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Thermal Behaviors in a Square Duct with Inclined-Baffle Inserts

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Abstract

This work presents an experimental study on thermal characteristics in a square-duct heat exchanger inserted with angled baffles. The test duct has a square section with a uniform wall heat-flux condition. The experiments are carried out by varying the airflow rate in terms of Reynolds number (Re) based on the hydraulic diameter of the duct from 4100 to 23,000. The heat transfer and pressure loss characteristics in the square duct are presented in terms of Nusselt number (Nu) and friction factor (f), respectively. Effects of the baffle inserts at various pitches and attack angles on heat transfer and pressure loss behaviors in the duct are investigated. The baffle characteristics such as baffle to duct height ratio or blockage ratio, (e/H = BR = 0.3), pitch to duct height ratio or pitch ratio, (PR = 1.0 and 1.5) and the attack angle, (α = 45^o, 60^o and 90^o) are introduced. The experimental result reveals that the insertion of the baffles provides considerably higher heat transfer and pressure loss values than the smooth duct. The baffle at α = 90^o and PR = 1 provides the highest heat transfer and pressure loss but the one at α= 45^o and PR = 1 provides the highest thermal enhancement factor.

Keywords*:* baffle; heat transfer; pressure loss; thermal behavior; square duct

1. Introduction

Many engineering techniques have been devised for enhancing convective heat transfer from the wall surface. The use of turbulator inserts is a simple technique for enhancing convective heat transfer in thermal system ducts which completely result in the change of the flow field and hence the variation of the local convective heat transfer coefficient and increases not only the heat transfer rate for the increased turbulence degree and for the effects caused by reattachment but also substantial the pressure loss.

Several investigations have been carried out to study the effect of turbulator inserts on heat transfer and flow friction behaviors in cooling or heating ducts. Chompookham et al. [1] studied the effect of combined wedge ribs and winglet type vortex generators (WVGs) in a channel. The Nusselt number and friction factor values obtained from combined the ribs and the WVGs were found to be much higher than those from the ribs/WVGs acting alone. Thianpong et al. [2] investigated the thermal behaviors of isosceles triangular ribs attached on the two opposite channel walls with AR=10 and suggested the optimum thermal performance of the staggered ribs should be at about e/H=0.1 and P/H = 1. Lee et al. [3] studied experimentally the heat and mass transfer in a rectangular channel with two different V-shaped ribs: continuous 60^{o} V-shaped and multiple (staggered) 45^{o} V-shaped ribs, and found that two pairs of counter-rotating vortices are generated in the channel. The effect of channel aspect ratio was more significant for the 60° V-shaped ribs than for the multiple 45° V-shaped ribs. Promvonge [4] investigated thermal characteristics of circular- and square-wire coils inserted tubes and found that the wire coil with square cross section provided higher thermal performance than the one with circular cross section.

Wang and Sunden [5] studied several inserted devices for both laminar and turbulent flow regions. They found that the coiled wire performs effectively in enhancing heat transfer in a turbulent flow region, whereas the twisted tape yields a poorer overall efficiency. Promvonge et al. [6] examined experimentally the turbulent flow over 30^{o}-angle-finned tape inserted diagonally in a square duct. They noted that at smaller fin pitch spacing, the finned tape at e/H= 0.3 provides the highest heat transfer and friction factor but the one at e/H=0.2 and PR=1 yields the best thermal performance. The thermal performance of the finned tape turbulator was also found to be much higher than that of the wire coil and twisted tape inserts. Eiamsa-ard et al. [7] studied the effect of insertion of tandem wire coil elements used as turbulator in a square duct. They reported that the full-length wire coil provides higher heat transfer and friction factor than the tandem wire-coil elements. Chandra et al. [8] carried out measurements on heat transfer and pressure loss in a square channel with continuous ribs on four walls. They found that the heat transfer and friction factor augmentation was increased with the rise in the number of ribbed walls.

