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Investigation of heat transfer enhancement by perforated helical twisted-tapes ☆

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ABSTRACT

Influence of perforated helical twisted-tapes (P-HTTs) on the heat transfer, friction loss and thermal performance characteristics under a uniform heat flux condition is reported. The P-HTTs were obtained by perforating typical helical twisted-tapes (HTTs) with a prospect to reduce the friction loss of fluid flow. The experiments were conducted using P-HTTs' three different diameter ratios (d/w) of 0.2, 0.4 and 0.6, and three different perforation pitch ratios (s/w) of 1, 1.5 and 2. The helical pitch ratio and twist ratio were fixed at $P/D = 2$ and $y/w = 3$. Tests were performed for Reynolds number between 6000 and 20,000. The experiments using the plain tube and the tubes with HTTs were also carried out for assessment. The experimental results reveal that the use of P-HTTs leads to the reduction of friction loss as compare to that of HTT. Heat transfer, friction loss and thermal performance factor increase as d/w decreases and s/w increases. For the present range, the maximum thermal performance factor of 1.28 is obtained by using the P-HTT with $d/w = 0.2$ and $s/w = 2.0$ at the Reynolds number of 6000. In addition, the empirical correlations for Nusselt number, friction factor and thermal performance factor give accurate predictions within ±4%, ±6% and ±3%, respectively.

1. Introduction

Helical screw tape inserts/twisted tape inserts as turbulators/swirl-generators are recommended as promising devices for enhancing heat transfer rate, due to their efficient thermal boundary layer disruption and improvement of fluid mixing. In general, the heat transfer and friction loss characteristics are strongly dependent on the geometry of the inserts [1–20]. For designing inserts, the reasonable tradeoff between the increases of both heat transfer rate and friction loss has to be taken into account. A better tradeoff between the factors reflects the greater overall energy saving.

Eiamsa-ard and Promvonge [6] found that the use of a full-length helical tape with rod leads to higher heat transfer rate than that of full-length helical tape without rod (a typical tape) but the tape dramatically increases friction factor. On the other hand, a regularly-spaced helical tape gives lower heat transfer rate but it offers more reasonable tradeoff between the increased heat transfer and friction loss penalty. Eiamsa-ard and Promvonge [7] reported that a loose-fit helical tape without core-rod offers about 50% higher Nusselt number while causes around 50% friction factor less than the one with core-rod. Accordingly, the enhancement efficiency offered by the helical screw-tape without core-rod is higher than that given by the one with core-rod at about 2 times. Sivashanmugam and Suresh [8,9] applied the full-length helical screw elements with non-uniform twist ratio and focused on the effects of twist ratio and the pattern of twist ratio change defined as increasing and decreasing orders. They found that heat transfer coefficient enhancement is increased with decreasing twisted tape but not affected by increasing and decreasing orders. Sivashanmugam, P. and Nagarajan [10] and Sivashanmugam et al. [11] investigated the heat transfer and friction factor characteristics of circular tube fitted with right–left helical screw inserts of equal length, and unequal length of different twist ratios. Their results reveal that the heat transfer coefficient enhancement for right-left helical screw inserts is higher than that for straight helical tape at a given twist ratio. Sivashanmugam and Suresh [12,13] employed the helical screw inserts with spacer length of 100, 200, 300, and 400 mm. Their results showed that for each 100 mm increment space length, Nusselt number decreases around 10% while friction factor decreases around 5%. This reflects an insignificant reduction of pumping power by extending the space length. However, as compared to the full length helical screw inserts, the friction factor caused by the helical screw inserts with spacer is nearly two times and four times lower, at low and high Reynolds number, respectively. This indicates the benefit of reducing pressure drop by replacing the full length helical screw inserts by the regularly spaced ones.

Ibrahim [14] studied the effects of twist ratio and spacer length of helical screw insert on the heat transfer enhancement in a horizontal double pipe. They reported that average Nusslet number and friction factor increase with decreasing twist ratio and spacer length. Recently, Bhuiya et al. [15,16] investigated the heat transfer enhancement by using helical tape inserts with different helix angles (9°, 15°, 21°

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Nomenclature

A	heat transfer surface area, m^2
C_p	specific heat of fluid, J kg^{-1} K^{-1}
d	perforation diameter, m
D	inner diameter of test tube, m
f	friction factor $= \Delta P/((L/D)(\rho U^2/2))$
h	heat transfer coefficient, W m^{-2} K^{-1}
I	current, A
k	thermal conductivity of fluid, W m^{-1} K^{-1}
L	length of test section, m
M	mass flow rate, kg s^{-1}
Nu	Nusselt number $= hD/k$
P	pressure of flow in test tube, Pa or pitch length, m
ΔP	pressure drop, Pa
Pr	Prandtl number $= \mu C_p/k$
Q	heat transfer rate, W
Re	Reynolds number $= \rho UD/\mu$
s	perforation pitch, m
t	thickness of the test tube, m
T	temperature, °C
$\tilde{T}$	mean temperature, °C
U	average velocity, m s^{-1}
V	voltage, volt
$\dot{V}$	volume flow rate, m^3 s^{-1}
w	tape width, m
y	pitch of twisted tape, m

