FLUID FLOW AND HEAT TRANSFER ENHANCEMENT IN WINGS WITH COMBINED SOLID RING TWISTED TAPE INSERTS CIRCULAR HEAT EXCHANGER TUBE

by

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Experimental examination is carried out to study the turbulent heat transfer and fluid-flow characteristics in circular heat exchanger tube using combined wing with solid ring twisted tape inserts. A series of experiments has been performed with the range of Reynolds number varied from 3000 to 21000, number of twisted taped inserts, N_{TT}, varied from 1.0 to 4.0 with constant value of other twisted tape parameters such as rings pitch ratio, $d_R/D_T = 1.0$, wing pitch ratio, $P_W/W_T = 3.0$, and wing depth ratio, $W_d/W_T = 1.67$. Based on the examined, turbulent heat transfer and fluid-flow in wing with combined solid ring twisted tape inserts results are compared with plain circular tube under same operating conditions. The experimental results show that the heat transfer is increased around 5.66 times than plane circular heat exchanger tube. The thermal and hydrodynamic performance parameter based on equal pumping power, η_p, was found to be highest for $N_{TT} = 3.0$. The optimum value of thermal and hydrodynamic performance has been found to be 2.74 for Reynolds mumber of 3000 within the range of the parameters investigated. Multiple wings with solid rings twisted tape inserts have been also shown to be thermally as well as hydraulically better in comparison to other similar twisted tape insert geometries.

Key words: *heat transfer enhancement, multiple twisted tapes, twists ratio, wing pitch ratio, wing depth ratio and solid rings*

Introduction

The heat exchanger tubes (HET) are the core components enriched with various insert geometries to enhance heat transfer rate in most of the mechanical and thermal equipment's used in engineering devices to industrial and house hold appliances [1-3]. In the present scenario many studies have been carried out with the aim of energy saving by minimize the size, cost and power consumption of various heat exchanger techniques [4-6]. The compact and geometrically enriched heat exchanger with various inserts was found an efficient way to enhance the

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performance and efficiency of various equipment's [7-9]. The HET equipped with twisted tape (TT) inserts are widely employed techniques to enhance heat transfer rate and always perform better than plane tube [10, 11]. To promote better fluid mixing, turbulence is generated near the wall giving rise to more velocities near the boundary-layer and consequently enhances the heat transfer rate. The contribution of many researchers has been reported for the development of effective heat exchanger techniques to enhance passive heat transfer rate [12, 13].

Akhavan-Behabadi *et al.* [14] experimentally studied seven diverse coiled wires inserts with H_{TT} ratios varies from 12.0 mm to 69.0 mm and diameters was taken 2.0 mm and 3.50 mm. Meng *et al.* [15] investigated the f_{TT} performances in DDIR tube was used to solve the field synergy equation numerically. The experimental results showed that the DDIR tube inserts has better comprehensive h_{TT} performance than the current h_{TT} enhancement tubes.

Gawandare *et al.* [16] experimentally investigated the h_{TT} and f_{TT} characteristics of circular tube fitted with full length copper square jagged TT inserts. They revealed that there is a noteworthy h_{TT} augmentation due to TT inserts. Al-Fahed *et al.* [17] carried out an experimental investigation to study and compare the results of h_{TT} coefficients and pressure drop for a plain tube, micro fins and TT inserts in laminar flow section. The maximum values of h_{TT} were obtained for TT inserts having y_{TT} 3.60 and 5.40 than that of loose fit TT inserts. Suri *et al.* [18] reviewed the various circular tube equipped with a variety of TT insert techniques on heat transfer enhancement. They showed that multiple TT inserts better heat transfer enhancement as compared other single TT insert HET. Kongkaitpaiboon *et al.*[19] experimentally investigated the influences of the PCR on the turbulent convective Nu_{TT}, and η_p. Promvonge *et al.* [20] investigated the devices consisted of the TT inserts with constant or cyclically changing pitch ratio, H_{TT}, of the wire coil inserts.

