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Turbulent thermal, fluid flow and thermodynamic characteristics in a plain tube fitted with overlapped multiple twisted tapes

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ABSTRACT

Turbulent thermal–hydraulic characteristics in a plain tube by using overlapped multiple twisted tapes (MTTs) with counter large/small combinations (C-L/S-C) were experimentally investigated. Reynolds number (*Re*) ranged from 5800 to 19200, tape number changed from 3 to 5 and overlapped twisted ratios ($P1$:$P2$) were 0.74 to 2.97. By using air as working fluid, heat transfer tests were performed under the constant heat flux conditions and pressure drop experiments were conducted at the isothermal conditions. Nusselt number (*Nu*) and friction factor (*f*), overall thermal performance evaluation criterion (*PEC*), entropy generation and entransy dissipation in the MTTs were compared. The results show that *Nu* and *f* increase with increasing tape number and decreasing overlapped twisted ratio. The experimental results demonstrates that both increasing tape number and decreasing overlapped twisted ratio result in the reduction of entropy generation due to heat transfer and the rise of entropy generation due to friction resistance. It is found that the indicator of equivalent temperature difference, reflecting entransy dissipation and heat transfer ability, has the same sequence to that of the heat transfer behaviors. In the scope of this study, both the maximum *Nu* and the largest increased *f* are obtained in the 5MTTs with values respectively about 98.4% higher and 9.13 times than that in the plain tube while the highest *PEC* is found in the 3MTTs with $P1:P2 = 0.74$ with a value of being about 1.08. The least total entropy generation is gained by the 3MTTs with $P1:P2 = 0.74$ at $Re = 17090$ and the smallest entransy dissipation per unit energy is achieved by the 5MTTs under $Re = 17294$. Furthermore, thermal–hydraulic empirical correlations with deviations of ±5% are developed and comparisons with previous studies are also conducted.

1. Introduction

Twisted tape, as an important passive heat transfer enhancement technology in energy saving, with no need in extra energy input, are usually designed to decrease volume size and reduce capital cost in constructing new heat exchangers and upgrading existing heat exchangers for retrofit. Due to easy fabrication, low cost and convenient dis-assembly and assembly, the twisted tape has attracted increasing focus and interest which plays an important role in energy conversion and saving [1], including energy and power engineering, chemical engineering, petroleum refining, solar water heater, heat exchangers in nuclear power and etc. The most varying factors investigated are twisted ratio, twisted pitch, tape width, tape thickness, tape number and tape arrangements in geometric parameters, and Reynolds number (*Re*), wall thermal boundary conditions (i.e., constant wall temperature or constant heat flux), Prandtl number (*Pr*) and working fluid kinds in operating conditions. Typical twisted tape, so called full length twisted tape, is thermal effective in laminar flow but not so good in turbulent heat transfer due to the limiting heat transfer rate or increased pressure drop. However, more common flow regime encountered in heat exchanger applications is turbulent flow. In order to reduce pressure resistance, or enhance heat transfer rate under reasonable friction loss, or improve overall thermal performance in turbulent flow, there have some efforts been paid on this driven theme. Generally, the improvements of twisted tape can be classified to five categories as followings: (1) regularly spaced or short length twisted tapes [2,3], (2) modified twisted tapes, including ribbed spiky twist tapes [4], jagged twisted tape [5], tapered twisted tapes [6], serrated twisted tapes [7,8], helically twisted tapes [9], twisted-ring twisted tapes [10] and etc., (3) simultaneous employment of twisted tapes and other heat transfer enhancement technologies, such as twisted tape/wire coil [11], twisted tape/

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Nomenclature

A	surface of test tube, m^2
Be	Bejan number, dimensionless
C_p	specific heat at constant pressure, J/(kg·K)
C_v	specific heat at constant volume, J/(kg·K)
D	diameter, mm
E_{diss}	entransy dissipation, W·K
f	friction factor, dimensionless
h	convective heat transfer coefficient, W/(m^2·K)
h_0	natural convection heat transfer coefficient between outer insulation surface and surrounding, W/(m^2·K)
H	height of differential pressure, mm
L	tube length, mm
M	mass flow rate, kg/s
Nu	Nusselt number, dimensionless
N_s	entropy generation, dimensionless
P	pitch length of twisted tape, mm
$P1$	pitch length of large twisted tape, mm
$P2$	pitch length of small twisted tape, mm
Pr	Prandtl number, dimensionless
PEC	performance evaluation criterion, dimensionless
ΔP	pressure drop along the length of the tube, Pa
P'	perimeter, mm
q	heat flux, W/m^2
q'	heat transfer rate per unit tube length, W/m
Q	average heat transfer rate, W
Q_{loss}	heat loss, W
Re	Reynolds number, dimensionless
r_{i}	inner radius of the insulation material, mm
r_0	outer radius of the insulation material, mm
$\dot{S}'_{gen}$	entropy generation gradient, W/(m·K)
$\dot{S}_{gen}$	entropy generation rate, W/K
$\dot{S}_{gen,t}$	entropy generation rate due to heat transfer, W/K
$\dot{S}_{gen,f}$	entropy generation rate due to friction resistance, W/K
T	temperature, K; tape thickness, mm
t	tube thickness, mm
T_{ow}	outer wall temperature, K
T_∞	surrounding temperature, K
u	mean velocity, m/s
W	tape width, mm
y	twisted ratio
λ	thermal conductivity, W/(m·K)
ρ	density, kg/m^3
μ	dynamic viscosity, kg/(m·s)
ϕ_s	augmented entropy generation number, dimensionless

