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Research Article

EFFECT OF PITCH SPACING OF DELTA-WINGLETS ON THERMAL CHARACTERISTICS IN A HEAT EXCHANGER TUBE

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ABSTRACT:
In this paper, the heat transfer, pressure loss and thermal performance by using delta-winglet pairs placed on double-sided straight tape inserted into a constant heat-fluxed tube are experimentally studied. Experimental work is conducted for the tape with different values of axial winglet pitch spacing (P) or winglet pitch ratio (P/D=PR= 0.5, 1.0, 1.5, 2.0 and 2.5). Air used as the working fluid and flows into the tube for Reynolds numbers (Re) ranging from 4100 to 25,400. The use of the delta-winglet tape (DWT) with the winglet attack angle of 45° is to generate two pairs of longitudinal vortex flows. The experimental results show that the DWT provides higher heat transfer rate and pressure loss than the smooth tube. The peak heat transfer rate is at PR=0.5 and is approximately 2.98–4.30 times above the smooth tube while the friction loss is around 10.01–36.34 times. To access the real benefits of the 45° DWT insert, thermal enhancement factor (TEF) is examined and found to be in the range of 1.22–1.55 for PR = 1.5.

Keywords: *Heat exchanger, Enhancement, Inserts, Thermal performance, Vortex generator*

1. INTRODUCTION

Growth industrial sector make necessary to improving the thermal performance of heat exchangers and heat transfer devices. In general, the thermal performance of heat exchangers system can be improve by heat transfer enhancement methods. A passive method of heat transfer enhancement has been of interest for many researchers because additional external power is not needed. The passive technique includes the use of treated surfaces, external surface, rough surfaces, extended surfaces, swirl generator devices, vortex generator devices, etc. [1,2]. Compared with other types in the passive technique, tube inserts have the advantage due to low cost, rapid manufacturing, ease of installation/maintenance.

For decades, several investigations have been made to examine the application of vortex generators (VG) for augmenting the heat transfer rate in heated/cooled tubes fitted with different insert-types of VGs. Swirl/vortex flow devices such as coiled wire [3], twisted tape [4], circular/conical ring [5,6], baffle [7], winglet [8] that belong to one key group of the vortex generators by inserting them into the tubes have been extensively employed in improvement of heat exchanger systems. A comparison of the thermal and hydraulic performances of twisted tape or wire coil inserts was introduced by Wang and Sunden [9] for both laminar and turbulent flow regimes. They found that the coiled wire performs effectively in enhancing heat transfer in a higher turbulent flow region whereas the twisted tape yields a poorer overall efficiency. Eiamsa-ard et al. [10] investigated the thermal performance of tubular heat exchanger fitted with regularly spaced twisted tape elements. A new design of double V-ribbed

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twisted-tapes in tubular heat exchanger was introduced by Tamna et al. [11] that showed that both the V-ribbed twisted-tape and the typical twisted-tape provided higher heat transfer rate and pressure drop increase. The thermal enhancement factor (TEF) of the V-ribbed twisted tape increased around 22% above that of the typical twisted-tape. The thermal and friction loss characteristics in a uniform heat-fluxed tube with V-nozzle inserts for different pitch ratios were studied by Eiamsa-ard and Promvonge [12]. Promvonge [13] examined the effect of conical ring inserts with three different ring diameter ratios where the rings were placed with three different arrangements (converging conical ring, diverging conical ring and converging–diverging conical ring) on heat transfer enhancement in a heat exchanger tube.

Various styles of VG devices, apart from wire coils and twisted tapes, have been widely applied in tubular heat exchangers to improve their thermal performance. The effect of baffles with various ratios of pitch to tube diameter and baffle orientation angles on forced convection heat transfer for turbulent flow in a circular tube was investigated by Tandiroglu [14]. The augmentation of convective heat transfer in a single-phase turbulent flow by using twisted tapes consisting of centre wings and alternate-axes was experimentally investigated by Eiamsa-ard et al. [15]. Wongcharee and Eiamsa-ard [16] employed the modified wing-formed twisted-tapes with three different shapes, namely, triangular, rectangular and trapezoidal wings on the tape rims for enhancing heat transfer in a heat exchanger tube.

