Performance improvement in a tubular heat exchanger by punched delta-winglet vortex generators

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Abstract. A novel tubular heat exchanger incorporated with punched delta-winglet vortex generators (called perforated delta-winglet vortex generator, P-DWVG) is proposed for improving its thermal performance and energy saving. The P-DWVG elements are punched out from a straight tape having its width nearly equal to the tube diameter before insertion. The main aim at employing the P-DWVG insert is to produce counter-rotating vortices along the tube to promote turbulence intensity inside as well as to transport the cold fluid at the central core to the near-wall regions. The experiment was performed to study thermal behaviors in a uniform heat-fluxed tube inserted with P-DWVGs. The P-DWVGs with the attack angle of 45° were mounted periodically with three different blockage ratios (B_R = 0.1, 0.2 and 0.3) and two pitch ratios (P_R = 2 and 3). Air as the test fluid was varied to obtain turbulent airflow for Reynolds number (Re) in a range of 4,150-25,500. The experimental results show that the P-DWVG provides a considerable increase in the rate of heat transfer around 3.1-4.01 times whereas friction factor increases around 11.44-34.23 times higher than the plain tube. To assess the real benefits of P-DWVGs, thermal performance factor (TEF) is examined and in the range of 1.39-1.48 where its maximum is at B_R = 0.1 and P_R = 2.

1. Introduction
Heat exchangers are widely used in air conditioning, ventilation, refrigeration and thermal systems. Improving the thermal performance of such systems is crucial to meet energy costs and environment impact. Many techniques for heat transfer augmentation have been widely adopted to obtain a compact and small size of the systems with lower operating costs. For years, many investigations on the utilization of vortex generators (VGs) in improvement of heat exchanger tubes have been performed experimentally and numerically. Several kinds of VGs were used in enhanced tubes such as coiled square wires [1]; snail entry/twisted tape and coiled-wire [2, 3]; ribbed tube with double twisted tapes [4]; conical-nozzle [5]; regularly-spaced twisted tapes [6]; perforated twisted-tapes with parallel wings [7]; and perforated VGs [8]. The modifications of all twisted tapes mentioned earlier were found to yield the improvement of thermal systems around 10-35% higher than the typical twisted ones.

In another type of VGs in the form of conical/circular/vortex/V-shaped rings, Promvonge [9] studied fluid friction and thermal behaviors in a round tube contained with three arrangements of conical
ring/nozzle geometries. Also, the effect of combined conical-nozzles and snail-type vortex generator mounted at the entrance on heat transfer behaviors was examined by Promvonge and Eiamsa-ard [10]. Promvonge et al. [11] again reported thermal characteristics in a circular tube inserted with 30° inclined vortex rings (VR) and found that the VR gives higher thermal performance than other twisted tapes, coiled wires and transverse rings. Chingtuaythong et al. [12] investigated heat transfer behaviors in a uniform heat-fluxed tube with V-shaped rings and showed that the V-ring is superior to other rings.

Applying winglet-type vortex generators (WVGs) mounted or punched on the heat transfer surface, is an innovation strategy to augment heat transfer with small increases of pressure drop penalty. Several investigations on the influence of wing/winglet parameters on the rate of heat transfer and pressure loss have been carried out. Promvonge [13] proposed that the use of V-winglet vortex generators was much better than the ribs or WVGs. Skullong et al. [14, 15] studied thermal and flow friction behaviors in a solar air heater channel with combined wavy-groove and perforated-delta wing; and winglet vortex generators. They showed that the combined devices yielded considerably higher thermal performance than the single device acting alone.

In the literature review mentioned above, the WVGs were used in flat surfaces/channels to generate longitudinal vortex flows along the channel. The investigation on thermal characteristics from using a straight tape with double-sided perforated delta-winglet vortex generator (P-DWVG) inserted into a circular tube has hardly been seen. In the current work, a novel 45° P-DWVG inserted into a circular tube is presented and designed to enhance heat transfer with appropriate pressure loss penalty. Thermal performance characteristics of the tube with P-DWVG inserts are studied experimentally for airflows in the Reynolds number range of 4,150 to 25,500.

