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Experimental investigation of thermal performance enhancement in tubular heat exchanger fitted with rectangular-winglet-tape vortex generator

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Abstract

The article presents an experimental study on thermal characteristics in a constant heat-fluxed circular tube fitted with rectangular-winglet tape (RWT) vortex generators. Air was employed as the working fluid based on Reynolds numbers (Re) in the turbulent regime between 4100 and 26,000. The effect of the RWT insert on heat transfer rate and friction loss was experimentally investigated. The RWT parametric study includes five winglet-to-tube height ratios or blockage ratios (b/D=BR= 0.15, 0.2, 0.25 and 0.3) at a single winglet inclination angle (θ = 45°) and a pitch ratio (P/D=PR=2). The experimental results show that the heat transfer and friction loss for the RWT insert increase with the increment of BR. The Nu for the inserted tube was approximately 3.7–4.3 times higher than that for the smooth tube, while the f was approximately 19.4–45 times greater. For the studied BR ranges, the highest thermal enhancement factor (η) of 1.46 is obtained for BR = 0.2 at lower Re.

Keywords: Heat exchanger, Heat transfer, Rectangular winglet tape, Thermal performance, Vortex generator

1. Introduction

The conventional heat exchanger tube was initially developed for smooth or plain heat transfer surfaces. The heat transfer ability of a convectional heat exchanger tube needs to be improved in order to obtain higher the convective heat transfer coefficients than a plain tube leading to size reduction as well as operating cost of the heat exchanger system. Among the different techniques to increase the heat transfer coefficient, the passive method [1] is quite popular and includes extended/rough surfaces, coil tubes, swirl/vortex flow, displaced insert and surface tension etc. The insertions of vortex-flow devices such as twisted-tape [2], wing-tape [3-4], wire coil [5], fin [6], baffle [7], vortex ring [8] are the most interested method of the passive technique apart from a number of geometrical arrangements to create rotating secondary flow. Based on the literature review, the RWT inserts with different blockage ratios have not been investigated so far. In the present investigation, experiments are carried out to determine the thermal performance enhancement of a tubular heat exchanger fitted with the RWTs having different BRs at a single pitch ratio (P/D=2) and an inclination angle (θ = 45°) for Reynolds number ranging from 4100 to 26,000.

2. Experimental setup

An arrangement of the experimental apparatus is shown in Figure 1a. The experiment was conducted in an air tube system, the test tube was heated by continually winding flexible electrical wire to provide a uniform wall heat-flux boundary condition. Air as the tested fluid was directed into the systems by a high pressure blower. In order to measure temperature distributions along the axial length of heated walls, 16 Copper constantan thermocouples were tapped equally along the local upper and side walls of the grooved outer tube surface. The inlet and outlet bulk temperatures of air were measured by two resistant temperature detectors (RTD) with accuracy of ±0.1 °C. The pressure drop of flow across the orifice-plate meter was measured using an inclined manometer to indicate the airflow rate while the pressure drop across the test tube was measured by a Dwyer 475 Mark III type digital-manometer.

The RWT vortex generator is shown in Figure 1b. All tapes used in the experiments were made of 0.6 mm thick aluminum sheets (δ) with 1200 mm (L) in length and 50.2 mm in width. In forming the rectangular-winglet pairs, the tapes were partially cut and extruded to become the rectangular winglet with 18 mm in length (l) and four different height (b) of 7.5, 10, 12.5 and 15 mm equivalent to