According to the literature above, swirl/vortex flow devices are frequently introduced in round tubes to enhance the degree of turbulence level and the fast fluid mixing whereas the heat transfer enhancement strongly depends on the baffle/winglet structure. However, the delta-winglet vortex generators are found to be widely used in a rectangular duct/channel and a fin-tube heat exchanger and are rarely applied in a round tube. In the present work, the insertion of a delta-winglet tape obtained by extruding and protruding the straight tape to form delta winglets mounted on the double-sided tape are examined. Hence, the aim of this article is to study the effect of pitch ratio (PR) of the DWT on pressure drop and heat transfer improvement in a tubular heat exchanger. Experimental set up and correlations for measuring of Nu, f and TEF are presented. The testing range of the Reynolds number (Re) is between 4100 and 25,400.

2. Experimental Set-Up

The DWT used in the present study is shown in Fig. 1. In the figure, each winged tape was made of aluminum sheet (straight tape) with 0.8 mm thickness (t) and length of 1200 mm (=L). In forming the delta-winglet pairs, the tape was partially cut and extruded/protruded to become the winglet as seen in Fig. 1. The 45º DWT with five ratios of wing-pitch to tube-diameter (called "pitch ratio", $P_R=P/D$=0.5, 1.0, 1.5, 2.0 and 2.5) were inserted into a round tube by wall-attached position.

The schematic of the experimental setup is depicted in Fig. 2. The setup mainly consisted of a calm section, test section and exit section. The test section was made of copper in which air flowed through the heated tube. The tube was heated by continually winding flexible electrical wire to provide a uniform heat-flux condition. The outer surface of the test tube was well insulated to minimize convective heat loss to the surroundings. The length of the test section (L) was 1200 mm. The inner (D) and outer tube diameters were 50.2 and 54.3 mm, respectively. The 1.5 kW blower directed the air with T_{in} = 25 ºC to the orifice flow meter. An inverter was utilized to adjust the air flow rate by changing the motor speed of the blower to achieve desired Reynolds number between 4100 and 25,400. The inlet and outlet temperatures (T_{in} and T_{out}) of the bulk air were measured at certain points with a multi-channel temperature measurement unit in conjunction with the RTD PT-100 type temperature sensors while the surface temperatures (T_w) were measured by 16 T-type thermocouples located equally on each of the top and side walls along the test section. The thermocouple voltage outputs were fed into a data acquisition system (Fluke 2680A) and then recorded via a laptop. A digital manometer was used to obtain the pressure drop of air across the test tube. More details on the experimental set-up, method and uncertainty analysis were similar as reported in an earlier author paper [17]. The parameter ranges of the investigation were given in Table 1.

