



Experimental investigation and development of new correlations for heat transfer enhancement and friction factor of BioGlycol/water based TiO₂ nanofluids in flat tubes

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ABSTRACT

Nanofluids, as a kind of new engineering material consisting of nanometre-sized additives and base fluids, have gained extensive attention due to their role in improving the efficiency of thermal systems. This paper presents an experimental investigation on the heat transfer coefficient and friction factor of BioGlycol/water based TiO₂ nanofluids flowing in a flat tube under turbulent flow conditions. TiO₂ nanoparticles with average diameters of 50 nm dispersed in BioGlycol/water of 20:80% mixture ratio respectively with volume concentrations of 0.5–2 vol.% were used as the working fluid. Moreover, this investigation was carried out at operating temperatures of 30, 50 and 70 °C and under constant heat flux boundary conditions. The results showed that the Nusselt number of nanofluid is higher than that of the base liquid and increased with the increasing of the Reynolds number and operating temperatures. The Nusselt number of nanofluids was approximately 28.2% greater than that of base fluid and the results also showed that the Nusselt number of the nanofluids at a volume concentration of 2.0 vol.% was approximately 3% lower than that of base fluids for certain conditions. For the friction factor, the results show that the friction factor of nanofluids at 1.0 vol.% was approximately 6.1% higher than the base fluid and increases with the increase of volume concentrations to be 14.3% at 2.0 vol.% higher than the base fluid. Finally, the new correlations were proposed for predicting the Nusselt number and friction factor of the nanofluids with maximum deviation of 10% and 3% respectively.

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1. Introduction

Heat transfer processes are widely used in numerous areas including heat exchangers, cooling processes, heating and chemical processes [1–5]. The poor heat transfer properties of common fluids (such as water, mineral oil and ethylene glycol) compared to most solids is a primary obstacle to effectiveness of heat processes [6,7]. Early passive techniques such as dispersion of micron-sized particles in a base fluid for heat transfer enhancement were undertaken. Nevertheless, practical problems arose due to clogging and erosion of pipe lines and high pumping power requirements with the dispersed particles, in spite of the fact that a certain degree of heat transfer augmentation is achieved [8].

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In contrast, recent studies with the nanometer-sized particles proved effective in achieving better heat transfer enhancements without any substantial increase in pumping power requirements and other associated practical problems. The nanofluids showed better stability and rheological properties, with no significant penalty on pressure drop [6]. The use of nanofluids for possible heat transfer augmentation has drawn the attention of many investigators [9–16]. In the recent decades, nanofluids with different types of base fluids such as water (W), ethylene glycol (EG) and propylene glycol (PG) have been one of the major interesting research subjects due to their vast applications in the transfer of thermal energy [17–27]. Masuda et al. [28] have initiated studies on the effect of Al₂O₃, SiO₂ and TiO₂ nanoparticles dispersed in water on the thermal conductivity and viscosity of the nanofluids. Murshed et al. [29] investigated the viscosities of water-based nanofluids with 15 nm TiO₂ nanoparticles. The results showed that the viscosity increase with the volumetric loading of nanoparticles and

Nomenclature

A	flat tube width, m	k_{BG}	thermal conductivity of BioGlycol, W/m K
B	flat tube height, m	k_r	thermal conductivity ratio = k_{nf}/k_{bf}
A_s	heat transfer surface area, m ²	μ_{bf}	viscosity of base fluid, mPa s
C_p	specific heat at constant pressure, J kg ⁻¹ K ⁻¹	μ_{nf}	viscosity of nanofluid fluid, mPa s
ID_h	inner hydraulic diameter of the test tube, m	μ_r	viscosity ratio = μ_{nf}/μ_{bf}
OD_h	outer hydraulic diameter of the test tube, m	K_{bf}	thermal conductivity of base fluid, W/m K
f	friction factor = $\Delta P/((L/D_h)(\rho U^2/2))$		
h	heat transfer coefficient, W m ⁻² K ⁻¹		
I	current, A		
L	length of the test section, m		
Nu	Nusselt number = hD_h/k		
P	pressure of flow in tube, Pa		
Pr	Prandtl number = $\mu C_p/k$		
ΔP	pressure drop, Pa		
Q	heat transfer rate, W		
Re	Reynolds number = $\rho U D_h/\mu$		
t	thickness of the test tube, m		
T	temperature, °C		
U	average axial flow velocity, m s ⁻¹		
V	voltage, V		
$\bar{V}$	volume flow rate, m ³ s ⁻¹		
BG	BioGlycol		
EG	ethylene glycol		
PG	propylene glycol		
K_{bf}	thermal conductivity of base fluid, W/m K		

Greek letters

ρ	density, kg/m ³
ϕ	volume concentration
ω	weight concentration in percent
μ	fluid dynamic viscosity, kg s ⁻¹ m ⁻³
η	thermal enhancement index

Subscripts

b	bulk
h	hydraulic diameter
e	plain flat tube
pp	pumping power
bf	base fluid
eff	effective
nf	nanofluid
p	particle
w	water

approximately 27% higher at 0.02 volume fraction when compared with the data of Masuda et al. [28].