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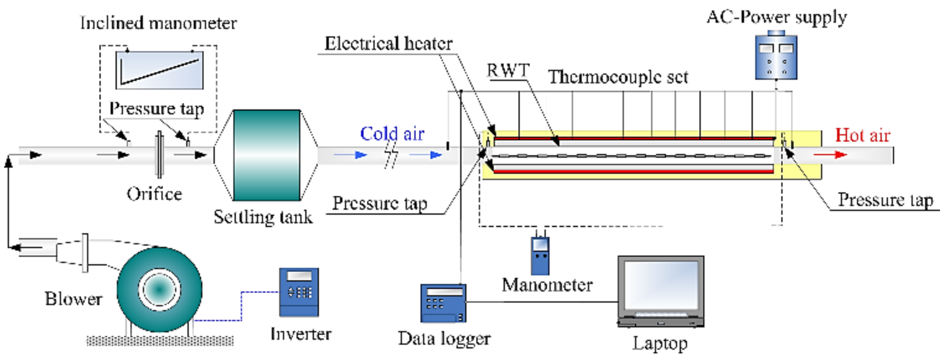
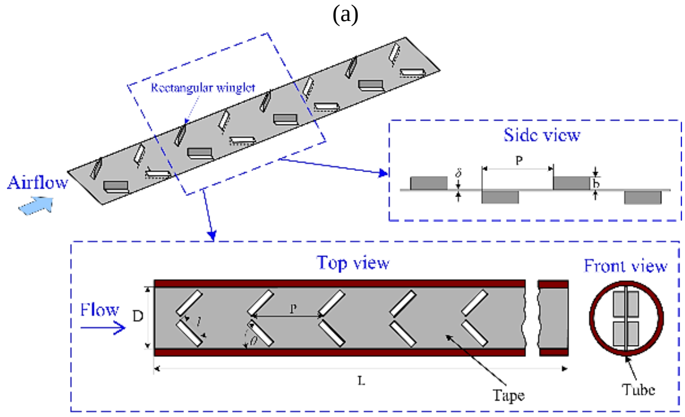


(a)



(b)

Figure 1 (a) Schematic diagram of experimental apparatus and (b) test section with RWT

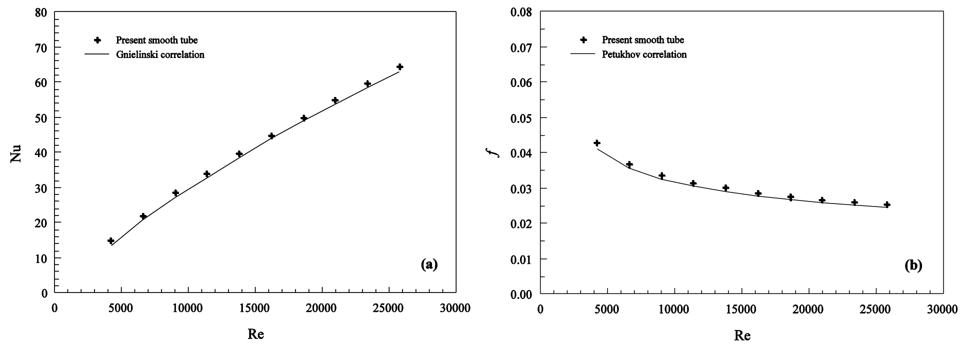


Figure 2 Verification of (a) Nu and (b) *f* for smooth tube

BR= *b*/D = 0.15, 0.2, 0.25 and 0.3, respectively. Note that a winglet inclination angle, θ= 45° and a pitch ratio, PR=2 were fixed throughout.

3. Data reduction

The average heat transfer coefficients are evaluated from the measured temperatures and heat inputs, with heat added uniformly to fluid (Q_{air}) and the temperature difference of surface and fluid $(T_w - T_b)$, average heat transfer coefficient will be evaluated by:

$$h = \dot{m}C_{p,a}\left(T_o - T_i\right)/A\left(\tilde{T}_w - T_b\right) \quad (1)$$