Zhang *et al.* [21] performed a numerical analysis of 3-D turbulence stream to study Nu_{TT} and fluid-flow characteristics for helical screw tape inserts without core rod inserts. Shabanian *et al.* [22] performed an experimental and computational analysis to study f_{rs}, Nu_{rs} and η_{rs} characteristics of an air cooled HET fitted with three different types of tape inserts. These inserts included classic, butterfly and jagged TT. Krishna *et al.* [23] investigate various Nu_{TT} enhancement techniques. They investigated that the heat enhancement in helical and left-right TT collectors was better than the plain circular tube collector. Eiamsa-ard *et al.* [24] carried out a comparative experimental study of Nu_{TT}, f_{TT}, and η_{rs} factor in a HET fitted with regularly spaced TT inserts. Jaisankar *et al.* [25] experimentally investigated the performance of Nu_{TT}, f_{TT}, and η_p characteristics of solar heater water tube equipped with TT inserts with different y_{TT}. Jaisankar *et al.* [26] performed experimental study to investigate the behaviour of Nu_{TT}, f_{TT} and η_p for thermosyphon solar water heating system equipped with helical and left-right TT.

Eiamsa-ard and Promvonge [27] investigated Nu_{TT} and f_{TT} characteristics for turbulent flow rate through a HET equipped with straight tape with double sided delta wings inserts and *T-W* with alternate axis. Seemawute and Eiasma-ard [28] carried out an experimental investigation to study the behaviour of h_{TT} characteristics for turbulent flow through a circular tube with peripherally-cut TT inserts with an alternate axis. Eiamsa-ard *et al.* [29] carried out comparative experimental study on Nu_{TT} enhancement for a round tube equipped with single TT inserts, full length dual and regularly spaced dual TT inserts under uniform wall heat flux conditions. Murugesan *et al.* [30] carried out an experimental analysis to study the behaviour of h_{TT}, η_p factor and f_{TT} characteristics in a plain circular tube and circular tube with V-cut TT inserts.

It has been seen that no study is available in which effect of wing with combined solid ring TT inserts circular HET has been investigated. In the present investigation, it has been planned to experimentally study the effect of variation in N_{TT} of circular HET. With the focus on circular HET, the Re_{TT} ranging from 3000-21000 is selected. The effect of number of TT inserts on thermal and hydrodynamic performance is experimentally studied. The optimum value of number of TT inserts circular heat exchanger parameters have been determined and discussed.

Twisted tape geometry and parameters range

Wings with combination of solid ring TT inserts HET are tested and number of TT inserts are compared in the experimental work. The geometrical dimensions of TT inserts HET are listed tab. 1 and figs. 1 and 2. The geometrical parameters for the HET with wings with combination solid ring TT inserts are diameter of tube, D_T, width of tape, W_T, pitch between wings, P_W, and wing depth, W_d. Dimensionless parameters expressed as rings pitch ratios, d_R/D_T, wing pitch ratios, P_W/W_T, and wing depth ratios, W_d/W_T.

Table 1. Geometrical parameter with range

Name of parameters	Range
N_{TT}	1.0-4.0
d_R/D_T	1.0
P_W/W_T	3.0
W_d/W_T	1.67
Re	3000-21000

Experimental details

An experimental investigation is carried out by fabricating the setup as per the ASHARE standards. A GI Pipe of 68 mm outer and 65 mm inner diameter is used to fabricate the setup. The dimensions of different setup sections viz. entry, test and exit section are 2.5 m, 1.4 m, and 1.5 m, respectively. A 3 HP, centrifugal blower is attached to the exit section for suction of air through the test section. The test section is provided by uniform heat flux of 1000 W/m^2 with a heating element and Variac transformer. The experimental set-up is equipped with sixteen thermocouples arranged in series, twelve for monitoring the temperature of tube wall and three for monitoring the variation of fluid temperature of test section at inlet and outlet. A U-tube manometer is employed for monitoring the fluid-flow rate at the test section. Digital micro manometer with least count of 0.1 Pa·s was used for measuring the pressure drop across the test section. The solid rings and TT with square wing perforation are made up from 0.50 mm thickness aluminium sheet. The schematic of the experimental set-up and photographic view of multiple wings with combined solid ring TT inserts is shown in fig. 3.

