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Effects of twisted tape structures on thermo-hydraulic performances of nanofluids in a triangular tube

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ABSTRACT

An experiment set for flow and heat transfer characteristics of nanofluids is established and the reliability of this experiment set is verified. Thermo-hydraulic performances of nanofluids flowing through a triangular tube with different structure twisted tapes are experimentally studied. The effects of nanoparticle mass fractions (ω = 0.1 wt%, 0.3 wt% and 0.5 wt%), Reynolds numbers (Re = 400–9000), different structure twisted tapes (P = 25 mm, 40 mm, 55 mm, 65 mm, 75 mm) on the Nusselt number and resistance coefficient enhancement ratios are experimentally investigated. It is found that the triangular tube with twisted tape can improve the Nusselt number by 52.5% and 34.7% at best in laminar and turbulent flow respectively compared with the corresponding smooth tube with the same fluid. The comprehensive performances of nanofluids in the triangular tube with twisted tape are also analyzed based on a comprehensive evaluation index. It is found that large nanoparticle mass fraction and small length of each twisted tape unit are more sensitive to the high comprehensive performance index. In addition, comprehensive performances between the triangular tube with twisted tape and the corrugated tube are compared. It is found that the triangular tube with twisted tape has an advantage over the corrugated tube in laminar flow.

1. Introduction

Water and smooth tube are widely applied in most heat exchanger systems. However, these heat exchanger systems cannot meet the high intensity heat transfer in some cases. In order to improve the heat transfer of heat exchanger systems, nanofluids and enhanced tubes are used instead of water and smooth tube.

Because of the high thermal conductivity and the drastic Brownian motion of nanoparticles [1], nanofluids have an excellent heat transfer characteristic compared with water. Nanofluids are applied in many fields including solar thermal conversion [2–5], heat dissipation of electronic components [6,7,8], boiling heat transfer [9,10], natural convection heat transfer [11,12], thermal dispersion [13], heat flux boundary condition [14], and radiation [15]. Hence, nanofluids, as an excellent kind of heat transfer medium, are applicable for heat exchanger systems [16].

Enhanced tubes can effectively reduce the laminar boundary layer and then improve the heat transfer, so they are investigated by many researchers. Such as corrugated tubes and dimpled tubes [17], outward convex asymmetrical corrugated tube [18], internally ribbed tube [19], and helically corrugated tube [20]. Enhanced tubes are also applicable for heat exchanger systems.

In view of these merits of nanofluids and enhanced tubes, flow and heat transfer characteristics of enhanced tubes filled with nanofluids are studied by many researchers. Qi et al. applied experimental and numerical simulation methods to study the heat transfer characteristics of TiO_2-water nanofluids in enhanced tubes respectively, such as horizontal elliptical tube [21], corrugated tube [22], and the influences of nanoparticle concentration and Reynolds number on the flow and heat transfer characteristics are discussed. It was found that nanofluids in these enhanced tubes can effectively enhance the heat transfer at the cost of little increase in pressure drop. Huminic et al. [23] investigated the heat transfer performances of two kinds of hybrid nanofluids in a flattened tube by numerical simulation. It was found that these two kinds of hybrid nanofluids can improve the heat transfer.

Many heat transfer enhancement technologies are adopted by researchers. Some researchers investigated the effect of magnetic field on the flow and heat transfer characteristics of nanofluids in tubes. Naphon et al. [24] investigated the influence of magnetic field on the flow and heat transfer of nanofluids in a micro-fins tube. It was found that the magnetic field can improve the heat

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Nomenclature

A_c	cross-sectional area, m^2
c_p	specific heat of nanofluids, $J\cdot kg^{-1}\cdot K^{-1}$
c_{pbf}	specific heat of base fluid, $J\cdot kg^{-1}\cdot K^{-1}$
c_{pp}	specific heat of nanoparticle, $J\cdot kg^{-1}\cdot K^{-1}$
d_e	hydraulic diameter, m
D	height of twisted tape, m
f	frictional resistance coefficient of nanofluids
f_c	equivalent smooth tube friction factor
h	convective heat transfer coefficient, $W\cdot m^{-2}\cdot K^{-1}$
I	electric current, A
l	length of tube, m
L	length of whole twisted tape, m
Nu	Nusselt number of nanofluids
Nu_c	equivalent smooth tube Nusselt number of nanofluids
$\Delta p/\Delta l$	pressure drop per unit length, $Pa\cdot m^{-1}$
P'	wetted perimeter, m
P	length of each twisted tape unit, m
p	pressure drop, Pa
q_m	mass flow rate, $kg\cdot s^{-1}$
Q_0	heating power, W
Q_f	effective heating power, W
Q_{loss}	heat loss, W
q_m	mass flow rate, $kg\cdot s^{-1}$
Re	Reynolds number
Re_c	equivalent smooth tube Reynolds number
r_i	inner radius, m
r_o	outer radius, m
T_{wo}	average temperature of outside wall, K
T_{wi}	average temperature of inside wall, K
T_{in}	inlet temperatures, K
T_{out}	outlet temperatures, K
T_f	average temperature of nanofluids, K
u	velocity of nanofluids, $m\cdot s^{-1}$
U	voltage, V