In the present work, the investigation on thermal behaviors for turbulent square-duct flow over the inclined baffles placed on the core area is carried out with the main aim being to study the changes in the flow pattern and heat transfer performance. The use of the baffle turbulator is expected to create vortex flows throughout the tested duct to better flow mixing in the core and wall regimes leading to higher heat transfer rate.

2. Experimental Setup

A schematic diagram of the experimental apparatus is presented in Fig. 1 while the detail of the angled baffles inserted in the test section is depicted in Fig. 2. In Fig. 1, a circular pipe was used for connecting a high-pressure blower to a settling tank, which an orifice flow-meter was mounted in this pipeline while a square duct including a calm section and a test section was employed after the settling tank. The square duct configuration was characterized by the duct height, H=45 mm, the baffle pitch to duct height ratio or pitch ratio (P/H=PR=1.0 and 1.5), the attack angle (α = 45°, 60° and 90°) and the baffle to duct height ratio or blockage ratio (e/H=BR= 0.3). The tested duct made of 3 mm thick aluminum plates had a cross section of 45x45 mm^2 and 1000 mm long (L). The baffle strip dimensions were 45 mm long (b), 13.5 mm high (e), and 0.3 mm thick (t).

The AC power supply was the source of power for the plate-type heater, used for heating all walls of the test section in order to maintain a uniform surface heat flux. Air as the tested fluid 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. The pressure across the orifice flow-meter was measured using inclined manometer. In order to measure temperature distributions on the principal upper, lower and side walls, twenty eight thermocouples were fitted to the walls along the test section. The thermocouples were attached 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 100 mm apart. To measure the inlet and outlet bulk temperatures, two thermocouples were positioned upstream and downstream of the test duct. All thermocouples were K-type, 1.5 mm diameter wire. The thermocouple voltage outputs were fed into a data acquisition system (Fluke 2650A) and then recorded by via a personal computer.

Two static pressure taps were located at the top of the principal wall to measure axial pressure drops across the test section, used to evaluate average friction factor. These were located at the centre line of the duct. One of these taps was 50 mm upstream of the test duct and the other was 50 mm downstream. The pressure drop was measured by a digital differential pressure.

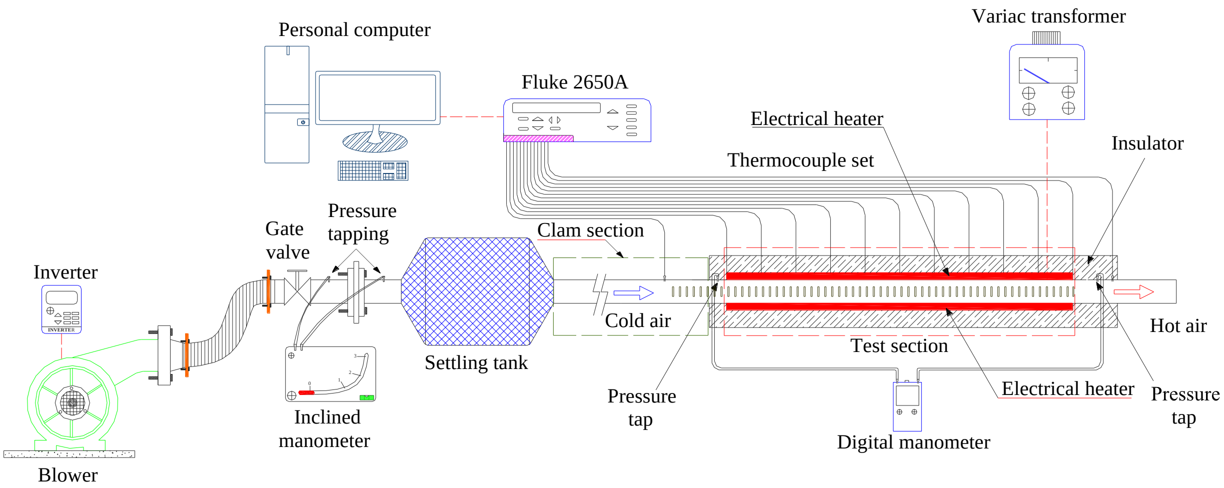


Fig. 1. Schematic diagram of experimental apparatus.

