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Effect of perforated twisted-tapes with parallel wings on heat transfer enhancement in a heat exchanger tube

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Abstract

This article reports an experimental investigation on heat transfer and pressure drop characteristics of turbulent flow in a heating tube equipped with perforated twisted tapes with parallel wings (PTT) for Reynolds number between 5500 and 20500. The design of PTT involves the following concepts: (1) wings induce an extra turbulence near tube wall and thus efficiently disrupt a thermal boundary layer (2) holes existing along a core tube, diminish pressure loss within the tube. The parameters investigated were the hole diameter ratio (d/W = 0.11, 0.33 and 0.55) and wing depth ratio (w/W = 0.11, 0.22 and 0.33). A typical twisted tape was also tested for an assessment. Compared to the plain tube, the tubes with PTT and TT yielded heat transfer enhancement up to 208% and 190%, respectively. The evaluation of overall performance under the same pumping power reveal that the PTT with d/W = 0.11 and w/W = 0.33, gave the maximum thermal performance factor of 1.32, at Reynolds number of 5500. Empirical correlations of the heat transfer, friction factor and thermal performance for tubes with PTTs were also developed. In addition, the swirling/axial flow patterns of tube with PTT were visualized using dye injection technique.

Keywords: Heat transfer enhancement; heat exchanger; twisted tape; thermal performance

1. Introduction

Heat transfer enhancement techniques are widely used in many engineering applications for example heat recovery process, shell-and-tube heat transfer exchanger, air conditioning and refrigeration systems, nuclear energy industry, chemical reactors, high power laser systems and chemical process plants, etc [1-2].

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The most significant variables in reducing the size and cost of a heat exchanger are basically the heat transfer coefficient and pressure drop. An increase in the heat transfer coefficient generally leads to another advantage of reducing the temperature driving force, which increases the second law efficiency and decreases entropy generation. Several enhancement of heat transfer devices have been introduced and improved for increasing the heat transfer rate and thermal performance in heat exchangers by both of active and passive methods. Active method is the approach that needs the extra power source for example mechanical aids, surface-fluid vibration, injection and suction of the fluid, jet impingement, and use of electrostatic fields. On the other hand, passive method does not require an extra power source. The devices in this category are surface coating, rough surfaces, extended surfaces, turbulent/swirl flow devices, tube insert (wire, spiral spring, porous, static mixer, twisted tape, louvered strip, miniature hydraulic turbine, mesh, and internal fin inserts), convoluted (twisted) tube, additives for liquid and gases. Application of twisted tape in heat exchanger tube [3-5] is the one of key heat transfer enhancement techniques. Convective heat transfer assisted by modified twisted tapes with different geometries have been extensively investigated such as twin twisted tapes, dual twisted tape elements in tandem, alternate clockwise and counter-clockwise twisted-tape, twisted tape consisting of centre wings and alternate-axes, peripherally-cut twisted tape and serrated twisted-tape. As compared to a typical twisted tape, heat transfer enhancement by the modified twisted tapes with such geometries is achieved by extra turbulence and thus better fluid mixing. However, an improvement in heat transfer rate is generally achieved at an expense of substantially increased friction. The most desired twisted tape is the one yields excellent heat transfer with minimum increase in friction.

To deal with an antagonistic requirement as mentioned above, the newly design twisted tape called perforated twisted tape with parallel wings (PTT) is proposed. The design of PTT involves the following concepts: (1) wings induce an extra turbulence near tube wall and thus efficiently disrupt a thermal boundary layer (2) holes existing along a core tube, diminish pressure loss within the tube. To evaluate practical applications, the overall energy performance in term of thermal performance factors under the same pumping power is evaluated. The investigation was performed for fully developed flow in turbulence regime (5500≤Re≤20500). Empirical correlations for heat transfer, friction factor and thermal performance factor are also reported.

