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Flow and convective heat transfer characteristics of Fe_2O_3–water nanofluids inside copper tubes☆

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ABSTRACT

Fe_2O_3–water nanofluids were prepared at mass fractions of 0.1%, 0.2%, 0.3%, and 0.4% using Fe_2O_3 nanoparticles with an average size of 50 nm. Dispersants such as sodium dodecyl benzene sulfonate (SDBS), gum acacia, and cetyl trimethyl ammonium chloride (1361bromide) were added at various proportions to improve the stability of the nanofluids. This study analyzed the flow and convective heat transfer characteristics of the Fe_2O_3–water nanofluids inside inner-grooved copper and smooth copper tubes, and results indicated that the dispersants enhanced the stability of the nanofluids significantly. In particular, SDBS was the most effective among them. The frictional resistance coefficient was greater in the inner-grooved copper tube than in the copper tube under laminar flow conditions and given a constant Reynolds number. This coefficient decreased in both tubes when both the mass fraction of Fe_2O_3 and the Reynolds number increased. The increase in the mass fraction of Fe_2O_3 also enhanced the convective heat transfer performance levels of the nanofluids.

1. Introduction

Many researchers are concerned with the proper leveraging of modern advances in science and technology to save energy and to improve energy transfer efficiency. Traditional heat transfer media, such as deionized water (DW), oil, and glycol, struggle to meet heat transfer requirements under certain conditions. Moreover, the poor thermal performance of these media has seriously handicapped the development of high-efficiency heat transfer and cooling technology. As such, a heat transfer medium with high thermal conductivity (TC) and excellent heat transfer performance can effectively meet the energy needs of various industries.

Solids generally conduct heat more effectively than liquids, and the TC of the former is several orders of magnitude stronger than the latter. Therefore, the heat transfer performance of a two-phase fluid with suspended solid particles is significantly better than that of a traditional single-phase liquid [1]. Many scholars conducted theoretical and experimental studies in which solid particles were added to liquid to improve the TC of liquid after Maxwell theory was proposed [2]. However, the studies on two-phase liquids have been limited to the use of a millimeter or micrometer particulate solid. Suspensions containing large particles are unstable and subside easily. Thus, they are prone to clogging, wear, and other undesirable phenomena that greatly hamper their industrial application.

In 1995, Choi [3] prepared nanofluids by mixing a moderate amount of metal or non-metallic nanoparticles with liquid to generate a homogeneous suspension. Once the nanoparticles were added, the liquid significantly improved in terms of TC and thermodynamic performance. The nanoparticles addressed the clogging and wear while improving lubrication and drag. Thus, nanofluids have numerous potential applications in flow and heat transfers.

Recent research has focused on the flow and convective heat transfer characteristics of nanofluids such as TiO_2, Al_2O_3, CuO, Cu, and SiC. Heyhat et al. [4] investigated the heat transfer coefficient and friction factor of nanofluids flowing in a horizontal tube under laminar flow conditions. Their results illustrated that the single-phase correlation with nanofluid properties cannot predict the enhancement of the heat transfer coefficients of nanofluids. Duangtongsuk and Wongwises [5,6] studied the heat transfer and pressure drop characteristics of TiO_2–water nanofluids in a double-tube counter flow heat exchanger. They also estimated the convective heat transfer coefficients for low concentrations of nanofluids using thermophysical property models. Furthermore, heat transfer was enhanced by the addition of γ–Al_2O_3 nanoparticles to DW that flowed through a copper tube under the laminar flow regime in the study conducted by Wen and Ding [7]. The Nusselt number increased by 47% when 1.6% volume of γ–Al_2O_3 nanoparticles was added to water. Guo et al. [8,9] investigated the thermal

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Nomenclature

d_{out}	outer diameter (m)
d_{in}	inner diameter (m)
f	friction coefficient
h	convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
$\overline{h}$	average convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
I	electric current value (A)
K	thermal conductivity of copper tube ($W \cdot m^{-1} \cdot K^{-1}$)
l	length of the test section (m)
Nu	Nusselt number
Pe	Peclet number
ΔP	pressure drop (Pa)
q_v	volume flow rate (m^3/h)
Q	heating power (W)
Q'	heating power of resistance wire (W)
q	average heat flux (W/m^2)
R	resistance (Ω)
Re	Reynolds number
S	internal surface area of the experimental section (m^2)
T_{in}	inlet temperature (°C)
T_{out}	outlet temperature (°C)
$\overline{T}_{nf}$	average fluid temperature (°C)
T_{wi}	inner wall temperature measured at the i measuring point (°C)
$\overline{T}_w$	average surface temperature (°C)
t_{nf}	fluid temperature (°C)
t_w	inner wall temperature (°C)
t_{w0}	wall temperature (°C)
u	flow rate units (m/s)

