. With a tubes equipped with QTs, the highest thermal performance of 1.33 was observed for CC-QTs due to their excellent heat transfer enhancement with relatively low friction loss penalty. This highlights the important role of CC-QTs in improving the performance. In addition, it can be noted that the counter tape arrangement in all cases was superior energy saving devices for the practical use, particularly at low Reynolds number.

V CONCLUSIONS

The influences of multiple twisted tapes with a co- or counter arrangements *(*e.g., ST, Co-DTs, Co-TTs, Co-QTs, C-DTs, PC-QTs, CC-QTs) and water as a working fluid on heat transfer enhancement are described in this study. The experimental results are compared with the tube equipped with plain tube and typical twisted tape inserts. The conclusions are drawn below:

➢ Nusselt number, friction factor and thermal performance factor increased as a number of tapes increased.

➢ The tapes in counter arrangement provided higher thermal performance factor than that in co-arrangement, Interestingly, CC-QTs exhibited superior twisted tape which delivers not only high Nusselt number but also high thermal performance factor.

➢ Over the range of Reynolds number 5000–25,000, Nusselt number in tubes with the Typical TT, Co-DTs, C-DTs, Co-TTs,C-TTs, Co-QTs, PC-QTs and CC-QTs was, respectively, 20.6-31.7%, 30.4-35.3%, 38.8-49.0%, 60.7-70.1%, 66.5-77.8%, 91.9-112.9%,95.5-120.6%, 128.8-106.4%, higher than that of the plain tube. The enhanced Nusselt number was accompanied with friction factors around 1.8-2.2, 3.7-4.6, 4-5, 5.6-6.9, 5.9-7.3, 7.4-9.3, 7.6-9.5, 7.9-9.8, times over that of the plain tube.

➢ Thermal performance factors for Typical TT, Co-DTs, C-DTs, Co-TTs, C-TTs, Co-QTs, PC-QTs and CC-QTs, were found to 0.96-1.33, 0.94-1.30, 0.92-1.26, 0.82-1.13, 0.82-1.08, 0.77-1.01, 0.75-0.98, 0.85-1.05, respectively.

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