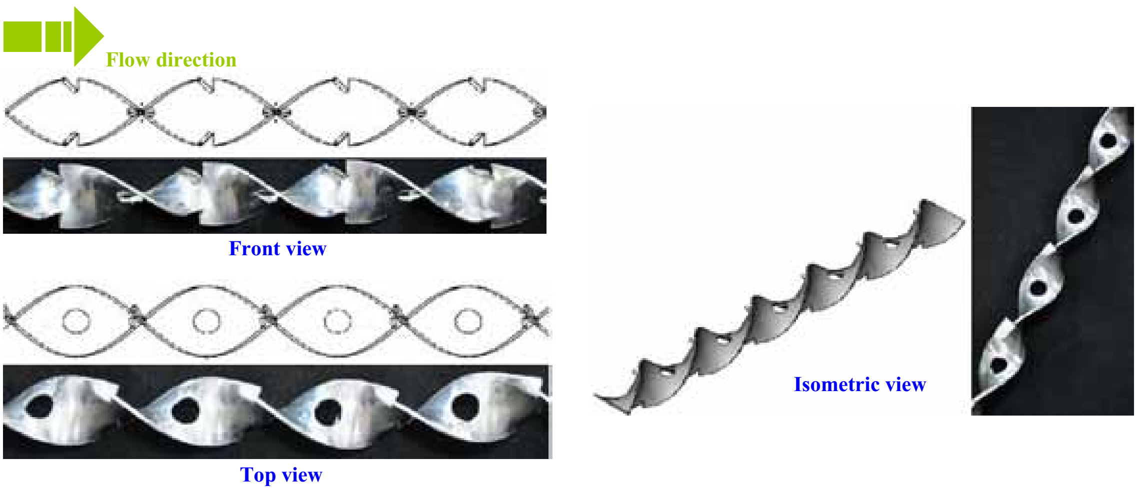


Fig. 1. Photograph and sketch of PTT with parallel wings

2. Perforated twisted tape with parallel wing

The tapes were made from the aluminum strip sheet having width (*W*) of 18 mm and thickness (δ) of 1.0 mm. All tapes were twisted at constant twist length of y = 56 mm which corresponds to twist ratio (y/W) = 3 to formulate typical twisted tapes (TTs). Then, TTs were modified by periodic generating holes along a core tube in straight line at every pitch length (180^o/twist length). Furthermore, each tape was cut at the edge on both sides between adjacent holes, each cut was subsequently arranged in 45^o to the axial flow in the same direction, so called parallel-wings the tap. The modified twisted tape (PTT) is depicted in Fig. 1. The parameters investigated were the hole diameter ratio (d/W = 0.11, 0.33 and 0.55) and wing depth ratio (w/W = 0.11, 0.22 and 0.33). The typical twisted tape (TT) was also subjected to the test, for comparison. All of the tapes were inserted at the core tube along the test section. More details of the twisted tape and experimental set-up can be found in the previous work given by Eiamsa-ard *et al.* [5].