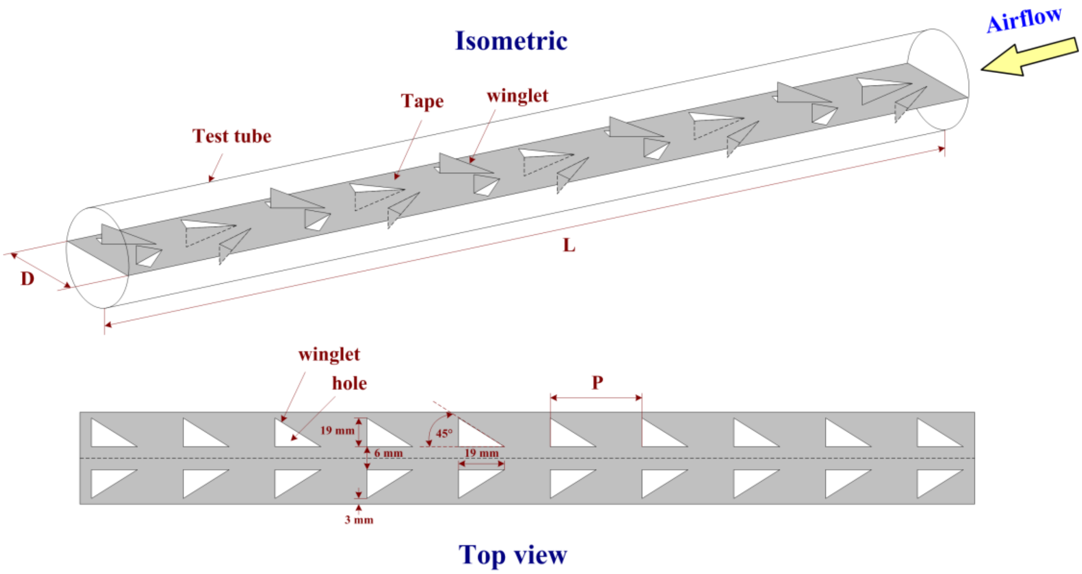


Fig. 1. Test tube with 45° DWT.

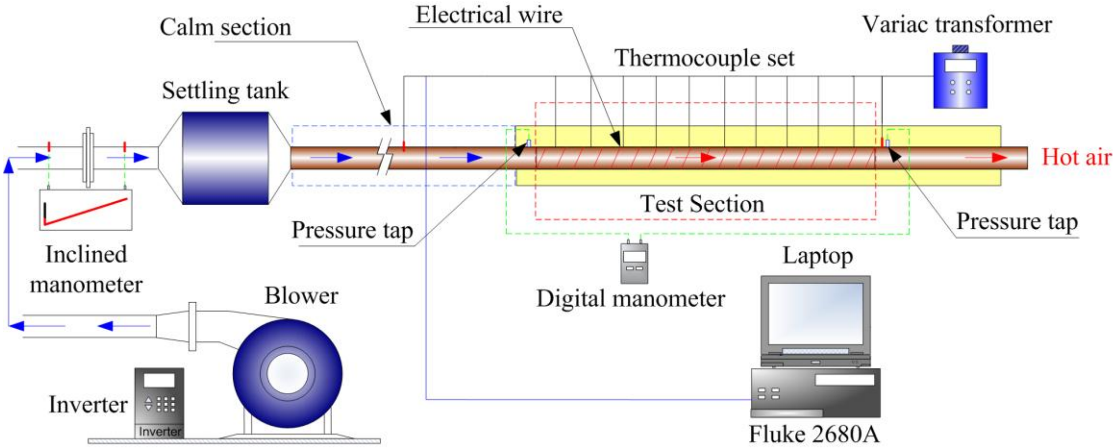


Fig. 2. Schematic sketch of the experimental system.

Table 1: Ranges of parameters in the investigation

Working fluid	Air
Reynolds number, Re	4100 to 25,400
Attack angle of winglet, α	45°
Winglet pitch ratio, $P/D=P_R$	0.5, 1.0, 1.5, 2.0 and 2.5
Tape thickness, t	0.8 mm
Tape width, W	50.2
Tape length, L	1200 mm
Winglet thickness, = t	0.8 mm

3. Data Processing

The purpose of the current work is to determine the heat transfer rate (Nusselt number, Nu), pressure loss (friction factor, f), and thermal enhancement factor (TEF) in a circular tube fitted with the DWT. The data processing is as follows:

The parameters of interest are Reynolds number (Re) and winglet pitch ratio (P_R). The Re is given by

$$\mathrm{Re} = \frac{\rho \cdot U \cdot D}{\mu} \tag{1}$$

The f calculated from pressure loss is written as

$$f = \frac{2}{(L/D)} \frac{\Delta P}{\rho \cdot U^2} \tag{2}$$

in which U is mean air velocity in the test tube.