The non-dimensional heat transfer coefficient or Nusselt number, Nu is calculated by

$$\mathrm{Nu} = hD/k \quad (2)$$

The Re is given by

$$\mathrm{Re} = UD/\nu \quad (3)$$

The friction factor (*f*) computed by pressure drop across the length of the test section (*L*) is

$$f = 2\Delta P/\left(\left(L/D\right)\rho U^2\right) \quad (4)$$

At a constant pumping power, the relationship between *f* and Re is presented in the form of thermal enhancement factor (η), Ref. [2–7] as given by

$$\eta = h/h\big|_{pp} = \mathrm{Nu}/\mathrm{Nu}\big|_{pp} = (Nu/Nu_0)(f/f_0)^{-1/3} \quad (5)$$

4. Results and discussion

4.1 Validation test

Experimental results of Nu and f are compared with correlations of Gnielinski and Petukhov found in the open literature for turbulent flow in circular tubes [9]. Comparing with the correlation data in Ref. [9], the deviations of both results are depicted in Figure 2. The figure shows a satisfactory agreement between the experimental and correlation data within ±8% deviation.

4.2 Heat transfer results

The effect of using RWT insert on heat transfer enhancement is shown in Figure 3a by plotting Nu versus Re. For all cases, the Nu increases with the rise of Re and BR. It is found that the application of RWT can help to increase considerably the heat transfer over the smooth tube alone up to 377%. This is because the RWT interrupts frequently the thermal boundary layer and also creates the longitudinal vortex flows resulting in higher turbulence intensity or fast fluid mixing. The Nusselt number ratio of the insert tube to the smooth tube alone (Nu/Nu_0) is displayed in Figure 3b. In the figure, the Nu/Nu_0 tends to slightly decrease with the increment of Re for all cases studied. The Nu/Nu_0 values for BR=0.15, 0.2, 0.25 and 0.3 are, respectively, around 3.8, 4.0, 4.1 and 4.2. The 45° RWT at BR=0.3 provides the maximum heat transfer rate because of highly interrupting the flow and promoting higher levels of vortex strength.

4.3 Friction factor results

The friction factor (f) is demonstrated in Figure 4a. It can be observed that the f tends to decrease with the increment of Re and BR, and apparently, the RWTs give rise to the f higher than the smooth tube alone. Again, the 45° RWT at BR=0.3 yields the highest f due to higher flow blockage and larger surface area.

The friction factor ratio (f/f_0) plotted against Re is depicted in Figure 4b. In the figure, the trend for all cases is that the f/f_0 considerably increases with increasing Re. The average increases in the f/f_0 for BR=0.15, 0.2, 0.25 and 0.3 are, respectively, about 25.5, 30.0, 34.7 and 38.7 times. According to the experimental results, the 45° RWT at BR=0.3 provides the maximum f/f_0 of about 29.1–45.0 times and is, respectively, 9.7–10.6%, 21.9–22.4% and 33.1–34.5% higher than that at BR=0.25, 0.2 and 0.15.

4.4 Thermal performance

The variation of η with Re for different BRs is illustrated in Figure 5. For all, the data of Nu/Nu_0 and f/f_0 are coupled at a similar pumping power condition. In the figure, the η tends to decrease with the increase in Re. The optimum RWT parameter in the present work is at BR=0.2 because at this point, the Nu/Nu_0 is still high while lower f/f_0 value is achieved, thus the highest η of 1.46 is found at lower Re. This peak of η value is 1–3% higher than others.

