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Effects of magnetic field on thermo-hydraulic performance of Fe_3O_4-water nanofluids in a corrugated tube

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ABSTRACT

An experimental system is established to investigate the thermo-hydraulic performance of Fe_3O_4-water nanofluids in a corrugated tube under various magnetic fields. The influences of magnetic induction intensities (B = 0 G, 100 G, 200 G, 300 G), nanoparticle mass fractions (ω = 0.0%, 0.1%, 0.3%, 0.5%), electromagnet arrangement modes (one-side electromagnet and two-side staggered electromagnet), kinds of tubes (smooth tube and corrugated tube), Reynolds numbers (Re = 800–12,000) on flow and heat transfer characteristics are discussed. It is obtained that the augmentation of heat transfer is more sensitive to high nanoparticle mass fraction, high magnetic induction intensity, two-side staggered electromagnet and corrugated tube. A Comprehensive evaluation index is applied to estimate the thermo-hydraulic performance. It can be discovered that the comprehensive evaluation index increases with the increasing Reynolds number at first and then decreases, and the rough surface of corrugated tube delays the appearance of critical Reynolds number.

1. Introduction

The augmentation of heat transfer performance is an inevitable challenge in industry, active and passive heat transfer enhancement technologies can be adopted in heat exchangers [1,2] and electronic components [3–5]. Active heat transfer enhancement technologies mainly include magnetic field [6–8], mechanical rotating and agitating [9]. Passive heat transfer enhancement technologies mainly include improvement of thermophysical properties of working fluids [10–12], rough surface such as corrugated tube [13–15], internal and external thread tube [16,17].

Due to the low thermal conductivity, some traditional working fluid, such as water and ethylene glycol, cannot meet the requirements of heat exchanger. On this background, nanofluids, as a kind of high thermal conductivity working fluid, have been used in many heat transfer fields, such as boiling heat transfer, convective heat transfer, photothermal conversion and photothermal conversion. For pool boiling heat transfer, Fan et al. conducted a study on the effects of length and diameter [18] on boiling heat transfer of carbon nanotube (CNT)-based aqueous nanofluids, also studied the influence of concentration on boiling heat transfer of graphene-based aqueous nanofluids [19] and aqueous nanofluids in the presence of graphene and graphene oxide nanosheets [20]. For convective heat transfer, Guo et al. [21] reported the heat transfer performance of nanofluids in a square cavity. Sheremet et al. investigated the influences of corner heater [22] and thermal dispersion [23] on the natural convection heat transfer of nanofluids. For photothermal conversion, Liu et al. [24,25] reported the solar-thermal conversion of various nanospheres. Wang et al. [26] and Liu et al. [27] investigated the solar steam generation by carbon-nanotube and graphene oxide nanofluids respectively.

Based on the passive heat transfer enhancement technologies (nanofluids instead of water and ethylene glycol), some researchers have adopted active heat transfer enhancement technologies (adding magnetic field on nanofluids).

For free convection heat transfer, Sheikholeslami et al. [28] applied a two phase model to investigate the influence of magnetic field on the double diffusion convection of nanofluids. It was found that temperature gradient increases with the suction parameter but deteriorates with the Schmidt number, thermophoretic parameters and Brownian motion. Sheikholeslami et al. [29] numerically investigated the influence of magnetic field on an open porous cavity full of nanofluids by lattice Boltzmann method. It was discovered that natural convection heat transfer can be improved with the increasing Darcy number. Sheikholeslami et al. [30] conducted a research on free convection of an enclosure full of Fe_3O_4-water

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Nomenclature

A_c	cross-sectional area, m^2
B	magnetic induction intensity, G
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_c	nanoparticle size, m
f	frictional resistance coefficient of nanofluids
h	convective heat transfer coefficient, $W\cdot m^{-2}\cdot K^{-1}$
k	shape factor
L	length of tube, m
Nu	Nusselt number of nanofluids
$\Delta p/\Delta L$	pressure drop per unit length, $Pa\cdot m^{-1}$
P	wetted perimeter, m
p	pressure drop, Pa
q_m	mass flow rate, $kg\cdot s^{-1}$
Q_f	effective heating power, W
Re	Reynolds number
r_0	external diameter, m
r_i	inner diameter, 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, $m\cdot s^{-1}$

