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Thermal performances of tubular flows enhanced by ribbed spiky twist tapes with and without edge notches

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ABSTRACT

Heat transfer enhancements (HTE) of the newly devised spiky ribbed twisted-tapes with and without edge notches are experimentally studied along with the associated pressure drop augmentations and transmitted efficiencies for heat convection. Axial Nusselt number (*Nu*) distributions, mean Fanning friction factors (*f*) and thermal performance factors (*TPF*) of the tubular flows enhanced by each type of present spiky ribbed twist tapes with five twist ratios (y) of 1.56, 1.88, 2.19, 2.5 and 2.82 are measured at the Reynolds numbers (*Re*) between $1000 \leqslant Re \leqslant 40{,}000$. While these ribbed spiky twist tapes enrich the varieties of the swirl-type insert technologies, especially for retrofit applications, the favorable twisted tapes with the higher degrees of HTE benefits and/or *TPF* at the less expense of pressure drops from the comparative group collected by this study are disclosed. The present V-notched ribbed spiky twist tapes with forward flows considerably elevate the HTE impacts from the comparative counterparts by bursting the near-wall jets through the notches and initiating the separated vortex system from the spikes and ribs. With $1.56 \leqslant y \leqslant 2.82$, the heat transfer ratios between present RST-V(FF), RST(FF), RST-V(BF) and RST(BF) tubes and the plain tubes are 3.92–7.86 (3.17–5.93), 3.72–6.08 (3–5), 3.52–6.24 (2.7–5.63) and 3.17–5.23 (2.75–4.38) at turbulent reference conditions; and 11.72–22.92 (9.15–17.26), 9.03–16.45 (6.51–12.85), 10.38–17.54 (8.27–14.45) and 7.69–14.02 (5.56–11.3) at laminar reference conditions. The corresponding *f* ratios between present RST(FF), RST-V(FF), RST(BF), RST-V(BF) tubes and the plain tubes fall in the respective ranges of 6.03–9.61, 1.42–2.94, 6.62–11.77 and 1.4–3.27. The *TPF* values for present RST(FF), RST(BF), RST-V(FF) and RST-V(BF) tubes are in the respective ranges of 1.86–2.57, 1.48–2.15, 2.49–3.43 and 2.07–2.7 with $1000 \leqslant Re \leqslant 2000$; and 0.69–1.06, 0.58–0.92, 0.71–1.31 and 0.64–1.12 with $5000 \leqslant Re \leqslant 40{,}000$. To assist the engineering applications, two set of empirical *Nu* and *f* correlations for the tubular flows enhanced by present two types of spiky ribbed twist tapes at forward and backward flow conditions are generated.

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1. Introduction

Driven by the energy saving incentives, the development of swirl-type insert technology for design and retrofit applications, aiming at HTE promotions for reducing the overall thermal resistances of tubular flows, is under constant pursuits. In this respect, the twisted tapes (TT) with various arrangements and/or geometries are recently proposed for acquiring the passive HTE benefits which are economically justified by maintaining the thermal performance factors (*TPF*) above than unity. With TT(s) in a tube, the straight flow passage transforms into twin semi-circular elongated helical passages. Acting by the centrifugal forces induced by the twisting motion of the bulk stream along each semi-circular helical passage, the axial swirl is generated as the major HTE mechanism which modifies the near-wall velocity/temperature gradients and enhances fluid mixings between tube-core and near-wall regions [1,2]. Such centrifugal forces also assist to segregate the liquid and gaseous/vapor phases by pushing the liquid phase toward the tube wall, leading to the increased critical heat flux (CHF) for heat transfers involving phase change. As the axial swirls promote the momentum transfer in the direction normal to tube wall, which mechanism is lacking for laminar flows in a plain tube but is ample at turbulent conditions, the larger extents of HTE impacts by TT generally resolve at laminar conditions [3–5]. Heat transfer coefficients (HTC) in a tube with the full-length smooth-walled TT (conventional TT) were respectively raised up to 30 and 3.5 times of the plain tube levels at laminar

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Nomenclature

A, a_s, b_s coefficients in heat transfer correlations
B exponent of Reynolds number in Nusselt number correlation
C, c_s, E, K, M coefficients in pressure drop correlations
C_p specific heat at constant pressure (J kg^{-1} K^{-1})
d inner diameter of test tube (m)
f_0 baseline Fanning frication factor of tube with spiky or spiky-V twisted tape
f mean Fanning friction factor =$(\Delta P/0.5\rho W_m^2)/(d/4L)$
f_∞ referenced Fanning friction factor = 16/*Re* (laminar) and $0.079Re^{-0.25}$ (turbulent)
k_f thermal conductivity of fluid (W m^{-1} K^{-1})
L length between two entry and exit pressure tapings = length of twisted tape (m)
L_s length of spike (m)
N number of spikes on twisted stripe in a pitch ratio
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 enhanced tube with spiky or spiky-V twisted tape
Nu_∞ Nusselt numbers in plain tube (48/11 for laminar flow and the Dittus–Boelter correlation of $0.023Re^{0.8}Pr^{1/3}$ for turbulent flow)
P axial distance of twist 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})
Re Reynolds number = $\rho W_m d/\mu$
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 width of twisted tape (m)
W_s width of spike (m)
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

