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Analysis of heat transfer and flow resistance of twisted oval tube in low Reynolds number flow

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ABSTRACT

Heat transfer enhancement of twisted oval tube is mainly concentrated in the high Reynolds number region. In the present study, the low Reynolds k-ε model is employed to investigate heat transfer and flow characteristics of water flow inside twisted oval tube (TOT) for Reynolds number in the range of 50–2000. Three dimensional numerical study is conducted to study the effects of the geometric parameters on the performance of twisted oval tube for a uniform wall temperature case. The flattening of 1.2, 1.4, 1.63, 1.8 and 2.0, and the twisted pitch ratio of 0.17, 0.25, 0.33 and 0.5. Local distributions of Nusselt number and friction factor are presented. The filed synergy principle is applied to reveal heat transfer enhancement mechanism. The results show that the heat transfer performance of twisted oval tube has been enhanced while having an increasing of pressure drop. One of the key findings of this study is that laminar to turbulent flow transition point was identified and located at $Re = 500$. The fluid is in laminar states with Reynolds number range of 50–250, while the fluid is in turbulent flow when the Reynolds comes to 500–2000. It is also found that the twisted oval tube performs well compared with the smooth tube due to the effect of secondary flow. The maximum enhancements factor *PEC* of 1.7 is obtained with flattening of 2.0, twisted pitch of 0.33 and Reynolds number of 350. Moreover, *PEC* of twisted oval tube increased with the increasing of flattening, but decreased with the increasing of twisted pitch ratio. These results would assist people in a comprehensive understanding of heat transfer performance of twisted oval tube in low Reynolds number flow, but also help in the design and development of compact heat exchanger.

1. Introduction

Heat transfer enhancement techniques, divided into passive and active methods, is widely used in many thermal engineering applications such as power engineering, chemical industry, and oil industry. Twisted tubes as the parts of shell and tube heat exchangers are applied in various heat transfer process [1–3]. Twisted tube heat exchangers were developed in the 1980s. Compared with the conventional smooth tube, twisted tubes change the linear flow into a spiral flow inside the tubes, resulting in a perpendicular to the main flow direction secondary flow [4]. Twisted oval tubes as a form of twisted tube are formed into an oval section, and two ends of the tube remain round taking into account the assembly requirements.

The thermal performances and heat transfer enhancement of twisted tube heat exchangers were widely investigated using experimental and numerical methods. Eiamsa-ard et al. [5] studied the influence of three-start spirally twisted tube combined with triple channel twisted tube insert on heat transfer enhancement, pressure loss and thermal performance behaviors with Reynolds number of 4000–20,000. Their results indicated that heat transfer and friction factor increased with tape width ratio. They also found that the thermal performance increased with decreasing Reynolds number. Zambaux et al. [6] studied the heat transfer enhancement technique for laminar flow in an annular heat exchanger. Alternating wall deformations applied to internal and external annular tube walls. They revealed that the heat transfer performances were increased compared with a smooth annular geometry and identified the phase-shifting value.

Tang et al. [7] investigated the influence of geometrical parameters on heat transfer performance and flow characteristics of twisted tri-lobed tube and twisted oval tube with Reynolds number of 8000–21,000. Their results showed that twisted tri-lobed tube provided better heat transfer performance and higher friction factor than twisted oval tube, and the heat transfer performance and friction factor increased with the reduction of twisted pitch. They also found that the heat transfer enhancement of twisted

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Nomenclature

a	major axis of tube cross section, m
a/b	flattening of tube cross section
A_{ht}	area of heat transfer wall, m^2
b	minor axis of tube cross section, m
c_p	specific heat capacity, J/(kg K)
D_h	hydraulic diameter, m
f	apparent friction factor
h	convection heat transfer coefficient, W/(m^2 K)
$\dot{m}$	mass flow rate, kg/m^3
Nu	Nusselt number
p	pressure, Pa
P	twisted pitch length, m
P/S	twisted pitch ratio
Pr	Prandtl number
Q	heat transfer rate, W
Re	Reynolds number
S	twisted zone length, m
T	temperature, K
u	velocity in x-direction, m/s
$\vec{U}$	fluid velocity vector
v	velocity in y-direction, m/s
w	velocity in z-direction, m/s
y^+	dimensional wall distance

Greek symbols

μ	dynamic viscosity, kg/(ms)
ρ	density, kg/m^3
θ	synergy angle, °
λ	thermal conductivity, W/(mK)

Subscripts

0	smooth oval tube
in	inlet
out	outlet
w	wall

tri-lobed tubes was attributed to the helical flow and secondary flow induced by twisted carved tube wall. Bhadouriya et al. [8] studied heat transfer and friction factor characteristics of air flow inside twisted square duct with Reynolds number of 600–70,000. Their results indicated that the maximum value for product of friction factor and Reynolds number was observed for a twisted ratio of 2.5 and a Reynolds number of 3000. They also revealed that twisted duct performed well in laminar and also to some extent in turbulent flow region due to strong presence of secondary flow.