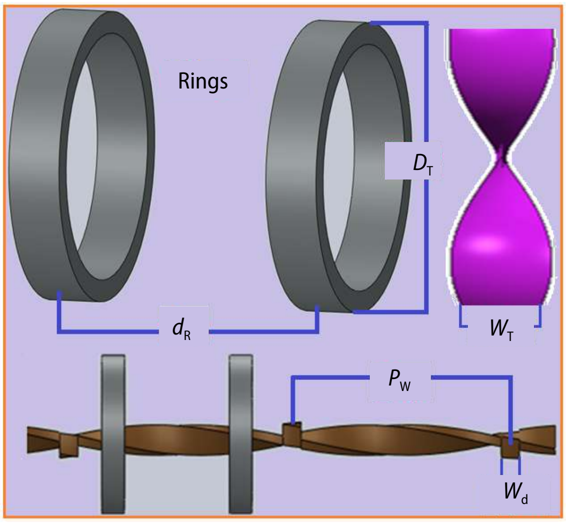

Figure 1. Discuss square wings with combined solid rings twisted inserts HET parameters

The geometrical parameters under investigation are rings pitch ratios, d_R/D_T mm, wing pitch ratios, P_W/W_T mm, wing depth ratios, W_d/W_T mm, number of twisted tapes, N_{TT}, and ratio of inner diameter to tube diameter, d_R/D_T mm. The details of the investigated geometrical and flow parameters are depicted in the tab. 2.

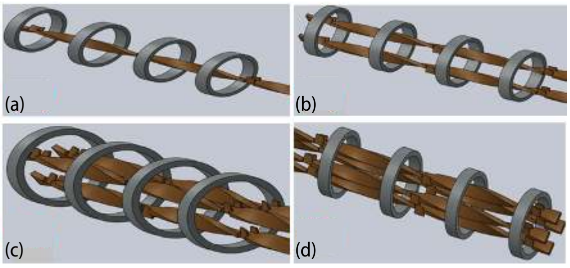

Figure 2. Schematic of TT with square wings with combined solid rings circular tube; (a) single TT, (b) double TT, (c) triple TT, and (d) multiple (four) TT

Data reduction

The experimental data for heat exchanger was recorded under steady-state conditions for given heat flux and mass-flow rate of air. The heat transfer rate to air flowing in the tube was computed. Under the steady-state conditions of the experiment for given air mass-flow rate, $\dot{m}$, the heat transfer rate, Q_u, heat transfer coefficient, h_{TT}, Nusselt number, Nu_{TT}, and friction factor, f_{TT} have been calculated using the following equations.

