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Fluid Dynamics and Transport Phenomena

Enhanced heat transfer in a heat exchanger square-duct with discrete V-finned tape inserts☆

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ABSTRACT

The article presents an experimental and numerical study on thermal performance enhancement in a constant heat-fluxed square-duct inserted diagonally with 45° discrete V-finned tapes (DFT). The experiments were carried out by varying the airflow rate through the tested square duct with DFT inserts for Reynolds number from 4000 to 25000. The effect of the DFT with V-tip pointing upstream at various relative fin heights and pitches on heat transfer and pressure drop characteristics was experimentally investigated. Both the heat transfer and pressure drop were presented in terms of Nusselt number and friction factor respectively. Several V-finned tape characteristics were introduced such as fin- to duct-height ratio or blockage ratio ($R_B = e/H = 0.075$, 0.1, 0.15 and 0.2), fin pitch to duct height ratio ($R_P = P/H = 0.5$, 1.0, 1.5 and 2.0) and fin attack angle, $\alpha = 45°$. The experimental results reveal that the heat transfer and friction factor values with DFT inserts increase with the increment of R_B but the decrease of R_P. The inserted square-duct at $R_B = 0.2$ and $R_P = 0.5$ provides the highest heat transfer and friction factor while the one with $R_B = 0.1$ and $R_P = 1.5$ yields the highest thermal performance. Also, a numerical simulation was conducted to investigate the flow structure and heat transfer mechanism inside the tested duct with DFT inserts.

1. Introduction

Many engineering techniques have been devised for enhancing the rate of convective heat transfer from the wall surface in order to increase heat transfer rate so that compact heat exchangers with high efficiency can be developed. The uses of turbulators such as fin, baffle, rib, twisted tape, wire coil, *etc.*, are proved effective due to the increased turbulence degree and pressure loss. Therefore, to achieve optimal thermal performance, the pertinent configuration parameters of the turbulator are to be considered.

Several efforts have been made to study the effect of the parameters of turbulators on heat transfer and friction factor behaviors. Promvonge *et al.*[1,2] investigated experimentally and numerically the turbulent flow over 30° angle-finned tapes inserted in a square channel. Promvonge *et al.*[3–6] and Kwankaomeng and Promvonge [7] studied numerically the heat transfer of laminar and turbulent flows in a square channel and found that a pair of counter-rotating vortices (P-vortex) created by the baffles/ribs placed on the channel walls can help induce impingement/reattachment flows on the wall resulting in greater increase in heat transfer due to vortex-induced impingement (VI) effect. Eiamsa-ard *et al.*[8] reported the effects of insertion of tandem wire coil elements used as a turbulator in a square duct and found that the full-length wire coil provides higher heat transfer and friction factor than the tandem wire coil elements. Eiamsa-ard *et al.*[9] investigated the influence of combined circular-ring and twisted tape inserts on thermal characteristics in a round tube and reported that the combined devices provided considerably higher thermal performance than the ring acting alone. Eiamsa-ard *et al.*[10,11] again examined heat transfer characteristics in a circular tube with helical and twisted tapes inserted. They observed that the enhancement efficiency of the short-length tape insert was lower than the full-length one and the Nusselt number values of the loose-fit, helical tape with and without core–rod were about 230% and 340%, respectively, over the smooth tube. Eiamsa-ard and Promvonge [12] studied experimentally thermal behaviors of turbulent tube flow through a straight tape with double-sided delta wings. They found that the delta-winged tape yielded Nusselt number and friction factor up to 165% and 14.8 times above the plain tube. Promvonge *et al.*[13], Chompookham *et al.*[14] and Thianpong *et al.*[15] examined the effects of ribs and winglet type vortex generators (WVGs) on heat transfer in a channel and reported that the Nusselt number and the friction factor for utilizing both the rib and the WVGs are found to be considerably higher than those for using the rib or the WVGs alone. Skullong and Promvonge [16] investigated the heat transfer and flow friction characteristics in a solar air heater channel fitted with delta-winglet type vortex generators. Sri Harsha *et al.*[17] and Gupta *et al.*[18] studied the local heat transfer distribution and pressure drop in a square channel and found that the 60° V-broken rib gives the heat transfer higher than the 90° continuous and profiled ones. Tanda [19] investigated the effect of transverse, angled ribs, discrete, angled discrete ribs, V-shaped, V-shaped broken and parallel broken ribs on heat transfer and flow

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friction. Chandra *et al.*[20] carried out measurements on heat transfer and pressure loss in a square channel with continuous ribs on four walls and reported that the heat transfer augmentation increased with the rise in the number of ribbed walls. Murata and Mochizuki [21] studied numerically the heat transfer distribution in a rib-roughened duct with transverse or angled ribs. The comparison between the laminar and turbulent results showed clear differences in heat transfer distribution because the higher momentum fluid of the turbulent case was more disturbed by the ribs as compared to the laminar case. Han *et al.*[22,23] examined experimentally the heat transfer in a square channel with ribs on two walls for nine different rib configurations. Lau *et al.*[24] presented the effects of V-shaped rib arrays on turbulent heat transfer and flow friction in a square channel.