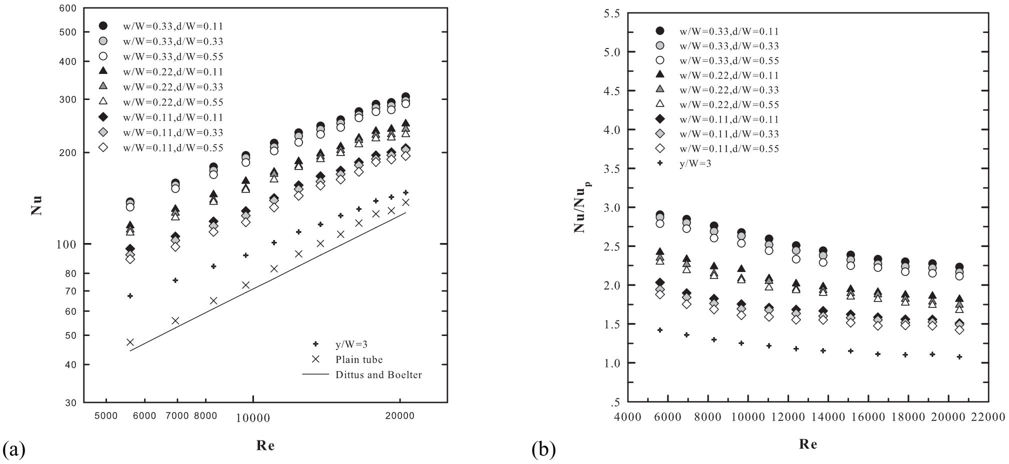


Fig. 2. Variations of (a) Nusselt number (b) Nu/Nu_p with Reynolds number

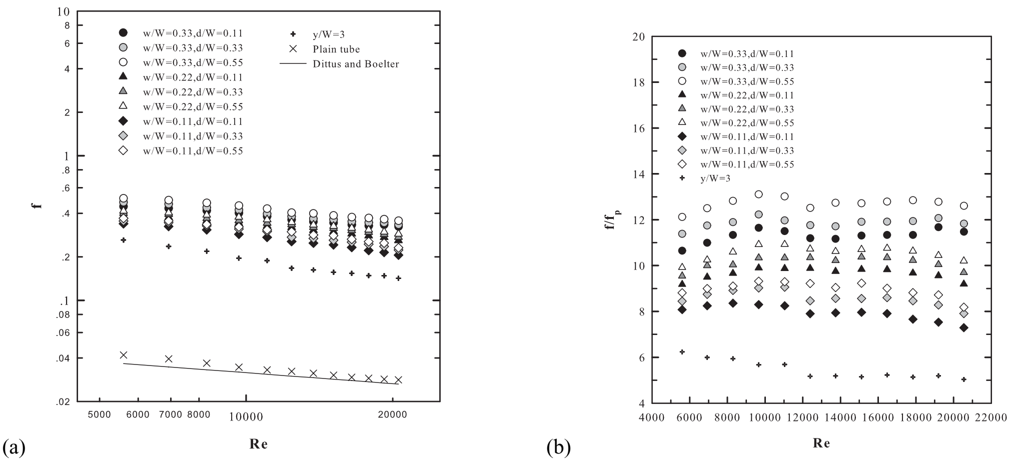


Fig. 3. Variations of (a) friction factor (b) f/f_p with Reynolds number

3. Results and discussion

The experimental investigations of heat transfer, friction factor and thermal performance behaviors in a heat exchanger tube fitted with the PTT with parallel wings of varying wing-cut ratio (*w/W*) and hole diameter ratio (*d/W*) are described. Prior to the main experiment, the plain tube was tested and validated. Figures 2 and 3 show the validations of the present experimental results and with those available in the earlier works. As shown, the present friction factors agree well with those obtained from Blasius equation within ±8.5% and the present Nusselt numbers are within ±8% of those calculated from Dittus-Boelter equation. The present results of the plain tube are therefore used as the bases for the evaluation of the effects of twisted tape on heat transfer enhancement.

3.1. Flow visualization

Since it is difficult to distinct the main flow from the secondary flows induces by TT and PTT via the dye visualization technique in turbulent regime, thus the visualization was performed in laminar regime instead, only for qualitative comparison. Figure 4 shows the flow visualization of the flows through tubes with and without twisted tape. Only axial flow was observed in the plain tube (Fig. 4a) while common swirl flow was found with the presence of TT (Fig. 4b). In case of PTT (Fig. 4c), apart from a common swirl flow, there was attack of dye streams on the wings of PTT leading to an extra turbulence as well as collision among dye streams and thus superior fluid mixing to the case of TT. It should be mentioned that the dye stream positioned around the mid of the tape was directed through a hole to another side of the tape, and the stream direction was between those of an axial flow and a swirl flow.

