Turbulent Heat Transfer Enhancement in a Heat Exchanger Using Rib and Delta Winglet

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ABSTRACT

Effects of combined rectangular ribs and delta winglets on forced convection heat transfer and friction loss behaviors for turbulent airflow through a constant heat flux heat exchanger channel are experimentally investigated in the present work. The ribs used to generate reverse/recirculation flow are placed on the one ribbed wall and two opposite walls plates of the tested channel while three pairs of delta winglets with 15 mm high (half height of channel, 0.5H), 60 mm long and two attack angles (α) of 60° and 45° were symmetrically placed on the lower plate at the entrance of the test channel to create longitudinal vortex flow at the entry. Three rib arrangements, namely, one ribbed wall, in-line and staggered ribs on two opposite walls were introduced. Measurements are carried out for the channel of aspect ratio, AR = 10 and height, H = 30 mm with a single rib height, e = 6 mm and rib pitch, P = 40 mm. The flow rate is in terms of Reynolds numbers based on the inlet hydraulic diameter of the channel in a range of 5000 to 22,000. The experimental results show that the use of winglets in conjunction with the ribs leads to the considerable increase in heat transfer coefficient and friction factor in comparison with the smooth channel. In common with the winglet, the in-line rib arrangement provides higher heat transfer and friction loss than the staggered one and the single rib but the staggered rib shows better thermal performance over others. The largest attack angle α = 60° yields the highest increase in Nusselt number and friction factor while the α = 45° provides the lowest. However, the highest thermal performance is found for using the α = 45°.

Keywords: *turbulent channel flow, rectangular rib, winglet, thermal performance, friction loss*

1. INTRODUCTION

A high performance heat exchanger is needed in many engineering applications such as solar air heater, thermal power plants, chemical engineering, automobile manufacturing and refrigeration to use energy source efficiently leading to the reduction of size and cost of the heat exchanger. Therefore, many engineering techniques have been developed for enhancing the rate of convective heat transfer from the channel surface for decades. Periodic flow interruption generated by ribs [1], baffles [2], [3], ribs/grooves [4] and winglets [5], [6] is an extensively used means for augmentation of heat transfer in the heat exchangers. The rib/wings increase not only the degree of heat transfer coefficients by restarting the thermal boundary layer after flow reattachment between rib/wings but also the pressure drop due to the decreasing flow area effects. Therefore, the geometry parameters of rib/wings in the channel are among the most importance in the design of channel heat exchanger. In particular, wing attack angle (α) and rib orientation/arrangement are all parameters that

influence both the heat transfer coefficient and the overall thermal performance.

Many attempts have been made to study the effect of these parameters of ribs on heat transfer and friction factor for two opposite roughened surfaces. Han and Zhang [7] also found that the 60° broken 'V' ribs give higher heat transfer at about 4.5 times the smooth channel and perform better than the continuous ribs. Gao and Sunden [8] examined the heat transfer and flow characteristics in a rectangular channel of a high aspect ratio with V-shaped ribs using laser Doppler velocimetry and smoke visualization, and reported that Λ-shaped ribs provides higher heat transfer and thermal performance than V-shaped ribs. Bhagoria et al. [9] experimentally studied heat transfer and flow characteristics in a solar air heater having absorber plate roughened with wedge ribs at e/D ratios of 0.015–0.033 and rib wedge angles of 8–15°. They reported that the Nusselt number and friction factor increased by 2.4 and 5.3 times over smooth duct and the wedge ribs performed better than the chamfer ribs for comparison.

Swirl/vortex flow generators are often used in augmentative heat transfer in many engineering applications to enhance the rate of the heat and mass transfer equipment such as drying process, vortex combustor, heat exchanger, etc. There are several methods in generation of decaying swirl/vortex flows such as the tangential flow injection to induce a swirling fluid motion along the tube [10]; the guide vanes [11] and the delta winglet types [12], [13]. The winglets are designed to create longitudinal vortices that help to increase turbulence levels resulting in improved heat transfer performance, albeit with a minimal pressure loss penalty in comparison with other methods. Heat transfer enhancement by winglet type vortex generators mounted at the leading edge of a flat plate was found to be about 50 – 60% improvement in average heat transfer over the surface of the plate [12].

