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Heat transfer and pressure drop measurements for tubes fitted with twin and four twisted fins on rod

Shyy Woei Chang [a,*], Wei Ling Cai [b], Ruo Sin Syu [b]

[a] Thermal Fluids Laboratory, National Kaohsiung Marine University, No. 142, Haijhuan Road, Nanzih District, Kaohsiung City 81143, Taiwan, ROC
[b] Department of Marine Engineering, National Kaohsiung Marine University, Taiwan, ROC

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ABSTRACT

Axial Nusselt number (Nu) distributions and tube averaged Fanning friction factors (f) for the tubular flows enhanced by twin or four twist-fin inserts with five twist ratios (y) of 2, 2.5, 3, 3.5 and ∞ (straight fins) were measured at Reynolds numbers (Re) of 750–70,000. For each enhanced tube with a twist-fin insert, the Nu and f augmentations from the plain-tube developed flow Nu_∞ and f_∞ references were compared with thermal performance factors (TPF) evaluated. Acting by the respective single- or twin-cellar axial swirls along the helical passages formulated by present twin or four twisted fins in the test tubes, the Nu/Nu_∞ ratios at laminar and turbulent reference conditions are respectively raised to 1.87–4.98 and 1.3–1.95; or 3.93–9.03 and 1.37–2.83. Relative to the Nu and f results measured from the test tubes enhanced by the two co-twisted tape inserts, present four twist-fin inserts considerably amplify both laminar and turbulent HTE ratios at the expenses of f augmentations with the laminar and turbulent TPF values in the respective ranges of 1.45–2.84 and 0.56–0.98. For assisting the relevant applications using present sets of Nu and f data generated by this study, the heat transfer and pressure drop correlations for the tubes with twin or four twist-fin inserts are devised.

1. Introduction

Heat Transfer Enhancement (HTE) technology offers opportunities for advancements of energy saving, thermal energy harvest, cooling of hot components in electric/mechanic devices and various chemical/manufacturing processes involving transport phenomena. While a HTE measure elevates heat transfer rates, the accompanying pressure drop augmentations have to be justified by the efficiency of heat transmission. The index for such counteractive assessment between heat-transfer and pressure-drop augmentations at constant pumping power is usually the thermal performance factor (TPF) defined as $(St/St_\infty)/(f/f_\infty)^{1/3}$ [1]; whereas the variation of Nusselt number ratio (Nu/Nu_∞) versus the f/f_∞ ratio at the identical Re reveals the comparative thermal performance at constant flow rate. The referenced Stanton number (St_∞) and Fanning friction factor (f_∞) respectively account for the heat transfer level and friction coefficient of plain tube flow. By collectively comparing the TPF values among a group of HTE devices at the same Reynolds (Re) and Prandtl (Pr) numbers, the ratio of St/St_∞ is reduced to the Nu/Nu_∞. A review of passive HTE methods with emphasis on swirl flow devices surveyed the thermo-hydraulic characteristics of coiled tubes, turbulators including ribs, fins, louvered strips and winglets, corrugated channels and a variety of tube inserts [2] such as twisted tape, conical ring, snail entry turbulator, vortex ring and coiled wire. With the benefits of retrofit application and fabrication convenience, the insertion technology is widely studied with many modified geometries proposed. These inserts generally induce longitudinal swirls among single/two-phase flows to introduce velocity components normal to tube wall and promote fluid mixing for momentum and heat transmissions. With less pressure drop augmentations, the twisted tape (TT) inserts were widely adopted as the HTE measures for tubular flows and classified as eight categories in [2]. The conventional TT with unidirectional full-length twist augmented turbulences and induced axial swirl to promote HTE benefits [3]. The elevated Nu/Nu_∞ and f/f_∞ values by decreasing twist ratio (y) were reported [3] as a common feature for the tubular flows enhanced by various types of TTs. With helically TTs [4], both Nu/Nu_∞ and f/f_∞ ratios were increased by decreasing y and helical pitch ratio, but the TPF values were driven in opposite trends as y and helical pitch ratio increased. Using the alternate clockwise and anti-clockwise TTs, the periodical re-developments of swirls further boosted the Nu/Nu_∞ ratios with the thermal performances improved as Re increased and/or y decreased [5]. To reduce the associated pressure drop augmentations using the TTs with rod and trailing-edge

* Corresponding author. Tel.: +886 7 8100888 5216; fax: +886 7 5712219.
E-mail address: swchang@mail.nkmu.edu.tw (S.W. Chang).