Sajadi et al. [9] investigated the heat transfer and flow resistance of oil flow in alternating elliptical axis tubes. The working fluid was heat transfer oil, and the flow's Reynolds number ranged from 300 to 2000. Their results indicated that decreasing the flattening and pitch length, increased heat transfer and flow resistance. Moreover, Sajadi et al. [10] proposed a new tube geometry called Alternating Flattened tube and experimentally and numerically studied the heat transfer and flow resistance of Alternating Flattened tube. Their results revealed that the Alternating Flattened tube had the best performance among the studied tubes and could be an advantageous alternative for circular tube. The work of Tan [11] on twisted tube is an example of a comprehensive study of an enhancement technique in turbulent flows for a wide range of flow conditions. They studied convective heat transfer and fluid flow in twisted oval tubes. Their results showed that the heat transfer coefficient and friction factor both increased with the increasing of axis ratio, while both decreased with the increase of twisted pitch length. They also found that the synergy angle between velocity vector and temperature gradient was reduced and the heat transfer process was enhanced.

He et al. [12] numerically investigated heat transfer enhancement and pressure loss penalty for fin-and-tube heat exchangers with rectangular winglet pairs in a relatively low Reynolds number flow. Their results revealed that the rectangular winglet pairs could significantly improve the heat transfer performance of the fin and tube heat exchangers with a moderate pressure loss penalty. Zhang et al. [13] studied the heat transfer characteristics of steam condensation on horizontal twisted elliptical tubes with different structural parameters. Their results indicated that the condensation heat transfer coefficients for all the tubes reduced with increase of wall subcooling, while the enhancement factor of each twisted elliptical tube was almost constant. They also found that a smaller twist pitch led to a lower condensation heat transfer coefficient.

Li et al. [14] numerically evaluated the flow and heat transfer performance of solar water heaters for different initial temperatures with elliptical collector tubes. Their results indicated that the temperature distributions of all the tube cross sections were alike, but the velocity distributions were much dissimilar. Khoshvaght-Aliabadi et al. [15] studied the heat transfer and laminar flow characteristics of nanofluid flow in the twisted mini-channels with different structural parameters. Their results showed that the nanofluid flow presented higher values compared to the base fluid and the nanofluid had better thermal-hydraulic performances than the base fluid when its volume fraction was 1%.

In general, the previous work on twisted tubes has indicated that twisted tubes give better heat transfer performance than smooth tubes. Regarding the above studies, great progress has been made in this field, however study of twisted tubes is mainly concentrated in the high Reynolds number flow. There is not sufficient work done about heat transfer and flow resistance of low Reynolds number flow in twisted tubes. The present work deals mainly with thermal performance and heat transfer enhancement of twisted tube in the low Reynolds number ranging from 50 to 2000.

The primary aim of the present study is (1) to measure the heat transfer and flow resistance of twisted oval tubes of low Reynolds number flow; (2) to conduct the numerical study on the effect of geometrical parameters of twisted oval tubes such as flattening and twisted pitch; (3) to measure the transition point from laminar flow to turbulence flow; (4) to understand heat transfer mechanism by giving the local distribution of velocity and temperature.

2. Model description

2.1. Physical model

In this study, the twisted oval tube model is shown in Fig. 1. The model is divided into three parts namely inlet zone, outlet zone and heat transfer zone. The inlet and outlet zones are smooth straight oval tubes, and the heat transfer zone is twisted oval tube. Twisted oval tube cross-section is elliptical: the major axis length is a, the minor axis length is b, the twisted pitch is P, and the length of the heat transfer section is S. The flow direction at the inlet is along the Z direction of Cartesian coordinate. In the present work, the twisted pitch P of the original twisted oval tube is 200 mm. Taking into account the computing time and computer hardware