For using combined/compound turbulators, Promvonge and Eiamsa-ard [14] – [16] investigated experimentally the effect of various nozzles along with a snail-type swirl generator (decaying swirl) on heat transfer characteristics in a uniform heat flux tube and found that the heat transfer rate increases considerably for using both enhancement devices and is about 20 – 50% above a single enhancement device.

The main aim of this work is to examine heat transfer and friction loss behaviors for airflow through a constant heat flux channel fitted with rectangular ribs and delta winglets. Effects of rib arrangements, namely, one ribbed wall, in-line and staggered ribs on two opposite walls on heat transfer and friction loss in the channel are experimentally investigated. The use of winglets (three winglet pairs) placed at the entrance of the lower wall of the test channel are expected to create multiple longitudinal vortex flows at the entrance in order to prolong the residence time of the flow and to wash up the reverse flow trapped behind the ribs leading to higher heat transfer rate in the channel from the open literature [17]. Experimental results using air as the test fluid from three rib arrays of the rectangular ribs and the winglets are presented in turbulent channel flows in a range of Reynolds number (Re) from 5000 to 22,000.

2. EXPERIMENTAL SETUP

The experimental work was conducted in an open-loop experimental facility as shown in Fig. 1. The loop consisted of a circular pipe connected a high-pressure blower to a settling tank, and an orifice flow-meter was placed in this pipeline. A channel including a calm section (1.3 m), test section (0.44 m) and exit (0.3 m) was employed after the settling tank. The rectangular channel configuration was characterized by the channel height, H and the axial length of cycle or pitch, P, the respective values of which are 30 mm and 40 mm. The overall length of the channel was 2000 mm which included 10 pitches of the test section with the channel width, W, of 300 mm. Each of the ribbed walls was fabricated from 12 mm thick aluminum plates, 300 mm wide and 440 mm long (L). The rib dimensions were 6 mm high (e) and 20 mm thick (t). The form of ribbed plates was accomplished by means of wire-EDM (electrical discharge machine) machining. The ribs were mounted on the one ribbed wall and two opposite walls plates of the tested channel and three pairs of delta winglets with 0.5H height and 60 mm length were placed symmetrically at the entrance of the test channel lower plate with the attack angle of 60° and 45° to create longitudinal vortex flow at the entry as depicted in Fig. 2.

The AC power supply was the source of power for the plate-type heater, used for heating the upper plate of the test section only in order to maintain a uniform surface heat flux. A conducting compound was applied to the heater and the principal upper wall to reduce contact resistance. Special wood bars, which have a much lower thermal conductivity than the metallic wall, were placed on the inlet and exit ends of the upper and lower walls to serve as a thermal barrier at the inlet and exit of the test section. Air as the tested fluid in both the heat transfer and pressure drop experiments, was

directed into the systems by a 1.45 kW high-pressure blower. The operating speed of the blower was varied by using an inverter to provide desired air flow rates. The flow rate of air in the systems was measured by an orifice plate pre-calibrated by using hot wire and vane-type anemometers (Testo 445). The pressure across the orifice was measured using inclined manometer. The thermocouples were installed in holes drilled from the rear face and centered of the walls with the respective junctions positioned within 2 mm of the inside wall and axial separation was 40 mm apart. The inlet and outlet temperatures of the bulk air were measured at certain points with a data logger in conjunction with two RTD-type thermocouples, calibrated within ±0.2 °C deviation by thermostat before being used. Ten K-type thermocouples were tapped on the upper wall of the channel to measure the temperature variation along the channel surface to obtain the mean wall temperature. The thermocouple voltage outputs were fed into a data logger and then recorded via a personal computer. Two static pressure taps were located at the top of the principal channel to measure axial pressure drops across the test section, used to evaluate average friction factor. These were located at the centre line of the channel. One of these taps is 1200 mm downstream from the leading edge of the channel and the other is 50 mm upstream from the trailing edge. The pressure drop was measured by a digital differential pressure connected to the 2 mm diameter taps.

