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Experimental and numerical investigation of convective heat transfer and fluid flow in twisted spiral tube

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ABSTRACT

Turbulent flow characteristics and heat transfer performances of twisted tri-lobed tube (TTT) and twisted oval tube (TOT) with Reynolds number of 8000–21,000 are experimentally compared in this research work, indicating that TTT provides better heat transfer performance and higher friction factor than TOT. Furthermore, numerical investigation of the influence of different geometrical parameters on heat transfer performance and flow characteristics for different twisted spiral tubes using computation fluid dynamics with a validated SST k–ω turbulence model is conducted. These geometrical parameters include different cross section shapes, twisted pitches, twisted direction and lobed numbers. The numerical result reveals that the tubes with larger diameters of out-scribed circle (D_2) offer higher Nusselt number and friction factor. It is noted that the heat transfer performance and friction factor increase with the reduction of twisted pitch length P. It is also found that twisted tube with right-left hand rotation shows better heat transfer performance than the tube with right hand rotation. In order to understand the heat transfer mechanism of the TTTs, streamlines, velocity and temperature distributions are also given. From the analysis it can be concluded that the heat transfer enhancement of TTTs is attributed to the helical flow and secondary flow induced by twisted curved tube wall. Radial velocity and tangential velocity are generated by centrifugal forces, leading to higher temperature gradients near the wall of lobed region inside twisted tube. Then the field synergy degree between velocity vector and temperature gradient is improved and the heat transfer is enhanced.

1. Introduction

Compact heat exchangers are widely used in many industrial fields, such as the chemical engineering, power production, waste heat recovery and air conditioning etc. Recently, more and more attentions have been paid on the energy saving due to the shortage of energy. In past decades, many studies of convective heat transfer enhancement have been reported. The heat transfer enhancement techniques can be classified in three ways (a) intense mixing between mainstream and fluids near the wall induced by roughened surface or twisted tape (b) thermal boundary layer decreased by impingement jet (c) swirl flow or secondary flow caused by vortex generator or rotating tube [1]. In order to improve the compactness and efficiency of heat exchangers, both the reduction of the pressure loss and enhancement of the heat transfer capacity are necessary.

Swirling flow in the pipe is considered as combination of vortex motion with axis motion in pipe axis. The helical pipe has been shown to increase axial velocities and induce a swirl (or tangential) component in the flow field, which can be beneficial to heat transfer [2]. Benefits of swirl-inducing devices are reduced pressure drops, and hence reduced power consumption. Helical pipe, belonging to one important group of swirl generators, are mostly applied in heat transfer enhancement. The mechanisms of heat transfer enhancement inside a helical tube is mainly divided into two ways: (1) geometrical characteristics resulting in an increase of flow velocity and curvature wall which drives secondary motions and (2) an increase of fluid mixing between the core and the near-wall flow regions [3].

The investigations of heat transfer augmentation and fluid flow in typical helical pipes including twisted flat tube (TFT) and twisted oval tube (TOT) have been extensively reported in recent years. In the early stage, Dzyubenko et al. [4] tested the performance of twisted tube to attain the heat transfer and pressure drop correlations at S/d_e = 6.2–34 and Re = 2000–40,000. Asmantas et al.

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Nomenclature

A_s	heat transfer area, m^2
a	major axis of elliptical part of tube, m
b	minor axis of elliptical part of tube, m
c_p	specific heat, J/(kg K)
D	diameter of round tube, m
d_e	hydraulic diameter, m
f	friction factor
h	heat transfer coefficient, W/(m^2 K)
L	effective length of tested tube, m
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number
Pr	Prandtl number
Δp	pressure drop, Pa
P	twisted pitch of twisted tube, m
T	temperature, K
ΔT	temperature difference, K
$\underline{U}$	overall heat transfer coefficient, W/(m^2 K)
U	velocity vector, m/s
u	velocity, m/s
Q	heat flux, J/m^2
r	radius of arc part of tube, m
D_1	diameters of inscribed circle of tube, m
D_2	diameters of out-scribed circle of tube, m
E	enhancement performance

Geek symbols

μ	dynamics viscosity, Pa s
υ	kinematic viscosity, m^2/s
ρ	density, kg/m^3
λ	thermal conductivity, W/(m K)
κ	turbulence kinetic energy (m^2 s^{-2})
ρ	density (kg m^{-3})
θ	synergy angle, °