In the experiment, air flows through the test tube under a uniform heat-flux condition. The steady state of the heat transfer rate is assumed to be equal to the heat loss from the test section which can be expressed as:

$$Q_{\mathrm{air}} = Q_{\mathrm{conv}} \tag{3}$$

where

$$Q_{\mathrm{air}} = \dot{m} \cdot C_{\mathrm{p,air}} \cdot (T_{\mathrm{out}} - T_{\mathrm{in}}) \tag{4}$$

The convection heat transfer from the test section can be written by

$$Q_{\mathrm{conv}} = h \cdot A \cdot (\tilde{T}_{\mathrm{s}} - T_{\mathrm{b}}) \tag{5}$$

in which

$$T_{\mathrm{b}} = (T_{\mathrm{out}} + T_{\mathrm{in}})/2 \tag{6}$$

and

$$\tilde{T}_{\mathrm{s}} = \sum T_{\mathrm{s}} / 16 \tag{7}$$

where T_s is local surface temperature located equally along the outer surface of the test tube. The average surface temperature, $\tilde{T}_s$ is computed by using 16 points of local wall temperatures. The average heat transfer coefficient (h) and Nu are estimated as follows:

$$h = \dot{m} \cdot C_{\mathrm{p,air}} \cdot (T_{\mathrm{out}} - T_{\mathrm{in}}) / A \cdot (\tilde{T}_{\mathrm{s}} - T_{\mathrm{b}}) \tag{8}$$

The heat transfer is calculated from the average Nu which can be obtained by

$$\mathrm{Nu} = \frac{h \cdot D}{k} \tag{9}$$

All of thermo-physical properties of air are determined at the overall bulk air temperature (T_b) from Eq. (6). To assess the practical use, thermal performance of the enhanced tube is evaluated relatively to the smooth tube at an identical pumping power in the form of thermal enhancement factor (TEF) which can be expressed by

$$\mathrm{TEF} = \left.\frac{h}{h_0}\right|_{\mathrm{pp}} = \left.\frac{\mathrm{Nu}}{\mathrm{Nu}_0}\right|_{\mathrm{pp}} = \left(\frac{\mathrm{Nu}}{\mathrm{Nu}_0}\right)\left(\frac{f}{f_0}\right)^{-1/3} \tag{10}$$

where h_0 and h stand for heat transfer coefficients of plain tube and inserted tube, respectively.

4. Result and Discussion

4.1. Confirmatory test

The smooth tube was initially tested to verify the experimental setup. A comparison of the present Nu and f results of the smooth tube with those obtained from the published correlations [18] of Dittus-Boelter and Petukhov, as given in Eqs. (11) and (12), is depicted in Fig. 3 and 4, respectively.

Dittus-Boelter correlation:

$$\mathrm{Nu} = 0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{0.4} \quad (11)$$

Correlation of Petukhov,

$$f = (0.79\ln\mathrm{Re} - 1.64)^{-2} \quad (12)$$

Figs. 3 and 4 show the comparison between the present work and correlation's data of Dittus-Boelter (Eq. 11) and Petukhov (Eq. 12). In the figures, the present results agree reasonably well within ±6% for Nu of Dittus–Boelter and ±7% for *f* of Petukhov correlations. This indicates that data of the experimental setup is reliable.

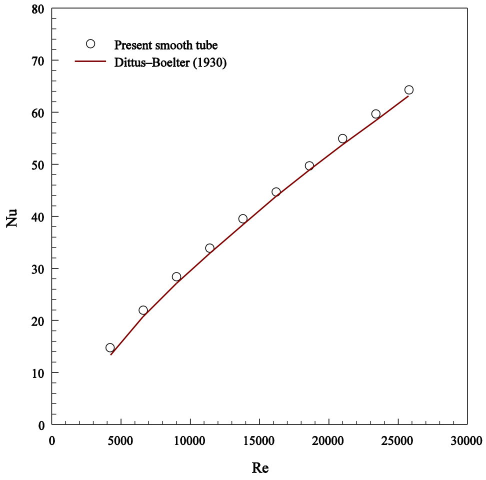


Fig. 3. Confirmatory test of Nu of smooth tube.