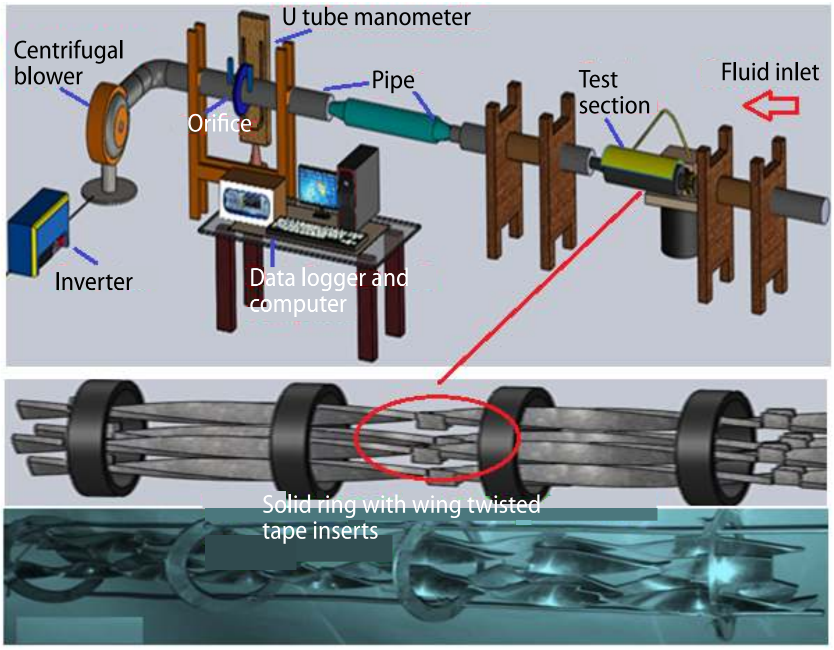

Figure 3. Schematic of experimental set-up and photo graphic view of multiple wings with combined solid ring TT inserts

The net local wall temperature, T_{TT}, inside the tube is the average temperature of all thermocouples embedded in the test section of experimental set-up:

$$T_{TT} = \frac{1}{12}\sum_{i=1}^{12} Tc_i \tag{1}$$

where $Tb_{TT} = (T_i + T_o)/2$ is bulk mean temperature of fluid and it is calculated by equation.

The flow rate of mass of fluid is estimated by using the following equation [24, 29, 31]:

$$\dot{m} = C_d A_o \sqrt{\left[\frac{2\rho_{TT}(\Delta P)_0}{1-\beta^4}\right]} \tag{2}$$

where $(\Delta P)_0 = 9.81(\Delta h_{TT})\rho_{TT} \sin\theta$.

The heat transfer coefficient of air mass fluid-flow in the test section is calculated using the following equation:

$$Q_u = \dot{m} C_p [T_o - T_i] \tag{3}$$

$$h_{TT} = \frac{Q_u}{A_0 (T_{TT} - Tb_{TT})} \tag{4}$$

Nusselt number of air mass-flow in the test section is calculated from the equation:

$$\text{Nu}_{TT} = \frac{h_{TT} D_{TT}}{k_{TT}} \tag{5}$$

The velocity of air mass-flow in HET is calculated from the given equation:

$$V_{TT} = \frac{\dot{m}}{W_T H_{TT} \rho_{TT}} \tag{6}$$

The Reynolds number of air mass-flow in the HET is calculated from equation:

$$\text{Re}_{TT} = \frac{V_{TT} D_{TT} \rho_{TT}}{\mu_{TT}} \tag{7}$$

The friction factor of air mass-flow in test section of HET is calculated from pressure drop equation as:

$$f_{TT} = \frac{2(\Delta P)_d D_{TT}}{4 \rho_{TT} L V_{TT}^2} \tag{8}$$

where $(\Delta P)_d = 9.81(\Delta h_{TT})_d \rho_{TT}$.

The thermal and the hydraulic performance of air mass-flow in a multiple square wing TT inserts is compared with plain tube by using the equation:

$$\eta_p = \frac{\dfrac{\text{Nu}_{TT}}{\text{Nu}_{ss}}}{\left(\dfrac{f_{TT}}{f_{ss}}\right)^{1/3}} \tag{9}$$

Uncertainties analysis

An uncertainty analysis for estimation of errors involved in experimental data measurement has been carried out. The uncertainty is estimated based on errors associated with measuring instruments [32]. The uncertainty results are presented in tab. 2.

Table. 2. Range of uncertainty in the measurement of essential parameters

Parameters	Error range [%]
Mass-flow rate	1.45-3.15
Heat gain	0.93-2.94
Heat transfer coefficient	1.56-3.54
Reynolds Number	0.78-1.56
Nusselt number	1.09-3.32
Friction Factor	0.78-1.67

Validation of experimental results

Empirical correlations of Dittus-Boelter and Gnielinski equation for Nu_{TT} and Blasius equation with Petukhov correlation for f_{TT} were validated with experimental data for plain tube heat exchanger.