Subscripts

c	cold water
h	hot water
in	inlet
t	tube side
p	plain tube
LMTD	logarithmic mean temperature difference
m	mean value
o	outer
s	shell side

[5] also studied heat transfer performance of twisted oval tube. The results showed that heat transfer rate and flow resistance is improved by 20%–40% and 50%–80%, respectively. Bishara et al. [6] numerically studied the laminar flow in a twisted oval tube at $Re < 1200$. They found that the secondary flow caused by the torsion of the tubes results in the heat transfer enhancement and pressure drop increment. Meng et al. [7] also studied the flow in a twisted oval tube numerically at $Re = 500–1500$. Yang et al. [8] experimentally studied on convective heat transfer and flow resistance characteristics of water flow in twisted elliptical tubes (TETs). Larger tube aspect ratios and smaller twist pitches resulted in higher heat transfer coefficients and friction factors. The best operating regime for TETs is at lower Reynolds numbers. Tan et al. [9] simulated the heat transfer and fluid flow characteristics in twisted oval tubes with Realized $k–\varepsilon$ model. Influence of the geometrical parameters including twisted pitch length P and aspect ratio a/b on the performance of the tube side were analyzed. The result reveals that the heat transfer coefficient and friction factor both increase with the increasing of axis ratio a/b, while both decrease with the increasing of twist pitch length. Gao et al. [10] experimentally investigated the heat transfer and flow resistance characteristics of water flow inside twisted tubes with large twist ratio in transition and turbulent flow regime. It was found that Nusselt numbers and friction factors for twisted tubes are 1.3–2.5 times and 1.2–1.5 times of those for the smooth tube, respectively. Recently, Bhadouriya et al. [11] studied the twisted square tube with twist ratio of 11.5 and 16.5 by experimental and numerical method. It was found that the maximum average Nusselt number is obtained with $H = 2.5$ at $Re = 3000$.

The literature review suggests that heat transfer and flow characteristics of fluid flow inside twisted duct of square and elliptical cross section were studied by many researchers. Recently, a novel twisted tri-lobed tube (TTT) for transporting solid–liquid mixture was presented [12]. More and more researches focused on the fluid flow in TTT due to high mixing efficiency. However, the use of TTT for heat transfer enhancement is rarely reported and heat transfer mechanism of the TTT is still not clear. The primary aim of the present study is (1) to measure the pressure drop and heat transfer coefficient for TOT and TTT with the same twisted pitch of $P = 200$ mm; (2) to conduct the numerical study on the effect of geometrical parameters of TTT such as different cross section shapes and twisted pitches on heat transfer enhancement, (3) to examine the heat transfer and flow characteristics inside tubes with different twisted direction; (4) to understand heat transfer mechanism by giving the local distribution of velocity and temperature.

2. Physical model

The cross section shape of heat transfer enhanced tube named as twisted tri-lobed tube is shown in Fig. 1. The TTT and TOT studied in present work were fabricated by circular tube via the following steps: (1) a normal circular straight tube is tagged and one end of the tube is compressed; (2) the tube is heated to a high temperature and (3) TTT is formed by cold drawing using a rotating die. All of the tubes are made of brass with a length of 1 m. Inner diameter and outer diameter of the smooth round tube is 20 mm and 21 mm, respectively. The structure of TTT in this work shows a little difference from the tube presented by Fokeer et al. [12] that in terms of present tube, the outlines of cross section are consisted of semi-ovals and arcs. Geometrical parameters of the TTT are diameters of inscribed circle of tube, D_1, diameters of out-scribed circle of tube, D_2, radius of arc, r, length of major axis and minor axis, a and b, and twist pitch length, P.

In the experiments, a smooth tube, a TTT and a TOT, which are shown in Fig. 2(a)–(c), are examined to compare the heat transfer and flow resistance performance and to validate the heat transfer experiment and numerical methods for enhanced tubes. Among the tubes for experiment, TTT and TOT are designed to be tubes with identical P and D_1. The dimensions of TTT and TOT studied in the experimental work are listed in Table 1.

3. Experimental study on TOT and TTT

In order to ensure the reliability of the numerical method, Nusselt number and friction factors for TTT and TOT obtained from