



Effects of turbulator with round hole on the thermo-hydraulic performance of nanofluids in a triangle tube

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ABSTRACT

For investigating the thermal and hydraulic characteristics of water-based SiO₂ nanofluids in a triangular tube with different turbulators, an experimental system has been designed and verified in this paper. The effects of different round hole diameters ($d = 3$ mm, 4 mm, 5 mm) and round hole pitch-rows ($l = 5$ cm, 10 cm, 15 cm) of perforated turbulators on the thermo-hydraulic characteristics are researched. Meanwhile, the influences of Reynolds numbers ($Re = 400$ –8000) and nanoparticles mass fractions (D-I water, $\omega = 0.1\%$, 0.3% , 0.5%) are also studied. These experimental results show that, under the same circumstance, the nanofluids in the triangular tube with $\omega = 0.5\%$ have the largest positive influence on the heat transfer enhancement ratio which is up to 16.73%. For a comprehensive study of the flow and heat transfer, thermal efficiency (comprehensive performance index) and exergy efficiency are adopted. It can be found that the larger the diameter and the smaller the pitch-row of the holes is, the greater the comprehensive evaluation index can be. In addition, all working conditions exhibit the superior exergy efficiency. The highest exergy efficiency can be got when $Re = 6000$ and $\omega = 0.5\%$.

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1. Introduction

With the development of technology in heat transfer equipment, conventional heat transfer medium and smooth tube cannot satisfy with the request of the increasing heat exchange amount. In order to achieve much higher heat exchange amount, there is a need to seek new fluid and enhanced tubes.

In recent years, nanofluids have been widely applied in the field of heat exchange due to their excellent thermal conductivity. For example, full-spectrum photo-thermal conversion [1,2], enhanced solar thermal conversion [3], defects-assisted solar absorption [4], solar steam generation [5,6], enhanced pool boiling heat transfer on porous surface [7] and superhydrophilic surface [8], CPU cooling [9–11].

As we all know, convection heat transfer is mainly divided into natural convection and forced convection. For natural convection, a plenty of scholars have explored it. Shi et al. [12] explored the

natural convection of nano-Fe₃O₄@CNT fluids, analyzed the influence of different directions and strength of magnetic fields, and proposed a controllable heat transfer method. Guo et al. [13] used Lattice Boltzmann Method (LBM) to simulate the natural convection of nanofluids in an enclosed field, and these results showed that heat transfer characteristics are improved by the increase of Ra number. Pordanjani et al. [14] explored the nanofluids based on nature convection in the cavity with various magnetic fields. The consequence revealed that thermal properties of the material can increase with the increasing magnetic field angle gradually. Nojoomizadeh et al. [15] researched the Fe₃O₄-H₂O nanofluids flowing through a two dimensional microchannel whose bottom half is filled with porous medium. These consequences revealed that the heat transfer characteristics increase with the rising Darcy number in the non-porous region but decrease in the porous region. Teimouri et al. [16] explored the numerical simulation of laminar mixed convection in horizontal eccentric annulus. The consequences showed that Nu numbers augment with the rising of downward eccentricity of inner cylinder. Sheremet et al. explored the natural convection based on a cavity which is full of nanofluids. In addition, the effects of the inclination angle [17], Brownian diffusion and thermophoresis [18] were analyzed. These consequences revealed that the rate of heat exchange can increase as the growth of inclination angle, and Nusselt numbers show a