To quantify the uncertainties of measurements the reduced data obtained experimentally were determined. The uncertainty in the data calculation was based on Ref. [18]. The maximum uncertainties of non-dimensional parameters were ±5% for Reynolds number, ±8% for Nusselt number and ±10% for friction. The uncertainty in the axial velocity measurement was estimated to be less than ±7%, and pressure has a corresponding estimated uncertainty of ±5%, whereas the uncertainty in temperature measurement at the channel wall was about ±0.5%.

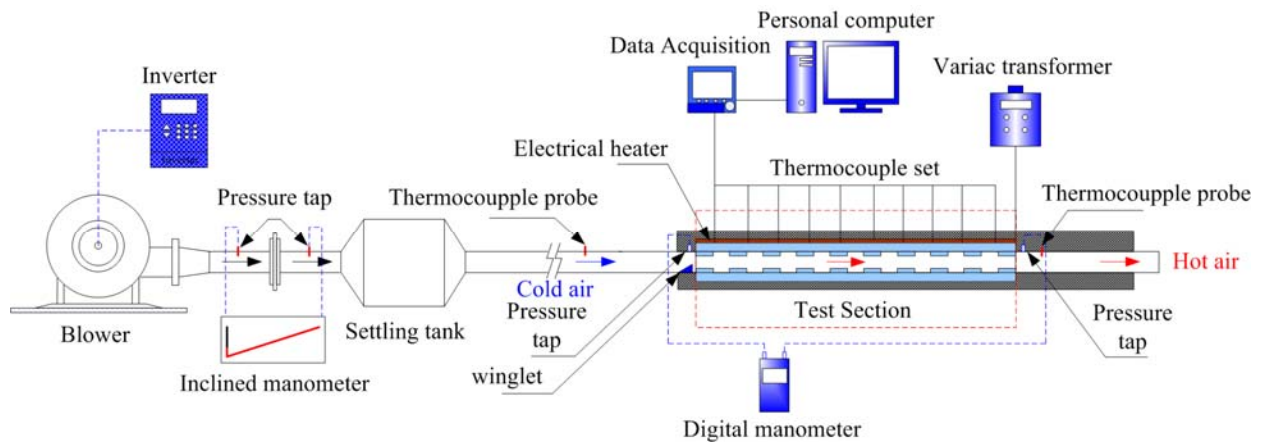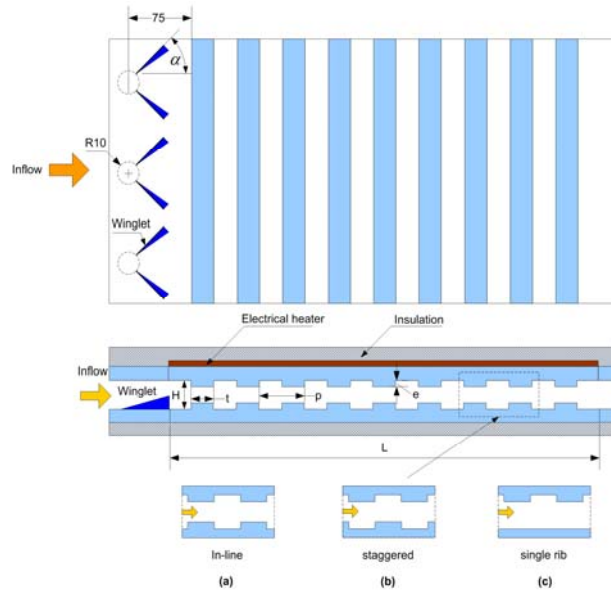**Fig. 1** *Schematic diagram of experimental apparatus.*

Fig. 2 *Test section with winglets: (a) in-line (b) staggered and (c) single rib arrangements.*