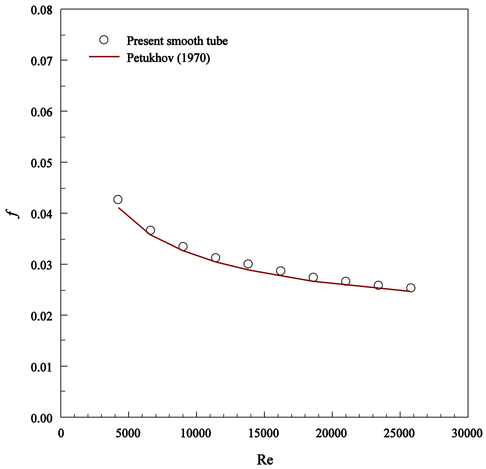


Fig. 4. Confirmatory test of f of smooth tube.

4.2. Effect of DWT on heat transfer

Fig. 5a, b and c presents the relationship of heat transfer coefficient (*h*), Nusselt number (Nu) and Nusselt number ratio ($\mathrm{Nu}/\mathrm{Nu}_0$) with Re for using the 45° DWT with different P_R values, respectively. The result shows that the *h* of the DWT is excellent for the tubular heat exchanger. The *h* increases with the rise of Re but with decreasing P_R (see Fig. 5a). The Nu of the DWT is seen to be higher than that of the smooth tube around 66–76%, and the best Nu is for P_R = 0.5 (see Fig. 5b). This is because the presence of the DWT induces stronger flow mixing resulting in destruction of the boundary layer and creates vortex-flows to prolong the residence time of flow. The ratio of augmented Nu of inserted tube to Nu of smooth tube ($\mathrm{Nu}/\mathrm{Nu}_0$) plotted against the Re is depicted in Fig. 5c. In the figure, Nu/Nu_0 tends to decrease slightly with the rise of Re for all cases. It is noted that the $P_R = 0.5$ provides the highest Nu/Nu_0. This is caused by the higher number of the winglets for $P_R = 0.5$ that can more often interrupt the flow leading to stronger vortex flow strength leading to higher rate of heat transfer between the working fluid and the heated wall. The Nu/Nu_0 shows a slightly decreasing trend with the increase in Re. Nu/Nu_0 values for the DWT are about 4.10–4.30, 3.85–4.03, 3.61–3.82, 3.30–3.51 and 2.98–3.18 times for P_R = 0.5, 1.0, 1.5, 2.0 and 2.5, respectively. The DWT at $P_R = 0.5$ yields the average Nu/Nu_0 around 6%, 11.5%, 21.7% and 26.9% higher than the one at P_R = 1.0, 1.5, 2.0 and 2.5, respectively.