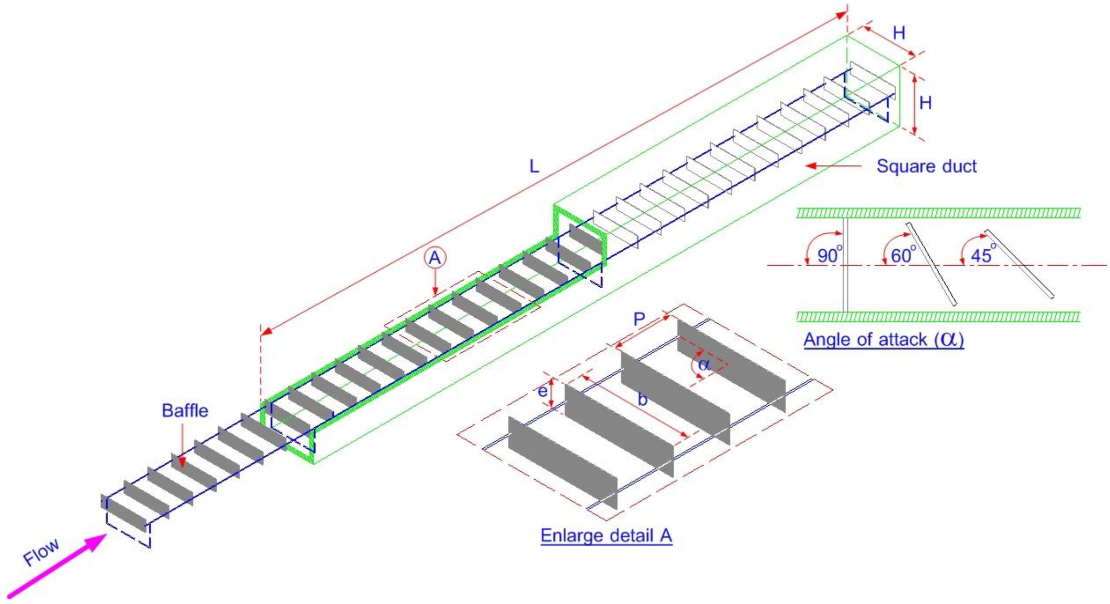


Fig. 2. Test section with angled baffle inserts.

To quantify the uncertainties of measurements the reduced data obtained experimentally were determined. The uncertainty in the data calculation was based on Ref. [9]. The maximum uncertainties of non-dimensional parameters were ±5% for Reynolds number, ±7% for Nusselt number and ±9% for friction. The uncertainty in the axial velocity measurement was estimated to be less than ±5%, and pressure has a corresponding estimated uncertainty of ±5%, whereas the uncertainty in temperature measurement at the tube wall was about ±0.5%.

3. Data Reduction

The main aim of this experiment is to investigate the performance enhancement of a square duct heat exchanger fitted with baffle turbulators. The experimental results are shown in dimensionless term of Nusselt number and friction factor. 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 ($\tilde{T}_s - T_b$), the average heat transfer coefficient will be evaluated from the experimental data via the following equations:

$$Q_{air} = Q_{conv} = \dot{m}C_p(T_o - T_i) = VI \quad (1)$$

$$h = \frac{Q_{conv}}{A(\tilde{T}_s - T_b)} \quad (2)$$

in which,

$$T_b = (T_o + T_i)/2 \quad (3)$$

and

$$\tilde{T}_s = \sum T_s/28 \quad (4)$$

The term A is the convective heat transfer area of the heated duct wall whereas $\tilde{T}_s$ is the average surface temperature obtained from local surface temperatures along the axial length of the heated channel. Then, the average Nusselt number is written as:

$$\mathrm{Nu} = \mathrm{hD_h/k} \tag{5}$$

The Reynolds number based on the duct hydraulic diameter (D_h) is given by:

$$\mathrm{Re} = \mathrm{UD_h/\nu} \tag{6}$$

The duct hydraulic diameter can define by:

$$D_h = \frac{4A_c}{P_w} \tag{7}$$

where A_c is the cross sectional area and P_w is the wetted perimeter of the cross section