3. DATA REDUCTION

The goal of this experiment is to investigate the Nusselt number in the channel. The Reynolds number based on the channel hydraulic diameter, D_h, is given by

$$Re = UD_h / \nu \tag{1}$$

where U and ν are the mean air velocity of the channel and kinematics viscosity of air, respectively. The average heat transfer coefficient, h, is evaluated from the measured temperatures and heat inputs. With heat added uniformly to fluid (Q_{air}) and the temperature difference of wall and fluid ($T_w - T_b$), the average heat transfer coefficient will be evaluated from the experimental data via the following equations:

$$Q_{air} = Q_{conv} = \dot{m}C_p(T_o - T_i) = VI - Q_{loss} \tag{2}$$

As found, the heat absorbed by the fluid for thermal equilibrium test is within 4% lower than the heat supplied by electrical winding in the test channel due to convection heat losses from the test section to surroundings. For data analysis, only the heat transfer rate absorbed by the air is taken for internal convective heat transfer coefficient calculation. The heat transfer coefficient can be written as follows:

$$h = \frac{\dot{m}C_p(T_o - T_i)}{A(\tilde{T}_s - T_b)}, \tag{3}$$

in which,

$$T_b = (T_o + T_i) / 2, \tag{4}$$

and

$$\tilde{T}_s = \sum T_s / 10. \tag{5}$$

The term A is the convective heat transfer area of the heated upper channel wall whereas $\tilde{T}_s$ is the average surface temperature obtained from local surface temperatures, T_s, along the axial length of the heated channel. The terms $\dot{m}$, C_p, V and I are the air mass flow rate, specific heat, voltage and current, respectively. Then, average Nusselt number, Nu, is written as:

$$Nu = \frac{hD_h}{k}. \tag{6}$$

The friction factor, *f*, is evaluated by:

$$f = \frac{2}{(L/D_h)} \frac{\Delta P}{\rho\, U^2} , \qquad (7)$$

where ΔP is a pressure drop across the test section and ρ is density. Thermo-physical properties of air are determined at the overall bulk air temperature, T_b, from Eq. (4).

The thermal enhancement factor, TEF, defined as the ratio of heat transfer coefficient of an augmented surface, *h* to that of a smooth surface, h_0, at the same pumping power:

$$\text{TEF} = \frac{h}{h_0}\bigg|_{pp} = \frac{\text{Nu}}{\text{Nu}_0}\bigg|_{pp} = \left(\frac{\text{Nu}}{\text{Nu}_0}\right)\left(\frac{f}{f_0}\right)^{-1/3} . \qquad (8)$$

4. RESULTS AND DISCUSSION

In the present work, experimental measurements of both heat transfer and pressure loss in channels with combined rectangular ribs and delta winglets are presented. Measurements were conducted in a channel of aspect ratio, AR = 10 for three rib arrangements over a range of Re as mentioned earlier.

4.1 Verification of Smooth Channel

The present experimental results on heat transfer and friction characteristics in a smooth wall channel are first validated in terms of Nusselt number (Nu) and friction factor (*f*). The Nu and *f* obtained from the present smooth channel are, respectively, compared with the correlations of Dittus-Boelter and Blasius found in the open literature [19] for turbulent flow in ducts.
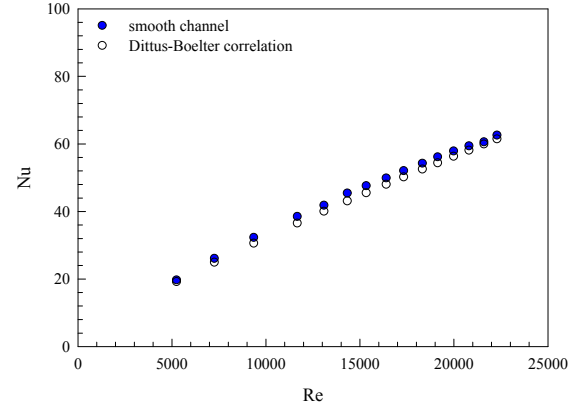
Correlation of Dittus-Boelter,

$$\text{Nu} = 0.023\,\text{Re}^{0.8}\text{Pr}^{0.4} \text{ for heating.} \qquad (9)$$

Correlation of Blasius,

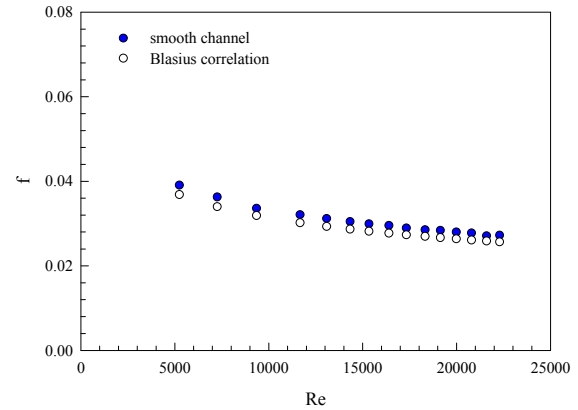$$f = 0.316\,\text{Re}^{-0.25} \qquad (10)$$