2. Experimental setup
Experimental approach has been adopted to generate the data in the dimensionless form of Nusselt number (Nu) and friction factor (f) for a tubular heat exchanger with 45° P-DWVG to explore the effect of Br, Pr and Re on Nu and f. The arrangement of the experimental apparatus is sketched in figure 1. In the apparatus settings, the copper test tube is 50.8 mm in inner diameter (D), 2 mm thick (t) and 3,000 mm long which included the test section length (L) of 1,200 mm. To obtain a uniform heat-flux condition, the test section was heated using a flexible electrical wire wound continually around it where the output power of the electric heater was controlled by a variac transformer. The outermost test tube was wrapped by insulations to prevent the convection heat loss to the surrounding. The room air from a 2.3 kW high pressure blower flowed toward the orifice meter to measure the volumetric airflow rate through the test section where the inclined manometer was used to measure the pressure drop across the orifice meter. The airflow rates in the test tube were varied by controlling the motor speed via an inverter. The fluid temperatures at the inlet and the outlet were measured by RTD thermocouples, Pt-100 type, while the temperatures along the tube surface were measured using 24 thermocouples, type-T, positioned equally on the upper and the sidewall of the tube. Once a steady-state condition was reached, all the temperature values were recorded through a data acquisition system (Fluke 2680A). The measurement of pressure drop of the tube was done by using a digital manometer. The complete details of experimental setup, method and uncertainty analysis are the same as another work of the authors [16, 17].

![Figure 1. Experimental set-up.](image-url)
Figure 2 presents details of the 45° perforated delta-winglet tape mounted inside the tube. The perforated delta-winglet tape in the present investigation was made of aluminum sheet (straight tape) with 1.0 mm thickness (t) and length of 1,200 mm. For forming delta-winglet, the tape was partially cut and extruded to become the delta winglet as seen in figure 2. There were two relative winglet pitches called pitch ratios ($P_R=P/D=2$ and 3), and three winglet blockage ratios ($B_R=b/D=0.1, 0.2$ and 0.3) with a single punched hole or pore diameter on the winglet ($d=2$ mm).

![Diagram of Test Tube with 45° P-DWVG Insert](image)

**Figure 2.** Test tube with 45° P-DWVG insert.

### 3. Data processing

The objective of the current work is to explore the heat transfer, friction factor and thermal enhancement factor in a tubular heat exchanger inserted with P-DWVGs. The independent parameters include Reynolds number (Re), pitch ratio ($P_R$) and blockage ratio ($B_R$). The Re is written as

$$Re = \frac{UD}{\nu}$$  

(1)

The calculation of friction factor ($f$) is performed using pressure drop ($\Delta P$) across the tube as given by

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

(2)

in which $\rho$, $\nu$ and $U$ are the density, kinematic viscosity and mean velocity of air, respectively.

In this work, the rate of heat transfer on the surface is identical to the heat absorbed by the air. Thus, the evaluation of the mean heat transfer coefficient ($h$) is conducted via

$$h = mc_p \left(\frac{T_i}{L} - \frac{T_o}{L}\right)$$  

(3)

where

$$\tilde{T}_w = \frac{\sum T_w}{24}$$  

(4)

The dimensionless heat transfer coefficient or Nusselt number ($Nu$) is defined by

$$Nu = \frac{hD}{k}$$  

(5)

At a similar pumping power, thermal enhancement factor (TEF) defined by Webb [18] is given as,

$$TEF = \frac{h}{h_{pp}} = \left(\frac{Nu}{Nu_{pp}}\right)\left(\frac{f}{f_p}\right)^{-1/3}$$  

(6)

where $h_p$ and $h$ stand for the heat transfer coefficients for a plain tube and inserted tube, respectively.
4. Results and discussion

4.1. Validation test

The validation test was conducted to verify the reliability of the experimental setup. Nu and f data from the current plain tube are, respectively, compared with data from correlations of Gnielinski and Petukhov [19]. Verification tests as displayed in figure 3 are in good agreement between experimental and correlation data. The average deviations are within 4% for Nu and 5% for f.