Greek symbols

ρ	density of nanofluids, $kg\cdot m^{-3}$
ρ_{bf}	density of base fluid, $kg\cdot m^{-3}$
ρ_p	density of nanoparticle, $kg\cdot m^{-3}$
φ	nanoparticle volume fraction,%
ω	nanoparticle mass fraction,%
δ	thickness of twisted tape, m
δ_{tube}	thickness of triangular tube, m
λ	thermal conductivity of copper, $W\cdot m^{-1}\cdot K^{-1}$
λ_f	thermal conductivity of nanofluids, $W\cdot m^{-1}\cdot K^{-1}$
μ_f	dynamic viscosity of nanofluids, Pa·s
$R3$	comprehensive performance index

Subscripts

bf	base fluid
f	nanofluids
p	nanoparticle
w	wall

transfer performance by 6.23% compared with those without magnetic field in the micro-fins tube. Naphon et al. [25] analyzed the heat transfer and pressure drop of a spirally coiled tube filled with nanofluids using artificial neural network. It was found that the numerical simulation results are consistent with the experimental results. Naphon et al. [26,27] reported the effects of magnetic field and pulsating flow on the convective heat transfer and pressure drop of TiO_2-water nanofluids in the spirally coiled tubes. It was found that magnetic field and pulsating frequency have a great positive influence on the heat transfer enhancement.

Also, some researchers investigated the influence of insert on the flow and heat transfer performances of tubes filled with nanofluids. Sun et al. [28] studied the flow and heat transfer performances of Cu, Al, Al_2O_3, Fe_2O_3, multiwalled carbon, and graphite nanofluids in external thread tubes with twisted belt by experiment. It was obtained that Cu nanofluids show much excellent heat transfer performance than other nanofluids. Kumar et al. [29] investigated the heat transfer characteristic of a double pipe heat exchanger filled with Fe_3O_4-water nanofluids, and discussed the effects of longitudinal strip inserts on heat transfer. It was found that longitudinal strip insert, particle concentration and Reynolds number are all advantageous to heat transfer enhancement. Sundar et al. [30] reported the effects of different wire coil inserts on the flow and heat transfer performances of Fe_3O_4-water nanofluids in a plain tube. It was found that nanofluids in the tube with the smallest ratios (p/d = 1) wire coil insert show the highest heat transfer performance. Also, Sundar et al. [31] reported the flow and heat transfer performances of a tube filled with nanodiamond-nickel hybrid nanofluids, and analyzed the effects of longitudinal strip inserts on heat transfer. It was found that hybrid nanofluids can improve the heat transfer by 93.3% compared with water in the tube with longitudinal strip insert. Goudarzi et al. [32] reported the heat transfer enhancement of Al_2O_3-EG nanofluids in a car radiator with wire coil insert by experiment. It was obtained that the wire coil insert enhances the heat transfer by 9%, and the combination of nanofluids and wire coil insert can enhance the heat transfer by 5% compared with the combination of water and wire coil insert.

In review of above studies, researchers make a large contribution to the heat transfer enhancement technologies, especially adding insert into the smooth tube. Although the smooth tube with different kinds of inserts is investigated, the studies on the enhanced tube with different structure inserts, especially the triangular tube, are few. The main innovations of this paper are as follows: (1) Unlike the smooth tube with insert in other published references, triangular tube instead of smooth tube with different kinds of inserts in this paper is investigated; (2) Unlike the comprehensive evaluation without distinguishing different working conditions in other published references, a novel comprehensive evaluation index is applied to analyze the thermo-hydraulic performances in details under the same pressure drop (equal pumping power), which is helpful for us to analyze and evaluate a new heat exchanger in the future.

2. Method

2.1. Experimental system

TiO_2-water nanofluids with three various mass fractions (0.1 wt%, 0.3 wt%, 0.5 wt%) are used as the heat transfer mediums. The preparation process, stability analysis and physical property parameters of TiO_2-water nanofluids have been studied in our previous paper [22].

The schematic diagram of the experimental system is shown in Fig. 1. For the heat transfer characteristics, ten T-type thermocouples and two armored thermocouples are applied to measure the surface temperature and the inlet and outlet temperatures of