Fig. 3a and b shows, respectively, a comparison of Nu and *f* obtained from the present work with those from correlations of Eqs. (9) and (10). In the figures,

the present results agree very well within $\pm\,6\%$ for both Nu and *f* correlations.

(a)

(b)

Fig. 3 *Verification of (a) Nu and (b) f for smooth channel.*

4.2 Effect of Rib and Winglet

The present experimental results on heat and flow friction characteristics in a uniform heat flux channel equipped with 6 mm rib height are presented in the form of Nu and *f*. The Nu obtained under turbulent flow conditions for rectangular ribs with only one rib pitch (P = 40 mm) are presented in Fig. 4. In the figure, the rib turbulators yield considerable heat transfer enhancements with a similar trend in comparison with

the smooth channel and the Nu increases with the rise of Re. This is because the rib turbulators interrupt the development of the boundary layer of the fluid flow and increase the turbulence degree of flow. The winglet, $\alpha = 60°$ is higher Nu than those for $\alpha = 45°$. This is caused by largest attack angle of using $\alpha = 60°$ interrupting the flow leading to stronger vortex flow strength and thus promoting high levels of mixing over others. The winglet, $\alpha = 60°$ and in-line rib arrangement provides higher Nu than the staggered and the single rib about 5–19%. The use of rib and winglet, $\alpha = 60°$ leads to an increase in Nu in a range of 333 to 431% over the smooth channel.

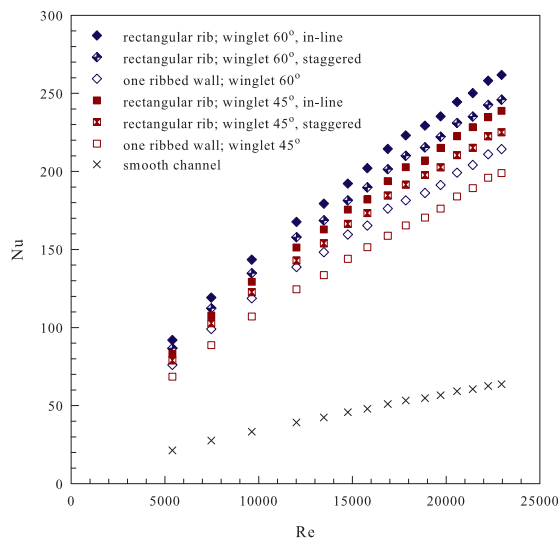**Fig. 4** *Variation of Nu with Re.*

The effect of using the combined rib and winglet on the isothermal pressure drop across the tested channel is presented in Fig. 5. The variation of the pressure drop is shown in terms of f with Re. In the figure, it is apparent that use of both turbulators leads to a substantial increase in f over the smooth channel. This can be attributed to flow blockage, higher surface area and the act caused by the reverse flow. The winglet, $\alpha = 60°$ is higher f than those for $\alpha = 45°$. The winglet, $\alpha = 60°$ and in-line rib arrangement provides higher f than the staggered and the single rib about 19–36%. The mean increase in f of using the in-line rib and winglet, $\alpha = 60°$ is about 36.6 times the smooth channel.
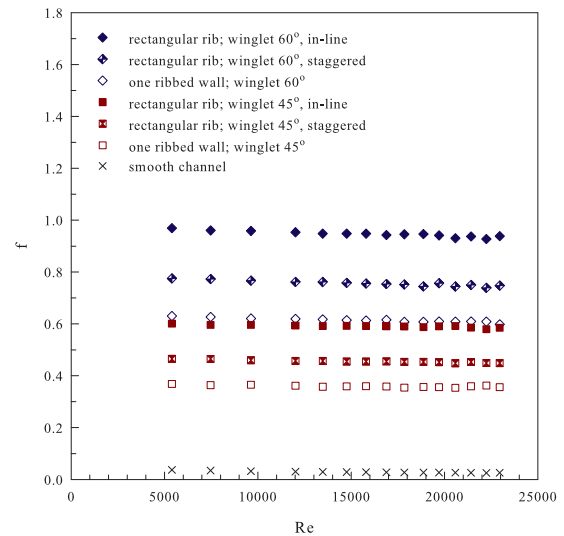