![Figure 3. Verifications of (a) Nu and (b) f for plain tube.](image)

4.2. Effect of P-DWVGs on heat transfer

The effects of extending the flow and the winglet parameter on the heat transfer are clearly depicted in figures 4a and b, respectively. The relationship between Nu and Re of the inserted tube is demonstrated in figure 4a. Obviously, P-DWVGs give higher Nu than the plain tube and the Nu shows the increasing trend with the rise in Re but with decreasing Pr. This comes from the fact that the P-DWVG insert produces longitudinal vortex flows assisting to promote the flow turbulence intensity and to move the central core fluid to the near-wall areas. Regarding to its parameters, the P-DWVG with larger B_R can generate more flow obstruction resulting in stronger flow disturbance than the one with smaller B_R.

![Figure 4. Variations of (a) Nu and (b) Nu/Nu_0 with Re for P-DWVGs.](image)

Nusselt number ratio (Nu/Nu_0) defined as Nu of the inserted tube divided by Nu of the plain tube is plotted against Re as depicted in figure 4b. It is noted that Nu/Nu_0 displays the increasing tendency with the increment of B_R but with the reduction of Pr due to higher turbulence degree level among the P-DWVGs. The quantitative results of the mean Nu/Nu_0 at Pr=2 and Pr=3 are, respectively, about 3.92, 3.78 and 3.61; and 3.51, 3.37 and 3.17 times for B_R=0.3, 0.2 and 0.1. This means that the employ of larger B_R and smaller Pr results in a considerable increase in the rate of heat transfer.
4.3. **Effect of P-DWVGs on friction loss**

The isothermal pressure drops for using the P-DWVG displayed in terms of $f$ and friction factor ratio, $(f/f_0)$ are, respectively, plotted against Re as shown in figures 5a and b. It is observed in figure 5a that $f$ of the P-DWVG found to be much higher than that of the plain tube, shows the down trend with the rise of Re and $P_R$.

![Figure 5](image)

**Figure 5.** Variations of (a) $f$ and (b) $f/f_0$ with Re for P-DWVGs.

In figure 5b, $f/f_0$ tends to increase with the increment of Re. It is seen that in general, $f/f_0$ increases with increasing $B_R$ but decreases with rising $P_R$. The mean values of $f/f_0$ at $P_R=2$ and $P_R=3$ are, respectively, about 29.47, 24.92 and 20.72; and 23.19, 19.33 and 15.17 times for $B_R=0.1, 0.2$ and 0.3.

4.4. **Effect of P-DWVGs on thermal performance**

To assess the potential of P-DWVG insert for real practical, thermal enhancement factor (TEF) is offered and is plotted against Re as depicted in figure 7. It is found that, in general, values of TEF are higher than unity, suggesting that the application of P-DWVG insert is superior to the plain tube. TEF displays the downturn with increasing Re for all the P-DWVG cases and its peak is 1.48 at $B_R=0.1$ and $P_R=2$. At $P_R=2$, TEF values are, respectively, around 1.22-1.48, 1.20-1.46 and 1.19-1.43 for $B_R=0.1, 0.2$ and 0.3.

![Figure 6](image)

**Figure 6.** Variation of TEF with Re for P-DWVGs.
5. Correlations for Nu and \( f \)

Correlations generally are fruitful for use in the prediction of thermal performance or to determine the optimum geometric parameters for a particular application. The empirical correlations for Nu and \( f \) of using the 45° P-DWVG inserts are correlated as shown below. Nu and \( f \) correlations provided are in the function of Re, \( B_R \) and \( P_R \). The discrepancies of Nu and \( f \) obtained from equation (7) and equation (8) are within ±6% and ±7%, respectively.

\[
\text{Nu} = 0.148 \text{Re}^{0.778} \text{Pr}^{0.043} B_R^{0.348} \text{Pr}^{-0.329} \]  
\[
f = 3.203 \text{Re}^{-0.043} B_R^{0.348} \text{Pr}^{-0.662} \]  

(7)  

(8)

6. Conclusion

Thermal behaviors in a constant heat-fluxed tube inserted with 45° P-DWVGs for various \( B_R \) and \( P_R \) values in the turbulent regime, \( \text{Re} = 4,150-25,500 \) are experimentally examined. The rate of heat transfer of the tube insert is augmented around 3.1-4.0 times above the plain/smooth tube alone whereas the friction factor is enlarged at about 15.2-29.5 times. However, the highest TEF around 1.48 is achieved for the delta-winglet tape at \( B_R=0.1 \) and \( P_R=2 \), pointing out that this optimal condition is regarded as a superior energy saving device for practical use.

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