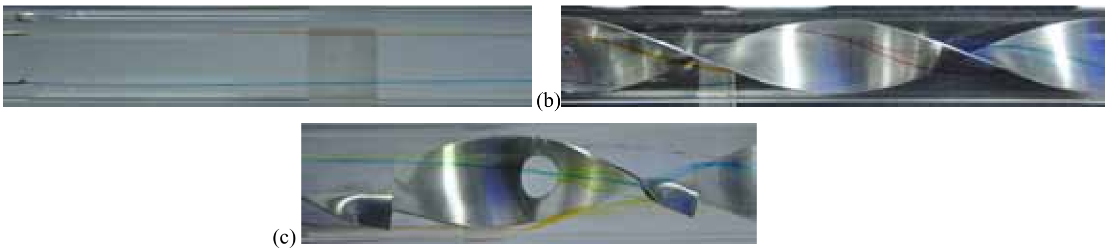
(a)


Fig. 4. Flow visualization of flows through (a) plain tube, (b) TT and (c) PTT

3.2. Effect of the presence of wing and wing depth ratio (w/W)

The experimental results of the tubes equipped with PTTs and TT as well as the plain tube obtained under turbulent flow conditions presented in Fig. 2(a-b). Influence of the presence of wing on heat transfer was significant, notified by the considerably higher Nusselt number given by PTT compared to those provided by TT. The superior heat transfer is responsible by the induction of extra turbulent flows near the tube wall as detected by the dye visualization (Fig. 4b). This efficiently disturbs a thermal boundary layer by generating periodic disruption of the viscous boundary layer. At similar operating conditions, it was found that Nusselt number increased with increasing wing depth ratio *(w/W)*. It can be explain by the fact that the larger depth ratio causes higher turbulence intensity and thus better mixing fluid near the tube wall. For the tape with the largest depth ratio (*w/W* = 0.33), the increase in heat transfer rate was up to 49% and 23% over those of the ones with *w/W* = 0.11 and *w/W* = 0.22, respectively. Figure 3(a-b) shows the variation of the friction factor with Reynolds number. Obviously, the use of the tape with larger wing depth ratio generated higher friction factor. This is directly related to the higher turbulence intensity as mentioned above. As found the tape with the largest depth ratio (*w/W* = 0.33) yielded 40.8% and 18.3% higher mean friction factor than the ones with *w/W* = 0.11 and *w/W* = 0.22, respectively. The result of thermal performance factor in which both heat transfer and friction are taken into account based in the same pumping power, is illustrated in Fig. 5. It is found that PTTs consistently gave higher thermal performance factor than TT, at similar conditions. Among PTTs, thermal performance factor increased with increasing wing depth ratio. Thermal performances varied between 0.71 and 1.01, 0.77 and 1.16, and 0.91 and 1.32 for the PTTs with *w/W* = 0.11, 0.22 and 0.33, respectively. It noteworthy that thermal performance was higher at lower Reynolds number, this implies that twisted tapes are more suitable for practical application at lower Reynolds number.

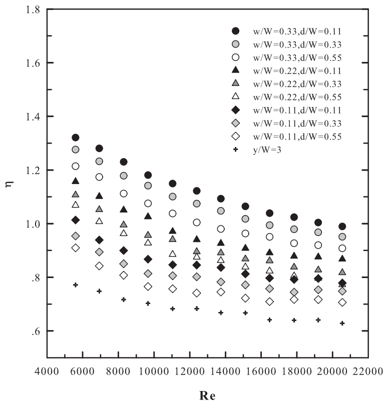
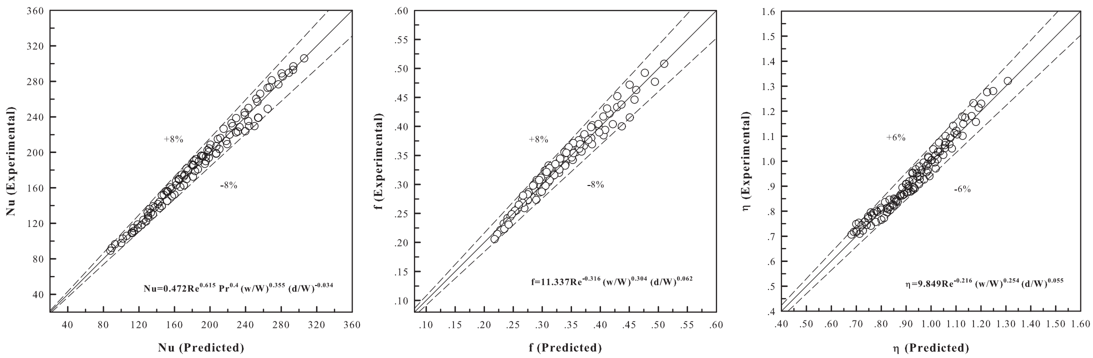