Fig. 5 *Variation of f with Re.*

4.3 Effect of Rib Arrangement

The present results are reported for using three rib arrangements: one ribbed wall, in-line and staggered ribs on two opposite walls. Comparisons of the heat transfer and friction loss in the channel fitted with the in-line, staggered and single rib array are also depicted in Figs. 4 and 5, respectively. It is visible in Fig. 4 that the channel with the in-line array provides higher heat transfer rate than that with the staggered one and single rib for all Re. This can be attributed to the higher flow blockage (e/H = 0.2) creating the stronger reverse/recirculation flow from the in-line array. The heat transfer rates obtained from using winglets with the in-line, staggered and single ribs are around 381–421%, 361–396% and 315–345% over those from the smooth channel, respectively, depending on the Re interval.

The variation of isothermal f value with Re for three different rib arrays is also depicted in Fig 5. In the figure, the f for the in-line is found to be considerably higher than that for the staggered and single rib, respectively, and tends to be nearly uniform with the increase of Re. The average increases in f for the in-line, staggered and single ribs are, respectively, around 20–33%, 16–26% and 13–21% over those from the smooth channel.

4.4 Effect of Attack Angle

The present results for using the winglets attack angle of 60° and 45° on heat transfer and friction factor in comparison with the smooth channel are also presented in Figs. 4 and 5, respectively. The heat transfer obtained from using the 60°–winglets is around 7–9% higher than that from the 45°. The 60°–winglet provides higher f than the 45° at about 37–41%.

4.5 Performance Evaluation

The Nusselt number ratio (Nu/Nu_0) defined as a ratio of augmented Nu to Nu_0 plotted against the Re value is displayed in Fig. 6. In the figure, the Nu/Nu_0 shows a slight decrease with the rise of Re values. For the combined ribs and winglets with in-line, staggered and single ribs, the increases in Nu/Nu_0 values at $\alpha =$ 60° and 45° are, respectively, about 4.11–4.32, 3.86–4.07 and 3.33–3.57; 3.72–3.91, 3.52–3.71 and 3.11–3.22 times above the smooth channel, depending on Re.
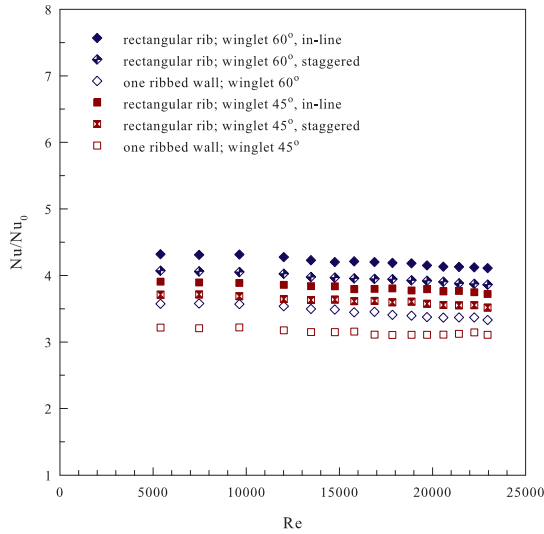