Subscripts

ave	average bulk temperature
b	bulk
e	enhanced tube
i	inner
in	inlet
ins	insulation material
out	outlet
p	plain tube
w	wall

dimpled tube [12], twisted tape/corrugated tube [13] and etc., (4) twisted tapes combined with nanofluids, for example, twisted tape/TiO_2 nanofluid [14], twisted tape/Al_2O_3 nanofluid [15], twisted tape/Cu nanofluid [16] and etc., (5) multiple twisted tapes, consisting of twin/triple twisted tapes [17] and counter/co-swirling twin twisted tapes [18,19], dual/quadruple twisted-tapes [20] and etc. Among these varied ones, the first ones were invented to give play to the heat transfer enhancement of self-sustaining swirl flow in the tape downstream with reduced pressure drop; the second ones were mainly constructed to give more flow disturbing and enhanced turbulent intensity, then improving heat transfer; the third ones were fabricated to utilize the synergy of compound heat transfer enhancement; the fourth ones employed the high thermal conductivity of nanofluid and the last ones made full use of multiple longitudinal vortexes/swirl flows to augment heat transfer rate. It is noted that the flow structure of induced multiple longitudinal vortexes are also similar to the desired flow patterns gained by different optimization objectives, such as minimum entransy dissipation reported by Jia et al. [21] and exergy destruction minimization reported by Wang et al. [22].

Distinctions with more easier fabrication, longer reliability and convenient assembly make the multiple twisted tape heat transfer enhancement technology standing out and have more potential promise in the industrial applications. In the last few years, there were several attempts in obtaining further understandings on heat and fluid flow behaviors in tubes/ducts with the multiple twisted tapes (MTTs), including the effect of diverse tape arrangements, tape number and co-use with other heat transfer enhancement technologies. Convective heat transfer characteristics in a plain tube equipped with single, twin, and triple twisted tapes were studied by Chang et al. [17] and the best thermal performance in turbulent flow was obtained in the triple twisted tapes. In order to reduce pressure loss in the inverted pressurised water reactor, Arment et al. [23] obtained new correlations in predicting of critical heat flux and pressure drop in tubes containing short-length MTTs. Vashistha et al. [24] performed experimental studies on heat transfer and flow characteristics of single, double and quadruple twisted tapes under Reynolds number (Re) of 4000 to 14000 and twist ratios (y) of 2.5 to 3.5, and found that the twisted tapes with four counter-swirl arrangement and y of 2.5 possessed the best thermal performance. The effects of free-spacing ratios (1.0 to 1.66) and y (2.5 to 3.5) on the thermal-hydraulic behaviors in a rectangular channel fitted with MTTs at $Re = 2700$ to 9000 were investigated by Eiamsa-ard [25], and increase in heat transfer rate of about 10.3 to 169.5% compared with the plain channel was gained. Nuntadusit et al. [26] employed oil film technique and thermochromic liquid crystal technique respectively to characterize the flow structures and temperature field of swirling impinging jets in the impinged surface by using of MTTs. The effect of twisted ratio on thermal performance characteristics in a helical-ribbed tube fitted with twin twisted tapes was experimentally analyzed by Promvonge et al. [27] and found that the enhanced tube with $y \approx 8$ had the best overall thermal performance. Bhuiya et al. [28] studied the effects of y (1.92–6.79) and Re (7200–50200) on convective heat transfer characteristics in a plain tube fitted with triple twisted tapes. In addition, the heat transfer and pressure loss behaviors of double counter twisted tapes [29] with varying y (1.95–7.75) and Re (6950–50050) and perforated double counter twisted tapes [30] with varying porosity (1.2–18.6%) and Re (7200–50000) in the plain tube were also examined by Bhuiya et al. Abdolbaqi et al. [31] presented heat transfer and frictional losses in a flat tube fitted with twin counter or co-twisted tapes with water as flowing fluid. In their studies, the twin counter twisted tapes exhibited higher heat transfer rates of about 22.5%