The standard equations to find the value of Nu_{TT} and f_{TT} for plain tube are given by Dittus-Boelter equation:

$$\mathrm{Nu_{TT}} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \quad \text{for} \quad \mathrm{Re} \geq 21000 \tag{10}$$

Blasius equation:

$$f_{\mathrm{TT}} = 0.085\,\mathrm{Re}^{-0.25} \tag{11}$$

The standard equations to find the value of $\mathrm{Nu_{TT}}$ and f_{TT} for plain tube are given by Gnielinski equation:

$$\mathrm{Nu_{TT}} = \frac{\left(\dfrac{f}{8}\right)(\mathrm{Re}-1000)\ \mathrm{Pr}}{1+12.7\left(\dfrac{f_{\mathrm{TT}}}{8}\right)^{\frac{1}{2}}\left(\mathrm{Pr_{TT}}^{\frac{2}{3}}-1\right)} \quad \text{for} \quad 3000 \leq \mathrm{Re} \leq 21000 \tag{12}$$

Petukhov equation:

$$f_{\mathrm{TT}} = (0.079 \ln \mathrm{Re} - 1.64)^{-2} \tag{13}$$

The standard values of $\mathrm{Nu_{TT}}$ and f_{TT} with respect to Reynolds number for plane HET are compared with the values obtained from experimental investigation and it is noticed that there is a logically good conformity between the three sets of values confirm the precision of the data collected from this experimental investigation as shown in the figs. 4(a) and 4(b).

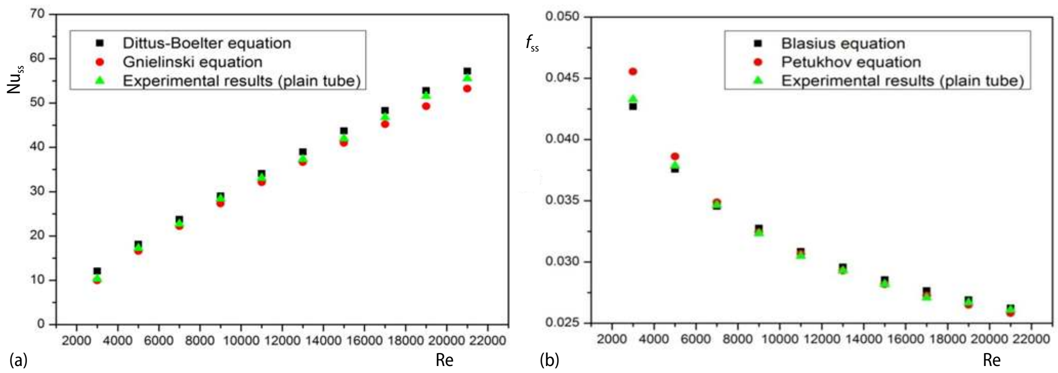

Figure 4. Comparison of present experimental results with previous correlations for; (a) $\mathrm{Nu_{TT}}$ and (b) f_{TT}

Results and discussion

In the present work the effects of HET with wings with combination of solid ring TT inserts with number of TT inserts and operating parameters on thermal and hydraulic performance are discussed.

Heat and fluid-flow

The variation of $\mathrm{Nu_{TT}}$ with varied ranges of Reynolds number for plane tube and multiple wings with solid rings TT inserts is presented in fig. 5(a). The other geometrical parameters are fixed such as $W_{\mathrm{d}}/W_{\mathrm{T}} = 0.167$, $P_{\mathrm{W}}/W_{\mathrm{T}} = 3.0$, and $d_{\mathrm{R}}/D_{\mathrm{T}} = 1.0$. It is shown that there is a considerable enhancement of $\mathrm{Nu_{TT}}$ with the increase of Reynolds number for multiple wings with solid rings TT inserts as compare to plane tube. Inside the HET without any inserts, the radial velocity components of the flow generate boundary-layer separation. The boundary-layer effect can be minimized by introducing multiple wings with solid rings TT inserts in HET. The multiple wings with solid rings TT inserts induces swirl flow inside the tube which further enhances flow turbulence intensity and consequently generates high convection heat transfer than the plain tube. Thus, the value of $\mathrm{Nu_{TT}}$is greater for higher swirling flow and found maximum for $N_{\mathrm{TT}} = 3.0$.