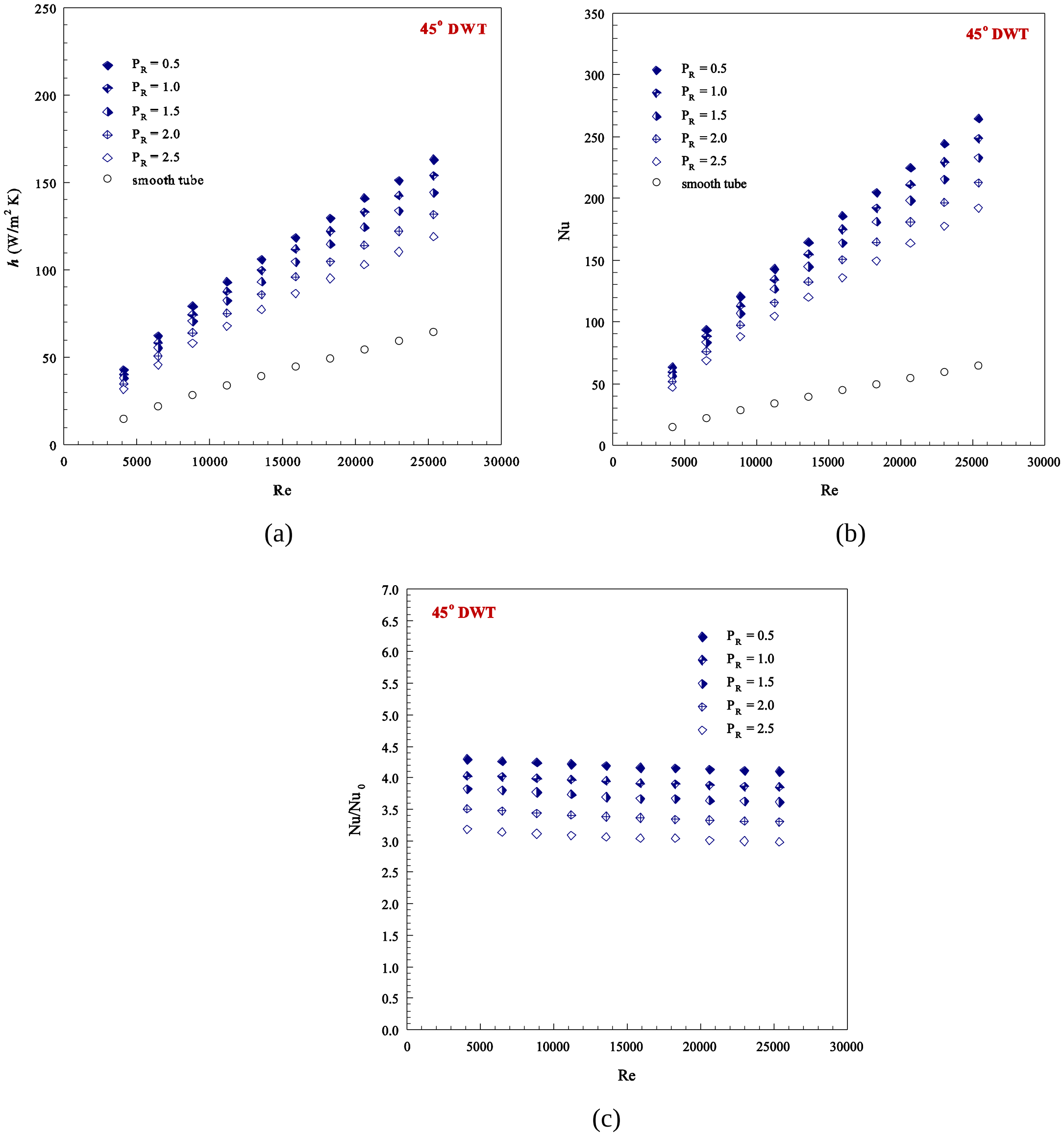
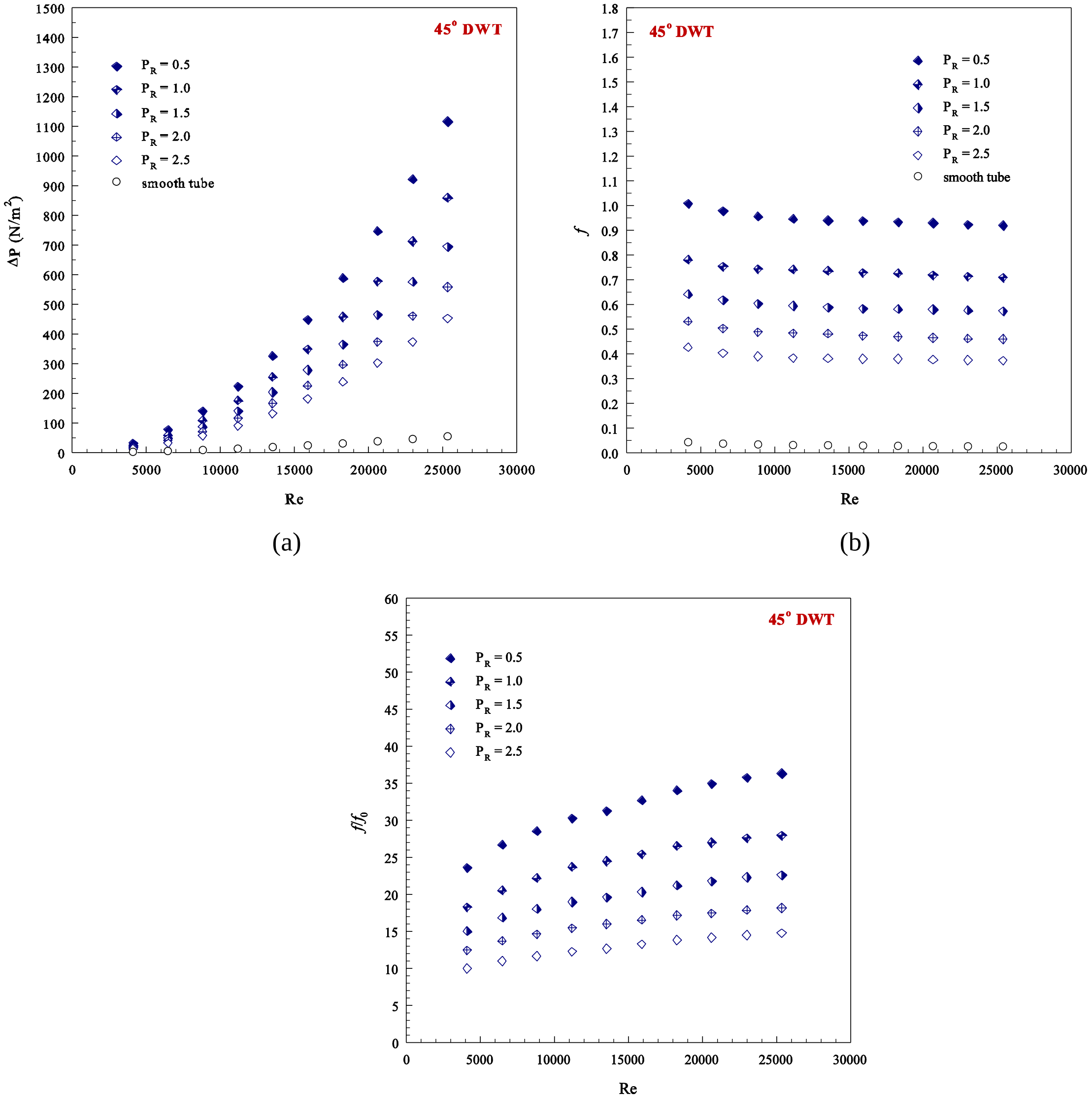