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Nomenclature

A	cross-sectional area, m^2	T_{in}	inlet temperature of tube, K
b_i	intercept of straight line	T_f	average temperature of nanofluids, K
c_1, c_2	coefficient in equation	T_w^*	outside surface temperature of tube, K
c_p	heat capacity of nanofluids, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$	T_w	inside surface temperature of tube, K
c_{pb}	heat capacity of base fluid, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$	u	velocity of nanofluids, $\text{m}\cdot\text{s}^{-1}$
c_{pp}	heat capacity of nanoparticles, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$	Greek symbols	
$C_{Q,P}$	the ratio of heat transfer rate between enhanced and reference surfaces under identical pumping power	δ	thickness of tube, m
$C_{Q,V}$	the ratio of heat transfer rate between enhanced and reference surfaces over the ratio of friction factor between enhanced and reference surfaces under identical flow rate	η	relative heat transfer enhancement ratios
$C_{Q,\Delta p}$	the ratio of heat transfer rate between enhanced and reference surfaces under identical pressure drop	λ	thermal conductivity of tube, $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
d	diameter of circular hole, mm	μ	dynamic viscosity, Pa·s
d_1	outer diameter of tube, m	ξ	comprehensive performance index
d_2	equivalent diameter of tube, m	ρ	density of fluid, $\text{kg}\cdot\text{m}^{-3}$
d_3	inner diameter of tube, m	ρ_p	density of nanofluids, $\text{kg}\cdot\text{m}^{-3}$
f	frictional resistance coefficient	ρ_{pb}	density of base fluid, $\text{kg}\cdot\text{m}^{-3}$
h	convective heat transfer coefficient, $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$	ρ_{pp}	density of nanoparticle, $\text{kg}\cdot\text{m}^{-3}$
k	thermal conductivity of nanofluids, $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	φ	volume fraction, %
k_i	slope of straight line	ω	mass fraction, %
l	pitch-row, cm	Subscripts	
L	length of tube, m	m_1, m_2	exponent in equation
Nu	Nusselt number	in	import
p	pressure, Pa	out	export
P	pitch of corrugated tube, m	0	circular tube
$\Delta p/\Delta L$	pressure drop per unit length, $\text{Pa}\cdot\text{m}^{-1}$	e	enhanced tube
Q	heat absorbed by nanofluids, J	nf	nanofluids
q_m	mass flow rate, $\text{kg}\cdot\text{s}^{-1}$	f	base fluid
r	outside-radius of tube, m	p	nanoparticle
r'	inner-radius of tube, m	P	under the same pumping power
Re	Reynolds number	Re	under the same Reynolds number
T_{out}	outlet temperature of tube, K	V	under the same mass flow rate
		Δp	under the same pressure drop
		w	wall

decreasing function of the heater size. Miroshnichenko et al. studied the natural convection of open oblique cavities with heating elements [19] and open cavities with multiple porous layers [20] which were full of water-based Al_2O_3 nanofluids respectively. These above-mentioned results showed that the average Nusselt number with an inclination angle of $\pi/3$ can show the largest value, and it increases with the volume fraction at $Ra = 10^5$ when the distance between the first porous layer and the left vertical wall is smaller than $\delta < 0.1$. Pourmehran et al. explored the effects of external magnetic field [21,22], rotational Reynolds number [23] and nanoparticle size [24] on nanofluids. These studies indicated that the large magnetic field, rotational Reynolds number and small nanoparticle size are helpful to reinforce the heat transfer. Izadi et al. studied the free convection of nanofluids in a $\perp$ shaped cavity [25], a porous undulant-wall enclosure [26], a porous enclosure under magnetic fields [27], and between two eccentric cylinders filled with porous material [28]. Results indicated that larger heat source aspect ratio, smaller Lewis number and higher magnetic number are beneficial to the heat transfer enhancement. Mahian et al. [29] used theoretical correlation to explore the heat transfer capability of silica nanofluids in square and triangle enclosures, and compared the calculated results with experimental data.

Researchers all over the world have also investigated the forced convection heat transfer. Shahsavani et al. [30] explored the thermo-hydraulic performance of non-Newtonian nanofluids in circular tubes and developed their new correlations to calculate the power law exponent, viscosity exponent and thermal conductivity. Sheikholeslami et al. explored the forced convection under

a magnetic field, and discussed various influencing factors of heat transfer, which include cubic cavity driven by a porous cap [31], Lorentz force [32], Kleinstreuer-Li (KKL) model [33], shape of nanoparticles [34], electric field dependent viscosity [35], porous media under electric field [36], compound turbulator [37], and hot sphere obstacle [38]. Naphon et al. explored the convection heat transfer in helically corrugated tubes based on TiO_2 -water nanofluids [39] and a coil pipe [40–42] under magnetic field, and analyzed the effects of pulsating flow frequency [39], magnetic displacement [40], and magnetic orientation [41] on the convection heat exchange. Also, the forced convective heat transfer with pulsating nanofluids was explored by applying artificial neural networks [42]. The above results indicated that additions of pulsating flow and magnetic field are advantageous to intensify the heat transfer. Zhou et al. [43] explored the numerical simulation on the forced convection heat transfer of nanoparticle-metal fluid in circular tubes. The impacts of Re and volume percentage of nanoparticle were discussed. It was found that the nanoparticle-metal fluid shows higher heat exchange performance than that of nanoparticle-water. Sun et al. have finished a series of experiments on the forced convection heat transfer in external thread tube [44] and internal thread tube [45] with nanometer refrigerant. The impacts of various nanofluids as well as nanoparticle mass fractions on the thermo-hydraulic characteristics were explored, and the conclusion showed that water-based Cu nanofluids demonstrated an excellent heat transfer characteristic compared with water-based Al, water-based Al_2O_3 , and water-based Fe_2O_3 nanofluids. Also, it was found that enhanced heat transfer

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