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Thermohydraulic investigation of turbulent flow through a round tube equipped with twisted tapes consisting of centre wings and alternate-axes

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ABSTRACT

The effects of the twisted tapes consisting of centre wings and alternate-axes (WT-A) on thermohydraulic properties in a round tube, were investigated. The effects of other three types of twisted tapes including: (1) the twisted tape with wings alone (WT), (2) the twisted tape with alternate axes alone (T-A), and (3) the typical twisted tape (TT), were also studied for comparison. All twisted tapes used were twisted at constant twist length (y) of 57 mm, corresponding to a constant twist ratio (y/W) of 3.0. The wings were generated along the centre line of the tape with three different angles of attack, ($\beta = 43°$, 53° and 74°). Test runs were conducted using water as a testing fluid with Reynolds number range between 5200 and 22,000. Under the similar condition, the heat transfer rate in the tube fitted with the WT-A was consistently higher than those in the tube equipped the WT, T-A and plain tube. It is also found that the heat transfer rate increased with increasing angle of attack. Over the range studied, the use of WT-A at $\beta = 74°$ was found to be the most effective for heat transfer enhancement, giving thermal performance factor of up to 1.4. Mean values of Nusselt number (Nu), friction factor (f), thermal performance factor (η) provided by the WT-A (at $\beta = 74°$) were respectively, 17.7%, 30.6% and 7.8% higher than those in the tube with WT (at $\beta = 74°$), 20.8%, 53% and 4.9% higher than those in the tube with T-A, and 62%, 123% and 24% higher than those in the tube with TT. The superior performance of the WT-A over those of the other tapes could be attributed to the combined effects of the following actions: (1) a common swirling flow by the twisted tape (2) a vortex generated by the wing (3) a strong collision of the recombined streams behind each alternate point. For a better understanding on flow phenomena, flow-visualization by smoke wire technique is also presented. In addition, the experimental correlations of Nusselt number, friction factor and thermal performance factor were also developed.

1. Introduction

Enhancement of heat transfer in a heat exchanger is widely applied in industries due to the need of more compact heat exchanger, a lower operating cost, energy saving as well as ecological benefit. Among many heat transfer enhancement techniques, utilization of twisted tape and deta-wing/delta-winglet vortex generators is a promising method. The approach possesses not only an effective heat transfer enhancement but also the advantage of a low cost and an ease of installation.

Twisted tapes have been extensively used as heat transfer enhancing devices in heat exchangers. The important effects induced by the tapes are: (1) swirl flow which improves fluid mixing, (2) helically twisting fluid motion which offers an effectively longer flow path, and (3) partitioning and blockage of the tube flow cross section which leads to a higher flow velocity [1]. All the effects mentioned above are directly responsible for the improvement of heat transfer within heat exchanger. The performances of twisted tape swirl generator have been intensively investigated by many researchers [1–14] for different tape geometries (e.g. broken, serrated, delta-wing, perforated, notched and jagged), working fluid types (e.g. water, air, oil, servotherm medium oil, turbine oil, ethylene glycol, nitrogen, and R134a), wall conditions (uniform heat flux and constant wall temperature) and flow regimes (laminar, transition and turbulent flows). Regarding to the results reported in the mentioned papers, it can be observed that the shape of twisted tape is an important key signifying the tape performance, for example serrated twisted tape [3], the modified tape with protrusive part could improve heat transfer rate significantly, however the tape caused an unavoidably dramatic increase of friction within system and this prohibits its practical applications. On

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Nomenclature

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

Greek symbols

β	angle of attack, degree
ρ	fluid density, $\mathrm{kg\,m^{-3}}$
δ	twisted tape thickness, m
μ	fluid dynamic viscosity, $\mathrm{kg\,s^{-1}\,m^{-1}}$
η	thermal performance factor