Greek symbols

μ_{nf}	dynamic viscosity of nanofluids (Pa·s)
μ_{bf}	dynamic viscosity of base liquid (Pa·s)
$\mu t_{w,nf}$	dynamic viscosity of nanofluids at the inner wall temperature (Pa·s)
v	kinematic viscosity (m^2/s)
ρ_{nf}	density of nanofluids (kg/m^3)
ρ_{bf}	density of the base liquid (kg/m^3)
ρ	density of nanoparticles (kg/m^3)
φ	volume fraction of nanoparticles
ω	mass fraction of nanoparticles

Subscripts

in	inlet
out	outlet
w	wall
nf	nanofluid
bf	base liquid

transport properties of nanofluids containing γ–Fe_2O_3 nanoparticles. They applied a mixture-based fluid composed of 55 vol% DW and used 45 vol% ethylene glycol (EG) as the base fluid. Their results indicated that the TCs of the nanofluids were higher than those of the base fluid and that the enhanced values increased further with the volume fraction of the nanoparticles. Moreover, Guo et al. investigated the thermal transport properties of γ–Fe_2O_3/EG nanofluids, including their TC and viscosity. In this study, TC increased with the addition of γ–Fe_2O_3/EG nanoparticles, and the viscosity of the nanofluid increased at low temperatures. Other experimental studies also examined the convective heat transfer and flow characteristics of nanofluids [10–15].

In particular, many scholars have investigated the flow and convective heat transfer characteristics of fluids in inner-grooved copper tubes [16–18]. However, few studies have investigated the convective heat transfer characteristics of Fe_2O_3–water nanofluids. Guo et al. [8] used a mixture-based fluid composed of 55 vol% DW, 45 vol% EG, and 100% EG. Nonetheless, the industrial use of this mixture is limited because it is more expensive than water. Thus, we determine the flow and convective heat transfer characteristics of Fe_2O_3–water nanofluids in inner-grooved copper and copper tubes as an alternative. An inner-grooved copper tube (GB/T 20928-2007) is produced with the materials used in air conditioning systems through a welding technique. Furthermore, the flow and heat transfer performance levels are compared across different channels. We also investigate the loss in energy during transmission and heat transfer efficiency following the incorporation of nanoparticles. The reduction of energy loss during heat transfer and the enhanced effect of heat transfer confirm that the nanofluids can be used industrially.

2. Nanofluid preparation

Nanofluids are not a simple liquid—solid mixture. In a suspension, nanoparticles can be easily stabilized because of their small size, irregular Brownian motion, and strong surface effect. They can also aggregate easily with specific weak connection interfaces, subside, and stabilize in the process because they contain both static electricity and van der Waals force. Therefore, the heat transfer performance of a working fluid can be enhanced by incorporating nanoparticles into a liquid medium and by preparing nanofluids with high dispersion, high stability, and low reunion. Nanofluid preparation methods include vapor deposition, dispersion, and blend methods. The blend methods are also known as the two-step method. Lo et al. [19] generated a Cu nanoparticle suspension through vapor deposition using a vacuum-submerged, arc nanoparticle synthesis system. However, this process is relatively expensive; hence, the more affordable two-step method is more popular. In fact, Nasiri et al. [20] and Wang et al. [21] used this method to prepare Al_2O_3 nanofluids.

The current study generates Fe_2O_3–water nanofluids with the two-step method [22,23] using Fe_2O_3 nanoparticles with an average diameter of 50 nm and a purity of 99%. The Fe_2O_3 nanoparticles are mixed directly with DW prior to adding the appropriate amount of dispersing agent. The mixture is then subjected to ultrasonic vibration to combine the Fe_2O_3 nanoparticles with the DW, to limit agglomeration, and to stabilize the nanofluids.

3. Nanofluid stability and dispersant selection

Nanofluid nanoparticles have larger specific surface areas and more surface energy than conventional liquid–solid mixtures. They also aggregate easily. Furthermore, the solid particles are denser than the base liquid and settle easily. The dispersion of the nanoparticles in the liquid medium should be uniform and stable to enhance the heat transfer capabilities of nanofluids [24] while maintaining good dispersion, high stability, and low nanofluid agglomeration.

In this experiment, the dispersants used were sodium dodecyl benzene sulfonate (SDBS), gum acacia, and cetyl trimethyl ammonium chloride (1631 bromide). These dispersing agents were added in mass fractions of 0.00%, 0.02%, 0.04%, 0.06%, 0.08%, 0.10%, 0.12%, and 0.14% after the appropriate mass fraction of 0.1% Fe_2O_3–water nanofluids was determined. The stabilities of the nanofluids are compared using a transmission ratio method for the various dispersing agents. The results are shown in Fig. 1. Specifically, Fig. 1(a) indicates that the 0.1% Fe_2O_3–water nanofluids gradually stabilize as the mass fraction of SDBS increases. The optimal mass fraction of SDBS is 0.1%, and further increases in mass fraction destabilize the nanofluid. The stability of the 0.1% Fe_2O_3–water nanofluid initially increases and then decreases as the