Figure 5(b) shows the values of $\mathrm{Nu_{TT}}$ as function of N_{TT} for the selected Reynolds number values where a maximum in the values corresponding to a $N_{\mathrm{TT}} = 3.0$ for all Reynolds number. It can be observed that $\mathrm{Nu_{TT}}$ enhance significantly with the increase of number of multiple wings with solid rings TT inserts from $N_{\mathrm{TT}} = 1$ to $N_{\mathrm{TT}} = 3.0$ and then it starts decreasing with the increase of N_{TT}. When circular tube is fitted with multiple wings with solid rings TT inserts then it decreases the hydraulic diameter of the tube and increases the fluid-flow with generation of addition swirl flow. Hence, the swirl flow creates disturbance in between the particles of fluid and boundary-layers, hence the heat exchange between the core layer and tube wall continues for a longer period. The HET multiple wings with solid rings TT inserts, generates additional flow jets to the main flow streams through the wings and consequently accelerates the main flow streams. The value of $\mathrm{Nu_{TT}}$ attain maxima in a plot for $N_{\mathrm{TT}} = 3.0$ with respect to the prescribed range of $\mathrm{Re_{TT}}$. In general, the multiple twisted tapes yield higher heat transfer rate than the single one around 10% to 15%. This improvement in $\mathrm{Nu_{TT}}$ for constant value of $W_\mathrm{d}/W_\mathrm{T} = 0.167$, $P_\mathrm{W}/W_\mathrm{T} = 3.0$, and $d_\mathrm{R}/D_\mathrm{T} = 1.0$ is around 10% to 15% for $N_{\mathrm{TT}} = 1$, 15% to 20% for $N_{\mathrm{TT}} = 2$, and around 18% to 25% for $N_{\mathrm{TT}} = 3.0$ is higher than that of plane tube.

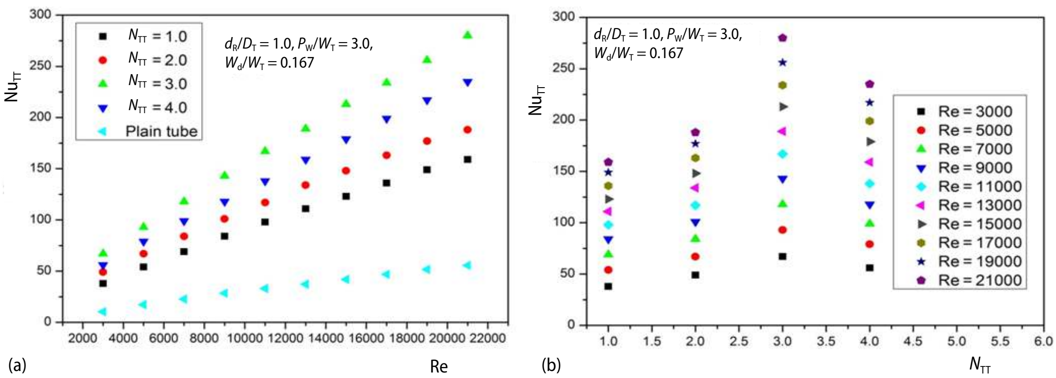

Figure 5. (a) Variation of $\mathrm{Nu_{TT}}$ with $\mathrm{Re_{TT}}$ for different values of N_{TT} (b) variation of $\mathrm{Nu_{TT}}$ with N_{TT} for different values of $\mathrm{Re_{TT}}$

The variation of f_{TT} with $\mathrm{Re_{TT}}$ for fixed range of $W_\mathrm{d}/W_\mathrm{T} = 0.167$, $P_\mathrm{W}/W_\mathrm{T} = 3.0$, and $d_\mathrm{R}/D_\mathrm{T} = 1.0$ with various N_{TT} is shown in the fig. 6(a). The TT inserts generate swirl flow which further increase the wetted surface area and dissipation of fluid pressure near the tube wall. Owing to this effect the fluid-flow has high pressure loss in the HET equipped with multiple wings with solid rings TT inserts. Figure 6(a) shows that the value of friction factor f_{TT} decreases with increasing value of Reynolds number. When the intensity of fluid-flow increases gradually then it would increase the heat flow for all wings TT inserts and it higher for $N_{\mathrm{TT}} = 4.0$, Figure 6(b) shows the values of f_{TT} as function of N_{TT} for the selected Reynolds number values where a maxima in the values corresponding to a $N_{\mathrm{TT}} = 4.0$ for all Reynolds number.