Fig. 5. Variation of (a) h, (b) Nu and (c) Nu/Nu0 with Re for DWT insert.

4.3. Effect of DWT on friction loss

Effects of pressure drop (ΔP), friction factor (f) and friction factor ratio (f/f_0) are exhibited in Fig. 6a, b and c, respectively. In Fig. 6a, ΔP for all cases shows the considerable increases with similar trend for the increase in Re and apparently, the inserted tube gives higher ΔP than the smooth one. It is clearly observed in Fig. 6b that the DWT provides a substantial increase in f above the smooth tube due to higher flow blockage especially for using smaller P_R apart from the dissipation of dynamic pressure of the fluid due to larger surface area. The f of the DWT increases around 90–97% above that of the smooth tube alone. Fig. 6c presents the variation of f/f_0 with Re for various P_R values. In the figure, the f/f_0 is increasing as a function of Re for all cases. The mean f/f_0 values for P_R = 0.5, 1.0, 1.5, 2.0 and 2.5 are, respectively, about 31.4, 24.4, 19.7 and 15.9 times. The maximum f/f_0 is about 36.34 times at smallest pitch ratio (P_R = 0.5). The f/f_0 of P_R = 0.5 is, respectively, about 22.4%, 37.3%, 78.4% and 59.2% higher than that of P_R = 1.0, 1.5, 2.0 and 2.5.



(c)

Fig. 6. Variation of (a) ΔP, (b) f and (c) f/f0 with Re for DWT insert.