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	wall thickness of tube, m
λ	thermal conductivity of copper, $W\cdot m^{-1}\cdot K^{-1}$
λ_f	thermal conductivity of nanofluids, $W\cdot m^{-1}\cdot K^{-1}$
λ'	X-ray wavelength, Å
β	line broadening full width at half maximum (FWHM) of peak
θ	Bragg diffraction angle, rad
μ_f	dynamic viscosity of nanofluids, $Pa\cdot s$
ζ	comprehensive evaluation index

Subscripts

bf	base fluid
f	nanofluids
p	nanoparticle
PP	same pumping power
w	wall

nanofluids under magnetic field. It was obtained that heat transfer performance decreases with Lorentz forces but increases with buoyancy forces. Sheikholeslami et al. [31] studied the effects of Lorenz forces on the free convection heat transfer of water based nanofluids. It was reported that the increasing Darcy number can reduce the thickness of the boundary layer but Hartmann number can increase it. In addition, Sheikholeslami et al. also investigated the natural convection heat transfer of nanofluids in porous enclosures by Darcy model [32], non-equilibrium model [33,34], control volume based finite element method [35,36] respectively.

For forced convection heat transfer, Sheikholeslami et al. [37] applied control volume based finite element method to analyze the forced convection heat transfer in a porous semi-annulus full of nanofluids considering the influences of the shape of nanoparticle and magnetic field. It was obtained that heat transfer performance decreases with Lorentz forces but increases with Darcy and Reynolds number. Sheikholeslami et al. [38] numerically studied the forced convection in a cubic cavity full of nanofluids considering the magnetic field. It was obtained that the temperature gradient increases with velocity of moving surface but decreases with the Lorentz forces. Sheikholeslami et al. [39] numerically investigated the force convection heat transfer of nanofluids in a lid driven enclosure considering the influence of electric field. It was obtained that the flow style is related to the electric field, and Nusselt number increases with Coulomb forces. Sheikholeslami et al. [40] numerically studied the forced convection heat transfer of an enclosure filled with nanofluids considering variable properties and the influence of electric field. It was found that Coulomb force is beneficial to enhance the heat transfer. Sheikholeslami et al. [41] numerically simulated the forced convection heat transfer of an enclosure full of nanofluids considering moving and sinusoidal walls. It was obtained that heat transfer performance decreases with Hartmann number but increases with Reynolds number. Sheikholeslami et al. investigated the forced convection heat transfer of nanofluids in porous enclosures considering the Lorentz forces [42], Brownian motion [43,44]. It was found that Hartmann number reduces the kinetic energy and convection heat transfer performance, and increases the temperature gradient.

Above researchers adopted the combination of nanofluids and magnetic field to improve the heat transfer, which promotes the heat transfer enhancement technology. However, the combination of nanofluids, magnetic field and rough surface (corrugated tube) is investigated less. Compared with smooth tube, corrugated tube not only has a larger heat exchange area when their hydraulic diameters are the same, but also can destroy the laminar boundary layer by its cyclical peaks and troughs. Besides, corrugated tube is widely applied in industry and has a strong ability of self-descaling. Hence, the thermo-hydraulic performance of Fe_3O_4-water nanofluids in a corrugated tube under a magnetic field is experimentally investigated. The effects of magnetic induction intensities (B = 0 G, 100 G, 200 G, 300 G), mass fractions of nanoparticle (ω = 0.0%, 0.1%, 0.3%, 0.5%), electromagnet arrangement modes (one-side electromagnet and two-side staggered electromagnet), kind of tubes (smooth tube and corrugated tube), Reynolds numbers (Re = 800–12,000) on flow and heat transfer characteristics are researched. A Comprehensive evaluation index is applied to evaluate the thermo-hydraulic performance.

2. Experimental method

2.1. Preparation of Fe_3O_4-water nanofluids and stability study

Two-step method is used to prepare Fe_3O_4-water nanofluids in this experiment. Fig. 1 presents the characteristics of nanoparticles and nanofluids. It can be found from scanning electron microscope (SEM), transmission electron microscope (TEM) photographs that nanoparticles easily gather together. It can be also found from X-ray Diffraction (XRD) photographs that intensity of nanoparticles measured has a good agreement with the standard card of Fe_3O_4, which means the nanoparticles in this experiment is Fe_3O_4