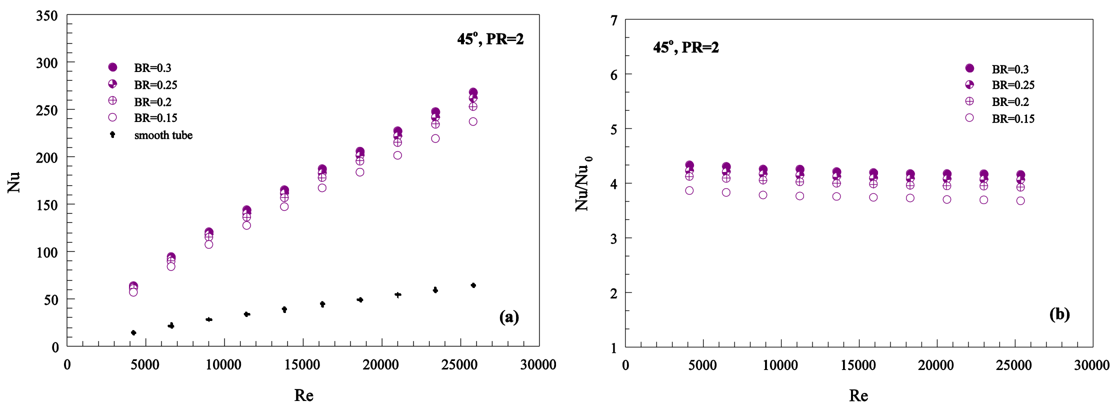


Figure 3 (a) Nu and (b) Nu/Nu_0 versus Re for 45° RWTs

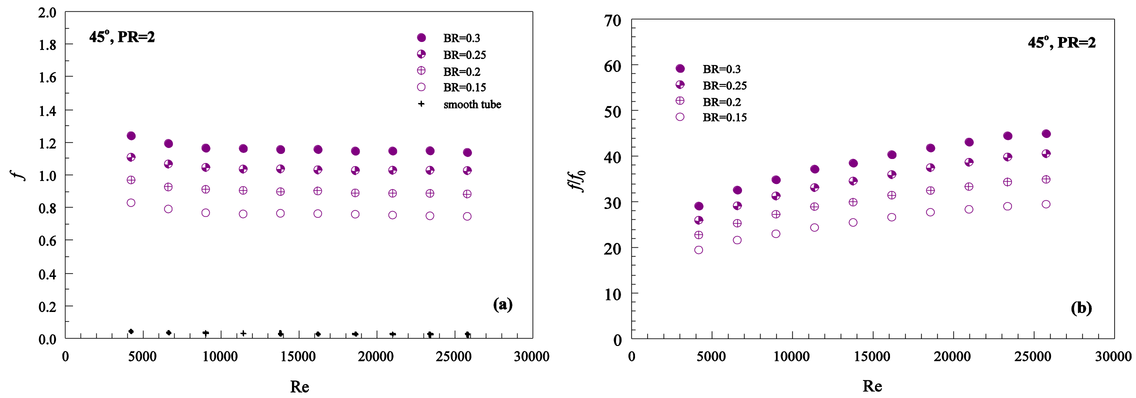


Figure 4 (a) f and (b) f/f_0 versus Re for 45° RWTs

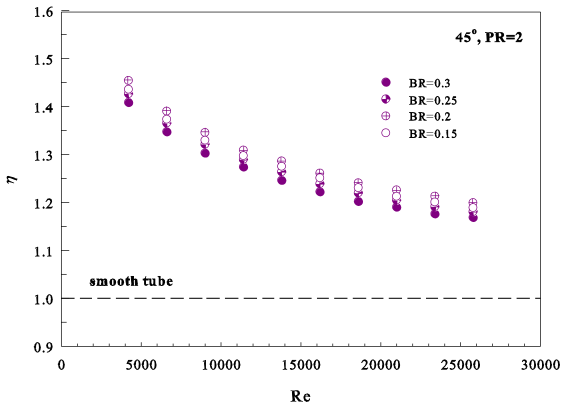


Figure 5 Variation of η with Re for 45° RWTs

5. Conclusions

An experimental study has been carried out to examine airflow friction and heat transfer characteristics in a uniform heat-fluxed tube fitted with 45° RWT at various BR for turbulent regime, Re from 4100 to 26,000. The use of RWT can induce vortex flows throughout the test tube and provides better flow mixing than the smooth tube alone. The heat transfer and friction loss in the tube with RWT inserts are, respectively, augmented around 3.7–4.3 and 19.4–45 times higher than those in the smooth tube. Over the BR range investigated, the maximum η of about 1.46 is obtained for BR = 0.2 and Re = 4100.

6. References

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