The friction factor is evaluated by:

$$f = \frac{2}{(L/D_h)} \frac{\Delta P}{\rho U^2} \tag{8}$$

where ΔP is the pressure drop across the test section and U is the mean air velocity of the channel.

The thermal enhancement factor (TEF) defined as the ratio of the heat transfer coefficient of an augmented surface, h to that of a smooth surface, h_0, at a constant pumping power [10] is given by:

$$\mathrm{TEF} = \left.\frac{h}{h_0}\right|_{pp} = \left.\frac{\mathrm{Nu}}{\mathrm{Nu}_0}\right|_{pp} = \left(\frac{\mathrm{Nu}}{\mathrm{Nu}_0}\right)\left(\frac{f}{f_0}\right)^{-1/3} \tag{9}$$

4. Results and Discussion

4.1 Verification of smooth duct

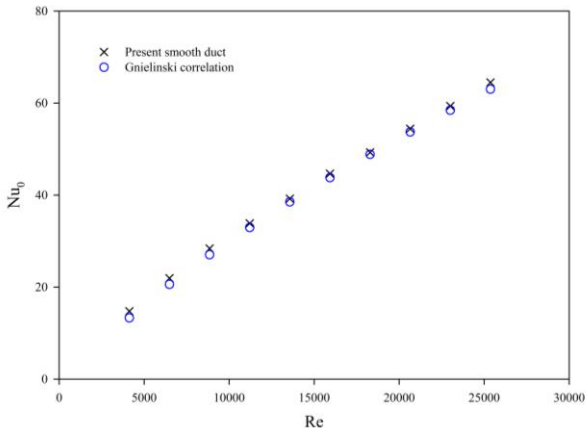
The present experimental results on heat transfer and flow friction characteristics in a smooth-walled square duct are first validated in terms of Nusselt number (Nu) and friction factor (f). The Nusselt number and friction factor obtained from the present smooth square duct are compared with the correlations of Gnielinski and Petukhov found in the literature [11] for turbulent flow in ducts.

Correlation of Gnielinski,

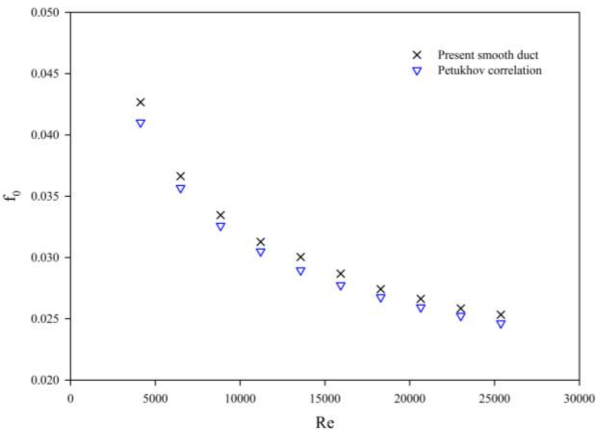
$$\mathrm{Nu} = \frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/8)^{1/2}(\mathrm{Pr}^{2/3}-1)} \tag{10}$$

Correlation of Petukhov,

$$f = (0.79\ln\mathrm{Re} - 1.64)^{-2} \tag{11}$$



(a)



(b)

Fig. 3. Validation of (a) Nu and (b) *f* for smooth duct.