Most of the literature review reports both turbulator and vortex generator in different shapes and arrangements placed only on the test section wall. The study on thermal performance of a heat exchanger square-duct with diagonal discrete V-finned tapes (DFT) inserts has never been reported. Therefore, a new DFT insert is proposed to provide higher thermal performance than wire-coil/twisted-tape inserts. The concept of this work came from another work of the authors [3] that the discrete ribs/fins were repeatedly placed on two opposite walls of a square duct while in the present work, the discrete V–fins were mounted periodically on a straight tape for ease of insertion. Thus, the main aim of the present work is to investigate the heat transfer and flow friction characteristics in a square duct heat exchanger fitted with the DFT. The experimental data are presented for turbulent duct flows over the DFT. The use of DFT inserts is expected to create vortex flows throughout the test duct to higher mixing of flows between the central core and wall regimes leading to greater heat transfer rate and lower pressure drop than the previous other turbulators.

2. Experimental Setup

A schematic diagram of the experimental apparatus is presented in Fig. 1 while the detail of the DFT inserted diagonally into a square duct is shown in Fig. 2. In Fig. 1, a circular pipe was connected between a high-pressure blower and settling tank where an orifice flow-meter to measure the flow rate was placed in this pipeline. The overall length of the duct was 3000 mm. The tested square duct made of 3 mm thick aluminum has a cross section of 45 × 45 mm^2 and 1000 mm length (L). The diagonal straight tape was made of aluminum with its dimension of 63 × 1200 × 0.5 mm^3. The fins made of 0.3 mm aluminum strip were attached on both sides of the straight tape. The four fin sizes were 3.375, 4.5, 6.75 and 9.0 mm high (e) with 0.3 mm thickness (t), equivalent to fin to duct-height ratios, $R_B = e/H = 0.075$, 0.10, 0.15 and 0.20 respectively, while there were four fin-pitch to duct-height ratios ($R_P = P/H = 0.5$, 1.0, 1.5 and 2.0) with the fin attack angle (α) of 45°.

The AC power supply provided energy for heating all walls of the test section and maintains a uniform surface heat flux. Air as the test fluid was directed into the systems by a 1.45 kW high-pressure blower. The operating speed of the blower was controlled by using an inverter to provide the desired airflow rate, which was measured by using an orifice plate system. The pressure drop across the orifice was measured using an inclined manometer. The temperature distributions along the test section were measured by twenty-eight thermocouples fixed into the 2 mm centered grooves drilled from the outer duct surfaces. To measure the inlet and outlet bulk temperatures, two thermocouples were positioned at the entrance and exit of the test duct. All thermocouples were type-K, 1.5 mm diameter wire. All measured temperature values were fed into a data logger (Fluke 2650A) and then recorded *via* a personal computer. Two static pressure taps were located at the top walls to measure axial pressure drops across the test section to calculate the friction factor. The pressure drop was measured by a digital differential pressure. The uncertainty in the data calculation was based on Ref. [25]. The maximum uncertainties of non-dimensional parameters were ±5% for Reynolds number, ±7% for Nusselt number and ±7% 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 duct wall was about ±0.5%.

3. Data Reduction

The experiment is conducted to investigate the thermal performance of a heat exchanger square duct with DFT inserts. The experimental results of the heat transfer and pressure drop are presented in dimensionless terms of Nusselt number and friction factor. In thermal equilibrium test, the heat supplied by electrical heater plates in the test duct is around 3% to 8% higher than the heat absorbed by the fluid due to convection and radiation heat losses from the test duct to the surrounding. However, in the present work, only the heat transfer rate absorbed by the fluid is taken for internal convective heat transfer coefficient calculation. 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 $\left(\tilde{T}_s - T_b\right)$, the average heat transfer coefficient is evaluated from the experimental data *via* the following equations:

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

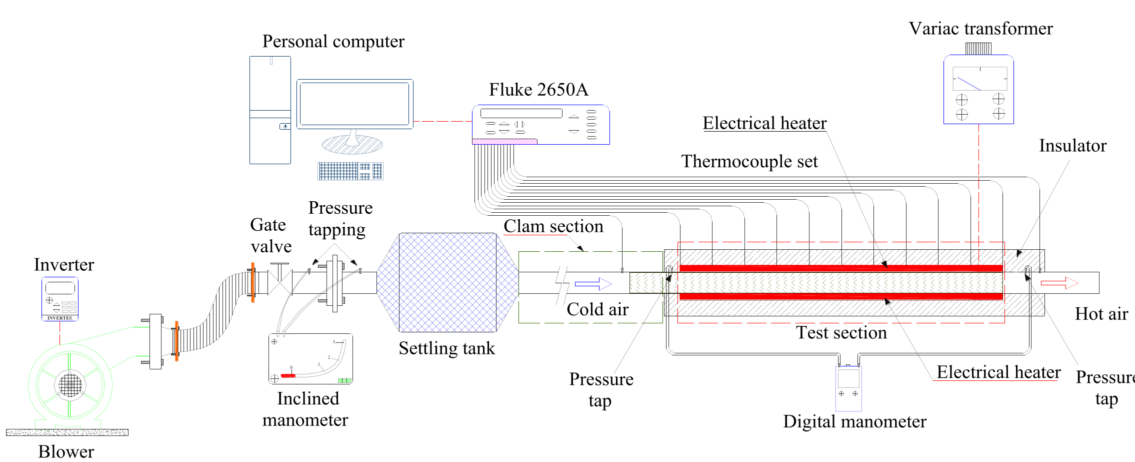

Fig. 1. Schematic diagram of experimental apparatus.