Although there are many studies about the application of water-based nanofluids for heat transfer enhancement, few of them focused on the limitation of using water-based nanofluids in cold countries like Alaska, Canada, Northern Europe and Russia, due to freezing of water at 0 °C [30]. So to avoid the freezing of water, ethylene glycol or propylene glycol are added in suitable proportions. Numerous studies have been conducted on the role of ethylene glycol based TiO₂ nanofluids in heat transfer enhancements [30–34]. Chen et al. [33] have also found a Newtonian behaviour for TiO₂/EG nanofluids containing 0.5, 1.0, 2.0, 4.0, and 8.0 wt. % spherical nanoparticles at 293.15–333.15 K and a relative viscosity dependent on particle concentration in a non-linear manner without temperature dependence. On the other hand, Lee et al. [34] have determined temperature-independent thermal conductivity enhancements up to 16% for 5.5 vol.% of TiO₂/EG nanofluids constituted by nanoparticles with rutile and anatase phases. The enhancement of density in relation to the base fluid is also higher for rutile nanofluids, reaching values of 3.8% at the highest concentration. These increments with the concentration are almost temperature and pressure independent.

Notwithstanding its diversity, the use of PG as a base liquid has been rarely studied [35–37]. Recently Palabiyik et al. [38] studied propylene glycol-based nanofluids of both Al₂O₃ and TiO₂ nanoparticles with a temperature range of 20–80 °C and volume concentrations of 1, 6 and 9%. The results showed that the enhancement of thermal conductivity is in a non-linear form as a function of concentration, and independent of temperature. Vajjha et al. [39] studied the viscosities of five nanoparticles (Al₂O₃, CuO, SiO₂, TiO₂, and ZnO) dispersed in a base fluid of 60:40 PG/W. The results illustrated a non-Newtonian behaviour within a lower temperature range of 243–273 K and a Newtonian behaviour within a higher temperature range of 273–363 K.

Titanium dioxide (TiO₂) is one of the promising materials for heat transfer enhancement purposes due to its excellent chemical

and physical stability [40]. In addition, TiO₂ particles are cheap and commercially available [40]. TiO₂ nanoparticles suspended in conventional fluids were extensively utilized in various forms of heat exchangers, including circular tubes [41], double tubes [30,42] and a shell and tube [43].

Duangthongsuk and Wongwises [44] had investigated the TiO₂ nanofluid heat transfer coefficients under turbulent flow with a double pipe heat exchanger for concentrations up to 2.0%. They observed an increase in heat transfer coefficient with Reynolds number, for concentrations up to 1.0% at the operating temperature of 25 °C. Nevertheless, the heat transfer coefficients decreased for concentrations of more than 1.0%, but are observed to be greater than the base liquid water. Furthermore, Azmi [8] observed a decrease in heat transfer coefficient with TiO₂ nanofluids when the volume concentration increased to 3.0% at the operating temperature of 30 °C.

Its noteworthy that BioGlycol (BG) showed more advantages compared to water, for instance a much lower freezing point and a much higher boiling point (–46 °C to 177 °C), respectively. Furthermore, one of the BG attributes is that it has a lower thermal conductivity than water of about one-third. Moreover, BioGlycol solution is produced domestically with renewable sourced fluid. It is non-toxic and produced at low temperatures that provides 30% lower viscosity compared to propylene glycol, which is petroleum-derived [45]. It also has greater thermal stability while possessing similar or better thermo-physical properties compared to propylene and ethylene glycols. It offers better performance than propylene glycol while giving its users an environmentally safer product than ethylene glycol [46]. It is noteworthy that the American Academy of Clinical Toxicology cites an average of 40–60 human deaths per year in the United States alone and estimates thousands of deaths per year to pets due to ethylene glycol poisoning, most of it from ingestion of spilled automotive antifreeze [47].

Recently Abdolbaqi et al. [48–51] studied the thermal conductivity and viscosity of Al₂O₃, TiO₂ and SiO₂ nanofluids with different volume concentrations and different base fluid ratios at a

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