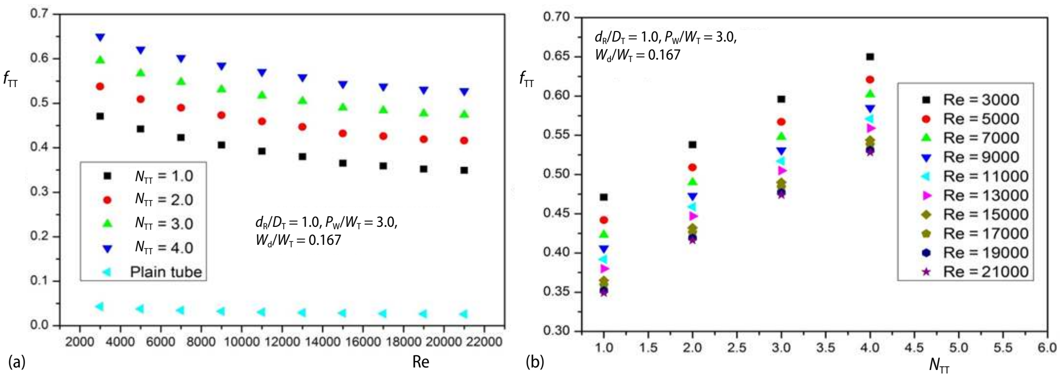

Figure 6. (a) Variation of f_{TT} with Re_{TT} for different values of N_{TT}, (b) variation of f_{TT} with N_{TT} for different values of Re_{TT}

Thermal hydraulic performance

The heat transfer in multiple wings with solid rings TT inserts is better than the plain tube. The effectiveness of TT inserts is measured by using thermal hydraulic parameter η_p [31, 33-35] in terms of Nu_{TT} and f_{TT}. In this investigation the value of these parameters for multiple wings with solid rings TT inserts is investigated and plotted in fig. 7. It is investigated that the multiple wings with solid rings TT inserts generate extra tangential flow which further increases the contact are and hydraulic length of flowing fluid.

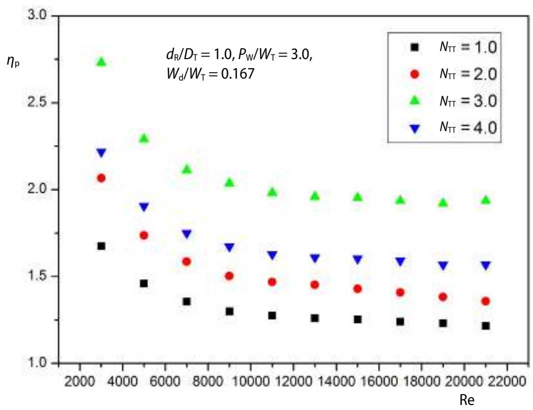

Figure 7. Variation of η_p with Re_{TT} for different values of N_{TT}

The HET equipped with multiple wings with solid rings TT inserts extract maximum amount of heat from the circular tube wall and transfer it to the flowing fluid. Figure 7 shows the thermal hydraulic performance of HET equipped with multiple wings with solid rings TT inserts for fixed range of $W_d/W_T = 0.167$, $P_W/W_T = 3.0$, and $d_R/D_T =$ = 1.0 for all prescribed range of Reynolds number, it can be seen from the graph that the maximum value of thermal hydraulic performance parameter η_p = 2.75 with respect to $Re_{TT} = 2000$ is observed for HET equipped with $N_{TT} = 3.0$ and it is also observed that the value of η_p decreases with the increase of Re_{TT} from 2000 to 21000. Table 3 shows the values of thermal hydraulic performance determined for this geometry multiple wings with solid rings TT inserts have been compared with other similar TT inserts. It can be seen that the multiple wings with solid rings TT inserts results is best thermal hydraulic performance.