(*Re* < 2000) and turbulent (5000 < *Re* < 45,000) reference conditions [6]. As the variations of *Nu* and *f* against *Re* exhibited the continuous varying trends as *Re* increases, Sarma et al. [7] inferred that the TT insert could result in the monotonic laminar to turbulent transition. Further thermal performance improvements for TT(s) are mainly directed toward the modifications of TT geometries for boosting HTC and/or reducing the accompanying pressure drop penalties.

As an attempt to reduce the pressure drops raised by full length TT(s), the thermal performances of tubular flows enhanced by the single or multiple short-length TT(s), which are spaced with plain intervals along a channel, are reviewed in [8] with the optimized configurations reported in [9]. Such HTE measure takes the advantage from the persistence of swirls downstream of the short-length TTs; while both HTC and CHF can still be enhanced over the plain intervals without the adverse *TPF* impacts caused by the augmented pressure drops. Based on the relative *TPF* performances at $10{,}000 \leqslant Re \leqslant 20{,}200$, the optimal configurations for short-length TTs were reported as $4.25 \leqslant y$ (twist ratio) < 4.75 and $28 \leqslant s$ (empty length ratio) < 33 at α (rotation angle) = 180° [9]. In addition to the regularly spaced TTs which seek for the similar HTE impacts with reduced *f* augmentations, further *TPF* improvements by means of HTE elevations with extended effective *Re* range adopt the enhanced TT(s) with modified geometries and various arrangements [10–30]. These modified TT(s) [10–30] either enhance the strengths of the axial swirls by using multiple TTs [10,14,15,25] or add HTE mechanisms in addition to the TT-induced axial swirls, which include the serrated [11,18], spiky [12,30], perforated [13,30], jagged/winglets [13,20,21,23,24], alternated [16,24,26], and notched [17,19,22,24,28,30] TTs. The various HTC and *f* performances attributed to the various enhanced TTs [10–30] were compared with those generated by the conventional TTs in [30]. In general, the *f* values raised by the enhanced TTs [10–30] were about 6–20 times of the plain tube references (f_∞) in order to elevate the corresponding *Nu* to the levels about 2–14 times of the plain tube references (Nu_∞) at laminar reference conditions; whereas the turbulent *Nu* raised by these enhanced TTs [10–30] could reach about 1.2–3 times of Nu_∞ at the expenses of f/f_∞ in the range about 2–52, together giving rise to the *TPF* range of 0.76–4.58 [30]. However, as previously reported in [3–5], the turbulent HTE elevations using the modified TTs [10–30] are far less than those obtained at laminar references conditions, which is worthy of further exploration.

While the major HTE mechanisms triggered by TT(s), namely the axial swirls, could be enhanced by the multiple conventional TT(s) [10,14,15,25], the appended flow mechanisms which generate the additional HTE benefits vary with the geometries/arrangements of the modified TT(s). With the serrated TT [11,18], the flow pathway transforms into the one-wall ribbed helical passage; along which the separated shear layers tripped by the serrated ribs promote turbulent activities without losing the integrity of complete enclosure for each helical passage. The synergetic effects of strong axial swirls and rib-induced HTE mechanisms significantly boost the HTC levels. But the considerable *f* augmentations generated by the serrated TTs, which inherit from the ribbed wall, offset the HTE benefits generated by the serrated TTs [11] so that the *TPF* values fall into the similar range with most of the enhanced twist tapes [10–30]. Another form of spiky TT formulates the twisted insert as the spirally arranged pin–fins [12,30] to trip vortical flows downstream the spikes and at the junctions between the spikes and tube wall, which break the boundary layers with considerable turbulence augmentations. But the complete enclosure of the semi-circular helical passage constructed by the spiky TT is broken, which consequently weakens the strength of axial swirl. The competitive influences between the broken helical enclosure and the HTE mechanisms tripped by these spirally arranged spikes result in the compatible Nu/Nu_∞ elevations [12,30] to those generated by the other types of enhanced twist tapes [10–30]; but the *Re* range for effective HTE benefits is considerably extended up to *Re* = 40,000 by the spiky TT. Further HTE promotions for this type of spiky TT(s) can be achieved by notching the V-cut into the tip of each spike, while the pressure drop augmentation can still be

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