Greek letter

ρ	fluid density, kg m^{-3}
δ	tape thickness, m
μ	fluid dynamic viscosity, kg s^{-1} m^{-1}
η	thermal performance factor

Subscripts

b	bulk
$conv$	convection
i	inlet
o	outlet
p	plain tube
pp	pumping power
t	turbulator
w	wall

and 28°) on heat transfer and pressure drop. According to the results, Nussselt number, friction factor as well as thermal enhancement efficiency increase with decreasing helix angles. The maximum thermal performance is obtained by using the double helical tape insert with helix angle 9° at high Reynolds number. Suresh et al. [17,18] examined the thermal characteristics of Al_2O_3/water and CuO/water nanofluids in laminar and transition flows through a circular duct fitted with helical screw tape inserts at different twist ratios. According to their thermal performance analysis based on the constant pumping power criteria, the helical screw tape inserts show better thermal performance when used with CuO/water nanofluid than with Al_2O_3/water nanofluid. S. Saha and S.K. Saha [19] studied the effect of the circular duct having integral helical rib roughness and fitted with helical screw-tape on the friction factor and heat transfer characteristics. Their results show that helical screw-tape inserts in combination with integral helical rib roughness perform significantly better than the individual enhancement technique. Recently, Zhang et al. [20] predicted the heat transfer, flow friction and thermal performance characteristics in the tubes fitted with helical screw-tapes with four different widths (w = 7.5 mm, 12 mm, 15 mm and 20 mm). The simulation results show that the helical screw-tape with w = 15 mm offers the greatest overall heat transfer performance as a result of the best tradeoff between the increases of heat transfer and friction penalty.

It can be concluded from the above literature that optimizing the tradeoff between the increases of heat transfer and friction penalty is an important factor for designing tape inserts. Eiamsa-ard et al. [21] reported that although a helical twisted tape gives lower heat transfer rate, it offers higher thermal performance than the typical helical tape because it causes more reasonable friction penalty. This motivates the further modification of the tape to minimize friction loss. The approach for the purpose is perforating the helical twisted tape. The studied parameters include perforation diameter ratio (d/w) and perforation pitch ratio (s/w).

2. Perforated helical twisted tapes

The photographs of perforated helical twisted-tapes (P-HTTs) are shown in Figs. 1–3. All tapes used in the experiments were made of aluminum sheets with an axial-length of 1500 mm (L), a width of 12.6 mm (w) and a thickness of 0.8 mm (δ). Firstly, a perforated twisted tape (P-TT) was fabricated by perforating the typical twisted tape along a center line. Subsequently, P-TT was subjected to form a perforated helical twisted-tape (P-HTT). P-HTTs were prepared at three different ratios of perforation diameter to tape width, d/w = 0.2, 0.4 and 0.6, and three different ratios of perforation pitch to tape width, s/w = 1, 1.5 and 2. Note that a helical pitch ratio and a twist ratio were fixed at P/D = 2 and y/w = 3. The

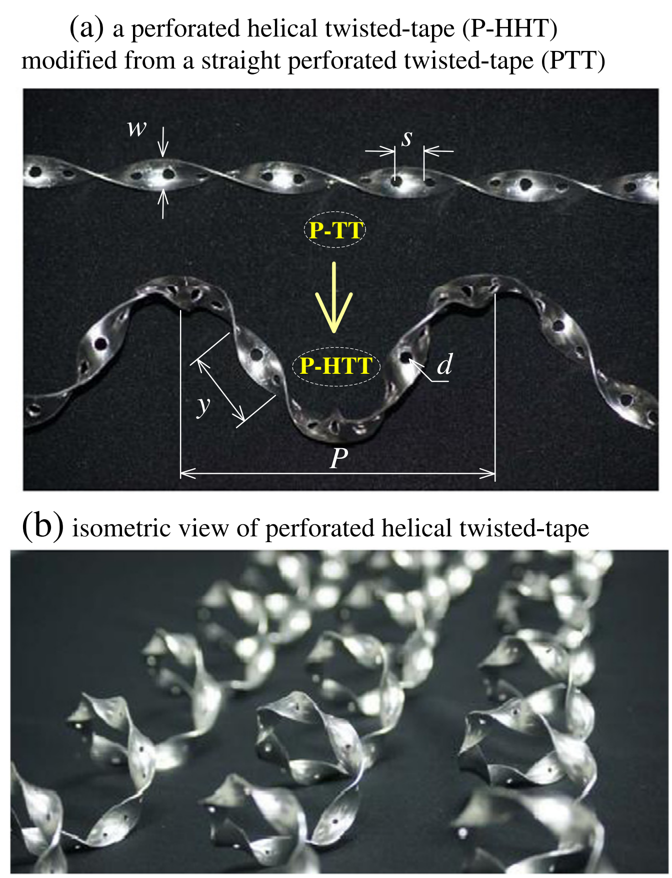

Fig. 1. Photograph of perforated helical twisted-tapes (P-HTTs): (a) a perforated helical twisted-tape (P-HHT) modified from a straight perforated twisted-tape (PTT) and (b) isometric view of perforated helical twisted-tape.