4.4. Effect of DWT on thermal performance

The assessment on potential of the DWT for real applications is made in the form of thermal enhancement factor (TEF) plotted against Re as exhibited in Fig. 7. The TEF is achieved by simultaneously evaluating the Nu and *f* in the inserted tube and the smooth tube under constant pumping power conditions taken into account by using Eq. (10). In the figure, TEF shows the decreasing trend with increasing Re for all inserts. The TEF values for the DWT at P_R = 0.5, 1.0, 1.5, 2.0 and 2.5 are, respectively, around 1.24–1.50, 1.27–1.53, 1.28–1.55, 1.26–1.51 and 1.22–1.48, depending on Re values. The highest TEF of 1.55 is found for P_R = 1.5 at the lowest Re. Therefore, the best choice of this insert device is the use of DWT at P_R = 1.5 to achieve superior thermal performance.

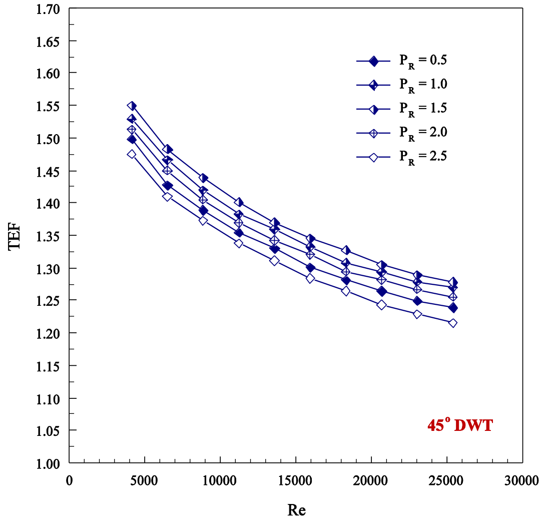


Fig. 7. Variation of TEF with Re for DWT insert.

5. Comparison with Other Inserted VG Devices

The comparison of thermal performance of the current research with similar published works (delta-wing tape of Skullong et al. [19], rectangular-winglet tape of Prasopsuk et al. [20] and double-sided delta wings with alternate axis of Eiamsa-ard and Promvonge [21]) is shown in Fig. 8. It indicates in the figure that the present delta-winglet tape provides considerably higher TEF than the mentioned delta-wing tape, rectangular-winglet tape and double-sided delta wing tape with alternate axis inserts. The current DWT yields the TEF higher than the wing/winglet inserts [19–21] at about 3–26%.

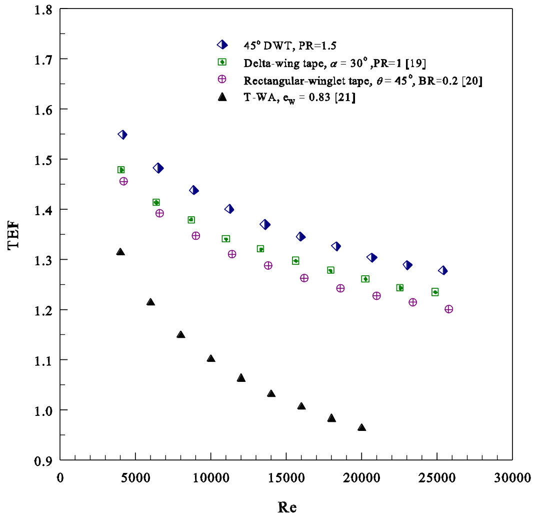


Fig. 8. Comparison of TEF of the present DWT with other similar VG devices.

6. Conclusion

An experimental procedure has been conducted to investigate a single phase turbulent flow and heat transfer behaviors in a tubular heat exchanger equipped with delta-winglet tape vortex generators. Air used as the working fluid enters the test tube in a range of Reynolds number between 4100 and 25,400 under a uniform wall heat-flux condition. The present result shows that the Nu reduces with the rise of P_R while increases with the increment of Re. The f decreases with increasing Re and P_R. The 45° DWT at P_R = 0.5 gives the highest Nu/Nu_0 and f/f_0 at about 4.30

and 36.34, respectively. The TEF of the DWT shows the decreasing trend with increasing Re and has a maximum around 1.55 at $P_R = 1.5$.

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