Fig. 3a and b shows, respectively, a comparison of Nusselt number and friction factor obtained from the present work with those from correlations of Eqs. (10) and (11). In the figures, the present results reasonably agree well within ±2.8% and ±3.2% for Nu and *f*, respectively.

4.2 Heat transfer and friction loss

The present experimental results on the heat transfer rate and friction loss are presented in the dimensionless form of Nusselt number and friction factor respectively.

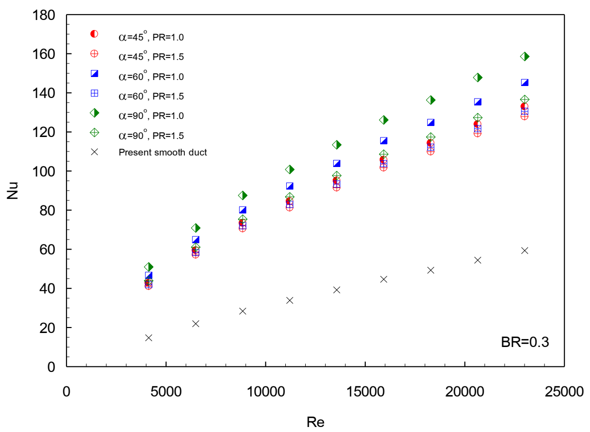


Fig. 4. Variation of Nu with Re.

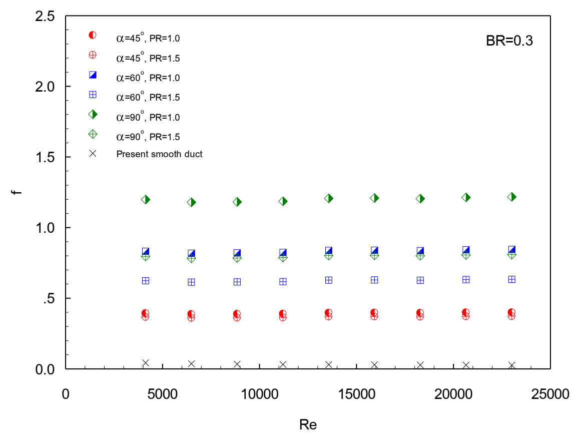


Fig. 5. Variation of *f* with Re.

Fig. 4 displays the variation of Nu with Re. The use of baffles enhances considerable heat transfer with a similar trend in comparison with the smooth duct. The Nu increases with the rise of Re. This is because the baffles interrupt the development of the boundary layer of the fluid flow and increase the turbulence intensity of flow. It can be observed that the Nu increases with the rise in the attack angle, but with the reduction of PR. It is interesting to note that the use of baffles at α = 90° and PR = 1.0 provide the highest heat transfer rate. This is because the baffles at α= 90° and PR=1.0 provide stronger interrupting the flow and diverting its direction, thus promoting high levels of mixing over the others.

Fig. 5 depicts the variation of *f* with Re for various baffles. In the figure, it is seen that the baffles provide a substantial increase in *f* above the smooth duct. This can be attributed to flow blockage and the act caused by the reverse flow in the presence of baffles. It is visible that the maximum friction factor is found at the highest attack angle and the lowest PR. As expected, the *f* of the baffles at α=90° and PR=1 are considerably higher than the others.

4.3 Performance evaluation

The Nusselt number ratio, Nu/Nu_0, defined as a ratio of augmented Nusselt number to Nusselt number of smooth duct, plotted against the Reynolds number value is displayed in Fig. 6. In the figure, the Nu/Nu_0 tends to decrease with the rise of Re for all cases. The Nu/Nu_0 values are found to be 2.2-3.5 times above the smooth duct.

The variation of friction factor ratio, f/f_0 with Re values is depicted in Fig. 7. It is visible in the figure that the f/f_0 tends to increase with raising the Re. The f/f_0 values are around 9-48 times above the smooth duct. This result indicates that the use of lower attack angle and higher pitch ratio can help to reduce the pressure loss considerably.