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Nomenclature

A, a_s	coefficients in heat transfer empirical correlations
B, b_s	exponent/coefficients of Reynolds number in Nusselt number correlation
C_p	specific heat at constant pressure (J kg^{-1} K^{-1})
d	inner diameter of test tube (m)
d_c	diameter of central rod with twist-fin (m)
d_h	hydraulic diameters of sector-shaped helical channel (m)
f_0	baseline Fanning frication factor of plain tube with abrupt flow entry/exit
f	mean Fanning friction factor = $(\Delta P/0.5\rho W_m^2)/(d/4L)$
f_∞	referenced Fanning friction factor =16/Re (laminar) and 0.079$Re^{-0.25}$ (turbulent)
h	convective heat transfer coefficient = $q_f/(T_w - T_f)$ (W m^{-2} K^{-1})
j	Colburn factor = $\overline{Nu}/(RePr^{1/3})$
k_f	thermal conductivity of fluid (W m^{-1} K^{-1})
L	length between two entry and exit pressure tapings (m)
M, N	coefficients in f correlations
Nu	local Nusselt number = $q_f\, d/\{(T_w - T_f)\, k_f\}$
$\overline{Nu}$	averaged Nusselt number for developing or developed flow region
Nu_0	baseline Nusselt number of plain tube with abrupt flow entry/exit
Nu_∞	Nusselt numbers in plain tube (48/11 for laminar flow and the Dittus–Boelter correlation of 0.023$Re^{0.8}Pr^{1/3}$ for turbulent flow)
P	axial distance of twist-fin pitch with 180° rotation of tape (m)
Pr	Prandtl number of coolant ($\mu C_p/k_f$)
ΔP	pressure difference between tube entry and exit (N m^{-2})
q_f	convective heat flux (W m^{-2})
R	curvature radius of the central helix = $(d + d_c)/4$ (m)
Re	Reynolds number = $\rho W_m d/\mu$
S_p	peripheral heating length of test tube = πd (m)
TPF	Thermal performance factor = $(\overline{Nu}/Nu_\infty)/(f/f_\infty)^{1/3}$
T_f	fluid bulk temperature (K)
T_w	wall temperature (K)
W_m	mean fluid velocity (m s^{-1})
x	axial location referred to flow entry as origin (m)
X	dimensionless axial location (x/d)
y	twist ratio (P/d)

Greek symbols

ρ	density of fluid (kg m^{-3})
μ	fluid dynamic viscosity (kg m^{-1} s^{-1})

Superscripts

DE	developing flow region
FD	fully developed flow region

spacer [6], the Nu/Nu_∞ ratios were decreased about 17% and 29% from the Nu/Nu_∞ levels acquired by fitting the conventional TTs, respectively. A variety of perforated TTs (PTTs) with wings [7], winglets [8], cuts [9–11] and serrations [12,13] along the twist tapes were proposed with the associated Nu/Nu_∞, f/f_∞ and TPF measured. Using PTTs with parallel wings, the heat transfer rates, friction factors and thermal performance factors increased with the increase of wing depth ratio but decreased as the perforation hole diameter ratio increased [7]. In [8], the comparative thermal performances between tubes fitted with oblique (O-DWT) and straight (S-DWT) delta-winglet twisted tapes revealed the higher Nu/Nu_∞ ratios for O-DWT. For the Peripherally-cut Twisted tapes without (PT) and with alternate axis (PTA), the highest TPF values at Re of 5000 were 1.25 for PTA, 1.11 for PT and 1.02 for conventional TT [9]. With the V-cuts on two edges of a TT [10], the Nu/Nu_∞, f/f_∞ and TPF values were further elevated from those generated by a conventional TT. Regional augmentations of near-wall turbulence and vorticity behind the peripheral cuts on two edges of the twisted tape were reported as the additional flow mechanisms to further enhance the HTE effects [11]. By twisting the ribbed plates to form serrated TTs (STT) for tripping/enhancing the axial swirls, the Nu/Nu_∞ ratios were substantially elevated; but with considerable f/f_∞ augmentations to counteract the TPF performances [12]. Using serrated-edge TT insert, the mean heat transfer rate of the tubular flow was increased about 72.2% from the plain-tube reference [13].

As the exchanges of momentum/heat flux in the direction normal to tube wall were prevailing over turbulent flows, it was concluded that the twisted tape inserts performed better in laminar flow with less effective HTE impacts at turbulent conditions; while other passive HTE measures using swirl flow devices such as helical ribs and conical nozzles were generally more efficient at turbulent conditions than in their laminar counterparts [2]. As an attempt to further boost the HTE effectiveness for TT technologies, the multiple TTs which induced multiple axial swirls and tripped turbulences at the edges of multiple TTs among tube core region were proposed [14–17]. For the comparative group of tubular flows enhanced by single, twin and triple TTs with the same y and twist orientation, both Nu/Nu_∞ and f/f_∞ ratios were increased as the number of TT increased [14]. With the double counter TT in a heat exchanger tube, the Nu/Nu_∞ and f/f_∞ ratios were increased from those enhanced by conventional single TT [15]; while the triple TTs further augmented Nu/Nu_∞ and f/f_∞ ratios with all the TPF values above than unity [16]. As a compound HTE measure using helical-ribbed tube with twin co-swirl TTs, the enhanced tubular flows performed the better thermal performances than those developed in the ribbed/smooth tubes [17]. Although the better thermal performances with the higher HTE ratios were achieved by fitting multiple TTs [14–17], each of the multiple helical flow passages is not fully enclosed. The axial swirl along each of these multiple helical passages is weakened due to the partial leakage from the open peripheries of the multiple TTs.

A number of previous works [18–30] examined the thermal performances of tubular flows enhanced by the helical screw-tapes with/without geometrical modifications. The heat-transfer and friction coefficients of laminar/turbulent flows enhanced by the full-length helical screw-tapes with increasing/decreasing orders of twist ratios (y) [18,19], the helical screw-tapes with right and left alternate twists [20] and the segmental helical screw-tapes with different spacer intervals [21,22] were experimentally studied. Among the full-length helical screw-tapes of ascending or descending y, the variations in HTE ratios were not noticeable at both laminar [18] and turbulent [19] conditions as the swirl intensities at tube entrance and exit were similar for all the twist arrangements tested. By reducing the twist ratio of full-length helical screw-tape to enhance the swirl intensity, the maximum heat-transfer and friction-factor augmentations were both found at the smallest y [18,19]. Using the right-left helical screw-tapes of equal/