Conclusions

In this article, experimental investigation is carried out to study the turbulent heat transfer and fluid-flow characteristics in circular HET using wings with combination of solid ring TT inserts. A series of experiments has been performed with the range of Reynolds numbers, Re_{TT}, varied from 3000 to 21000, number of twisted taped inserts, N_{TT} varied from 1.0 to 4.0 with constant value of other TT parameters such as rings pitch ratio, $d_R/D_T = 1.0$, wing

Table 3. Comparative study of previous investigations

Investigator	The TT shapes	Maximum value of
[18]	Solid ring with multiple TT	2.03
[19]	Perforated conical-ring	1.65
[20]	Non-uniform wire coil combined with TT	1.29
[21]	Helical screw tape	1.75
[22]	Classic, Jagged and Butterfly with inclined angle of 90° TT	1.54
[23]	Jagged TT	1.12
[24]	Regularly spaced TT	1.18
[25]	Left-Right inserts of twist with various spacer length.	1.51
[26]	The TT geometry with twist ratio 3.0 (helical, left-right).	1.49
[27]	Helical screw-tape inserts.	1.43
[28]	Peripherally-cut TT with an alternate axis.	1.31
[29]	Dual TT	1.88
[30]	V-cut TT insert	1.71
Present study	Multiple square wings with solid rings	2.75

pitch ratio, $P_W/W_T = 3.0$, and wing depth ratio $W_d/W_T = 1.67$. Based on the examined, turbulent heat transfer and fluid-flow in wing with combined solid ring TT inserts results are compared with plain circular tube under same operating conditions. The main findings of this paper are as follows.

- The turbulent heat transfer and friction factor of the circular HET are strong function of number of TT inserts, N_{TT}. The maximum enhancement in the turbulent heat transfer has been found to be 5.66 times over the plain tube corresponds to $N_{TT} = 3.0$.
- A significant enhancement in the value of the thermal hydrodynamic performance has been found. The value of the thermal and hydrodynamic performance varies between 1.29 and 2.74 for the range of operating parameters investigated.
- The thermal and hydrodynamic performance parameter based on equal pumping power, η_p was found to be highest for $N_{TT} = 3.0$. The optimum value of thermal and hydrodynamic performance has been found to be 2.74 for Reynolds number of 3000 within the range of the parameters investigated.
- Multiple wings with solid rings TT inserts has also been shown to be thermal as well as hydraulic better in comparison to other similar TT insert geometries.

Nomenclature

A – convection heat transfer area of channel, [m^2]
C_d – coefficient of discharge
C_p – specific heat capacity of air, [Jkg^{-1}K^{-1}]
D_T – diameter of tube, [m]
d_R/D_T – rings pitch ratios, [–]
f_{TT} – friction factor
H_{TT} – head difference, [m]
h_{TT} – heat transfer rate coefficient, [Wm^{-2}K^{-1}]
k – thermal conductivity of air, [Wm^{-1}K^{-1}]
L – length of tube, [m]
$\dot{m}$ – mass-flow rate of air, [kgs^{-1}]
N_{TT} – number of twisted tape
Nu_{TT} Nusselt number, [–]
P_W – pitch between wings, [m]
Pr_{TT} – Prandtl numebr
ΔP – pressure drop, [Pa]
Re Reynolds number, [–]
T_i – inlet temperature, [K]
T_o – outlet temperature, [K]

P_W/W_T – wing pitch ratios, [–]
W_T – width of tape, [m]
W_d – wings depth, [m]
W_d/W_T – wing depth ratios, [–]

Greek symbols

β – ratio of orifice diameter to pipe diameter, [–]
η_p – performance evaluation factor
ρ_{TT} – density, [kgm^{-3}]

Acronyms

HET – heat exchanger tube
TT – twisted tape

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