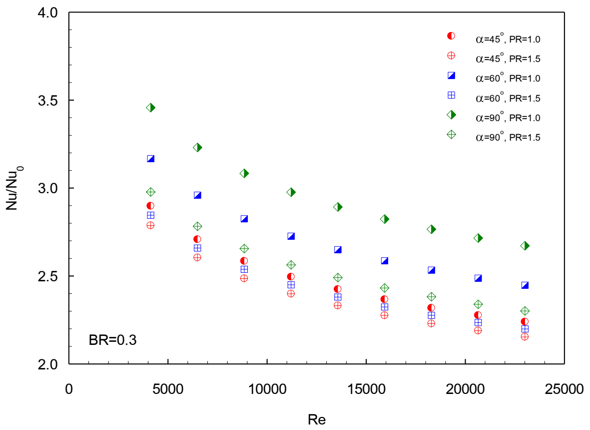


Fig. 6 Variation of Nu/Nu_0 with Re.

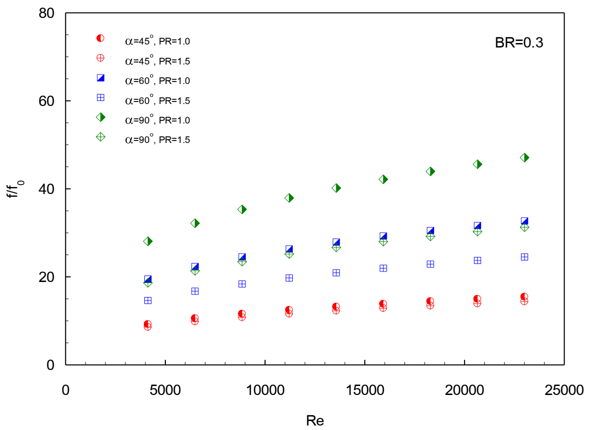


Fig. 7. Variation of f/f_0 with Re.

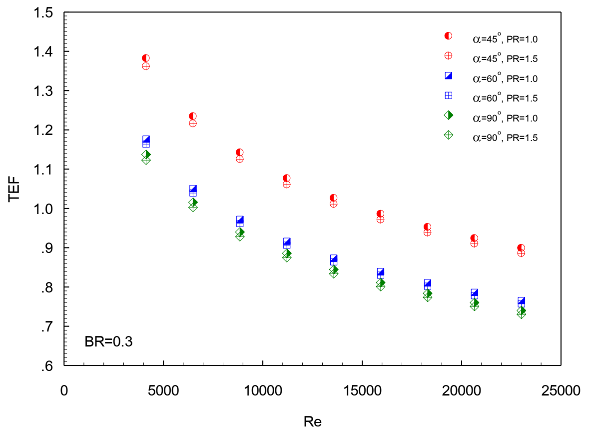


Fig. 8. Variation of TEF with Re.

Fig. 8 shows the variation of the thermal enhancement factor (TEF) with Re values for various baffle inserts. For all, the data obtained from Nu and *f* values are compared at a similar pumping power as defined in Eq. (9). The TEF tends to decrease with the rise of Re values for all cases. It is seen that the baffles at α= 45° and PR=1.0 gives the highest TEF of about 1.4 at the lowest value of Reynolds number.

5. Conclusion

An experimental study has been carried out to examine airflow friction and heat transfer characteristics in a square duct fitted with angled baffles for the turbulent regime, Re from 4100-23,000. The angled baffles provide a considerable increase in pressure drop and heat transfer over the smooth duct. The heat transfer rate and the flow friction increase with rising the attack angle and lowering the pitch ratio. The use of the baffle turbulator with α= 90° and PR= 1.0 leads to the highest transfer rate and pressure drop while the best operating regime for this work is found at the use of baffle turbulator with α= 45° and PR=1.0, which yields the maximum TEF is about 1.4 at the lowest Reynolds number.

6. Acknowledgement

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7. References

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