Fig. 5. Variation of thermal performance factor with Reynolds number



(a) (b) (c)

Fig. 6. Comparison between the predicted and experimental data of (a) Nu, (b) friction factor and (c) thermal performance factor

3.3. Effect of perforated diameter ratio (d/W)

The effect of perforated diameter ratio *(d/W* = 0.11, 0.33 and 0.55*)* on the heat transfer rate is shown in Fig. 2(a-b). Apparently, Nusselt number increased with the decrease of diameter ratio. This supports the finding by the dye visualization (Fig.4c) that the stream directed through a hole behaved between an axial flow and a swirl flow, with the larger hole diameter, the flow is assumed to be more similar to the axial flow leading to the loss of swirl intensity imparted to the flow between tape and surface wall. Heat transfer rate decreased up to 2.8% and 6% by the uses of the tapes with *d/W* = 0.33 for *d/W* = 0.55 compared to that of the tape with *d/W* = 0.11. By the same reason, friction generated by PTTs decreased with the increase diameter ratio *(d/W)* as presented in Fig. 3(a-b). The tapes with *d/W* = 0.33 for *d/W* = 0.55 yielded 6% and 11.6% lower mean friction factor than the one with *d/W* = 0.11. Effect of the perforated diameter ratio (*d/W*) on the thermal performance factor in a heat exchanger tube fitted with PTT is presented in Fig. 5. The thermal performances from using PTT with smaller hole diameter ratio (*d/W*) were observed to be higher than that those achieved from the tape with larger *d/W*. This signifies the dominant effect of increased heat transfer over that of increased friction factor as hole diameter decreases. It was found that the tape with the smallest diameter ratio (*d/W* = 0.11) provided higher thermal performance factor than the ones with *d/W* = 0.33 and 0.55 by around 4.9% and 10.4%, respectively. Note that for the present range, thermal performances achieved by using all tape inserts are above unity (low *Re*), indicating the economic benefit due to the heat transfer enhancement. The experimental results of Nusselt number, friction factor and thermal performance were fitted, using least square regression analysis, in which a wing-cut ratio (*w/W*) and a hole diameter ratio (*d/W*) were taken into account. The predicted data from the correlations of the Nu_{pred}, f_{pred} and η_{pred} are plotted against experimental data of the Nu_{exp}, f_{exp} and η_{exp} in Fig. 6(a-c). As shown from these figures the maximum deviations between the experimental data and correlations are ±8%, ±8%, and ±6%, respectively.

4. Conclusions

Augmentation of heat transfer rate in heat exchanger tubes by means of perforated twisted tapes (PTT) inserts is investigated experimentally. The results showed those heat transfer and friction factors were significantly influenced by the presences of wings and holes on PTTs. Both heat transfer and friction increased with the increase of wing depth ratio (*w/W*) and the decrease of perforation hole diameter ratio (*d/W*). Due to the dominant effect of increased heat transfer over that of increased friction factor, the thermal performance factor was found to be increased as wing depth ratio (*w/W*) increased and hole diameter ratio (*d/W*) decreased.

Acknowledgements

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