Fig. 6 *Variation of Nu/Nu_0 with Re.*

Fig. 7 depicts the variation of the friction factor ratio (f/f_0) with the Re value. It is observed that the f/f_0 tends to increase with increasing the Re for all turbulators used. The in-line rib array provides a considerable increase in the f/f_0 than that with the staggered and single rib, respectively, under the same conditions. For the combined ribs and winglets with in-line, staggered

and single ribs, the increases in f/f_0 values at $\alpha = 60°$ and 45° are, respectively, about 26.3–36.6, 21.1–29.1 and 17.1–23.3; 16.3–22.8, 12.6–17.5 and 10–13.9 times above the smooth channel, depending on Re.
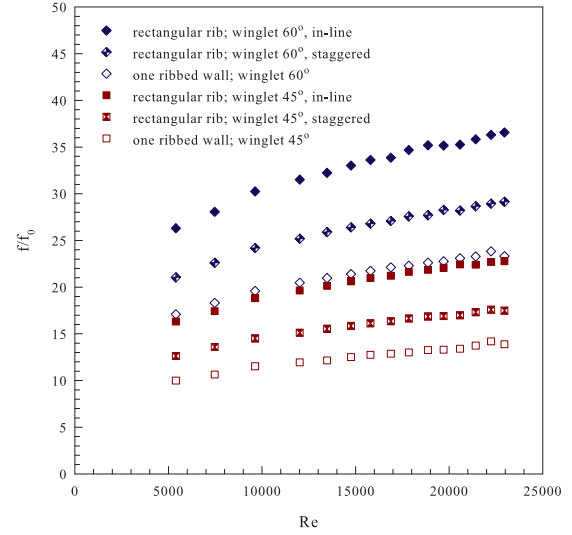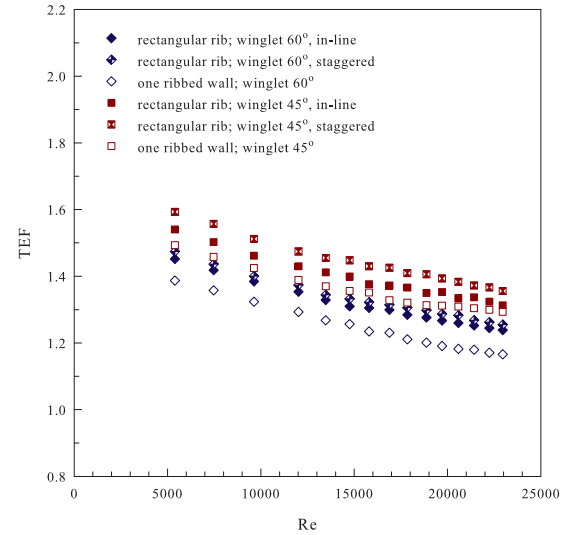

Fig. 7 *Variation of f/f_0 with Re.*

Fig. 8 *Variation of TEF with Re.*

Fig. 8 shows the variation of the thermal enhancement factor (TEF) with Re. The data obtained

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by the measured Nu and f values are compared at equal pumping power. In the figure, the TEF tends to reduce with the increase in Re for all the cases. It is seen that the combined ribs and winglets with $\alpha = 45°$ and staggered array gives the highest TEF at lower Re. For the $\alpha = 45°$ combined ribs and winglets of in-line, staggered and single rib, the maximum TEFs are, respectively, about 1.54, 1.59 and 1.49. At a given rib arrangements value, the use of $\alpha = 45°$ yields the TEF around 5–9% higher than that of $\alpha = 60°$.

5. CONCLUSIONS

An experiment has been carried out to investigate airflow friction and heat transfer characteristics in a high aspect ratio channel fitted with combined rib and delta winglet turbulators for the turbulent regime, Re from 5000 to 22,000. In the present study, the following conclusions can be drawn.

- The use of the rib and winglet turbulators with winglet attack angle $\alpha = 60°$ causes not only the very high pressure drop increase but also provides considerable heat transfer augmentations, $Nu/Nu_0 = 4.11$–4.32.
- The augmentation of Nu both turbulators tends to be nearly uniform values with the rise of Re values. In common, with the winglet, the in-line rib arrangement provides higher heat transfer and friction loss than the staggered and single ribs, respectively, for a similar mass flow rate.
- The largest attack angle $\alpha = 60°$ yields the highest increase in Nu and f but the one at $\alpha = 45°$ yields the highest TEF.
- The staggered rib of 45°–winglet yields the highest TEF of about 1.59 at lower Re.
- The best operating regime for using these compound turbulators is found at the staggered arrangement, lower attack angle and/or Re values.
- The Nu and TEF of the present device is seen to be higher than that of the rib/the winglet alone as shown in the literature [6].

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