Subscripts

b	bulk
c	convection
i	inlet
o	outlet
p	plain
s	surface
t	turbulator
w	water

Abbreviations

TT	typical twisted tape
T-A	twisted tape with alternate-axes
WT	twisted tape with centre wings
WT-A	twisted tape with centre wings and alternate-axes

the other hand, the twisted tapes with space such as perforated, notched [2], and regularly-spaced [6] twisted tapes generated lower friction loss but their heat transfer enhancement and thus thermal performance factor are unattractive. Differently, the twisted tapes consisting of protrusive parts together with spaces on the tapes such as broken [4] and delta-wing twisted tapes [8] offered promising outcomes in both viewpoints of heat transfer enhancement and friction loss since the protrusion effectively improved mixing while the space brought down the friction to satisfactory level. This resulted in thermal performance factor above unity which is beneficial for energy saving and hence made the twisted tape suitable for industrial applications.

Delta-wing and delta-winglet vortex generators were used for heat transfer augmentation by many researchers [15–23]. Tiwari et al. [15] and Fiebig [16] described that vortices enhanced the mixing of fluid in the periphery region with that in the core region of the flow field by the swirling motion as a secondary flow. This effect led to the destabilization of primary flow and thermal boundary layer thinning, and thus heat transfer improvement. The numerical investigation by Biswas et al. [17] and the experimental finding by Valencia et al. [18] indicated that the proper use of vortex generators resulted in an effective heat transfer augmentation with low or moderate pressure drop penalty. Vortex generators can be incorporated into a plate, a fin surface or a channel with an attack angle by means of punching, embossing, stamping, or attachment process [19]. There are two types of vortices: transverse vortex and longitudinal vortex. The axis of a transverse vortex lies perpendicular to the flow direction while that of the longitudinal vortex (also called streamwise vortex) is parallel to the main flow. Practically, longitudinal vortex and transverse vortex are induced simultaneously and the dominance of the one over the another depends on the attack angle. The longitudinal vortex is governing at small attack angle whereas the transverse vortex becomes more influential with increasing attack angle [20]. This issue gains significance in design of delta-wing for specific applications [21]. It was also mentioned that a longitudinal vortex offered less friction loss and more efficient heat transfer than a transverse vortex [20,22]. Regarding to results by Fiebig [23], delta-wings were more efficient than rectangular wings, and punched wings were slightly better than mounted wings for the same vortex generator area.

Most of the delta-wing and delta-winglet vortex generator appear in a flat plate. In our previous report [8], the delta-winglet was located on the periphery of twisted tape. Our results indicated that under the similar operating conditions, the Nusselts numbers in the test tube equipped with peripheral delta-winglet twisted tape were considerably higher than those in the tube equipped with typical twisted tape. Besides, our evaluation revealed that the thermal performance factor in the tube with the modified twisted tape was enhanced up to 1.24. This points out that the presence of the winglet on twisted tape gives a promising result for heat transfer enhancement.

In present work, the modified twisted tape was alternatively designed by generating wings on the centre line of the twisted tape and then forming alternate axes (twisted tape with wings and alternate axes, WT-A). The modification has been assumed to induce the combined effects of the common swirl flow by the twisted tape, vortex by wings and also additional flow fluctuation by alternate axes, leading to excellent results for heat transfer enhancement. The effects of other three types of twisted tapes including (1) the twisted tapes with wings alone (WT), (2) the twisted tape with alternate axes alone (T-A), and (3) the typical twisted tape (TT), were also studied for comparison. The experiments were conducted to investigate the effects of twisted tapes used on the heat transfer rate, friction factor as well as thermal performance factor in a turbulent tube flow with Reynolds number between 5200 and 22,000 using water as a working fluid.

2. Wing twisted tape with/without alternate axis

All twisted tapes used in the present work, were made of aluminum strips with thickness (δ) of 0.8 mm, width (W) of 19 mm and length (L) of 1000 mm. The twist ratio y/W defined as ratio of twist length (y, 180°/ twist length) to tape width of twisted tapes (W), was kept constant at 3.0. All tapes were initially formed as typical twisted tapes. The twisted tape with centre wings (WT) was