International Communications in Heat and Mass Transfer 57 (2014) 247–253

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Turbulent forced convection effectiveness of alumina–water nanofluid in a circular tube with elevated inlet fluid temperatures: An experimental study☆

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ARTICLE INFO

Available online 16 August 2014

Keywords:
Nanofluid
Turbulent force convection
Heat transfer enhancement
Inlet fluid temperature

ABSTRACT

The present study aims to explore experimentally the influence of elevated inlet fluid temperature on the turbulent forced convective heat transfer effectiveness of using alumina–water nanofluid over pure water in an iso-flux heated horizontal circular tube at a fixed heating power. A copper circular pipe of inner diameter 3.4 mm was used in the forced convection experiments undertaken for the pertinent parameters in the following ranges: the inlet fluid temperature, $T_{in} = 25$ °C, 37 °C and 50 °C; the Reynolds number, $Re_{bf} = 3000$–13,000; the mass fraction of the alumina nanoparticles in the water-based nanofluid formulated, $\omega_{np} = 0$, 2, 5, and 10 wt.%; and the heating flux, $q''_o = 57.8$–63.1 kW/m^2. The experimental results clearly indicate that the turbulent forced convection heat transfer effectiveness of the alumina–water nanofluid over that of the pure water can be further uplifted by elevating its inlet temperature entering the circular tube well above the ambient, thereby manifesting its potential as an effective warm functional coolant. Specifically, an increase in the averaged heat transfer enhancement of more than 44% arises for the nanofluid of $\omega_{np} = 2$ wt.% as the inlet fluid temperature is increased from 25 °C to 50 °C.

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1. Introduction

In the present study, experiments have been undertaken to explore the influence of elevating inlet temperature of alumina–water nanofluid on its turbulent convective heat transfer effectiveness to replace the pure water as the heat transfer fluid in an iso-flux heated horizontal circular tube. Among various passive techniques proposed for convective heat transfer enhancement, nanofluids formulated through dispersing various metallic or non-metallic nanoparticles in common heat transfer liquids, such as water, oil, or ethylene glycol, feature an anomaly enhanced thermal conductivity over their base fluids and have thus drawn an enormous research interest for the past decades, as clearly reflected in the recent biographical reviews of the progress and challenges in exploring the heat transfer characteristics of various formulations of nanofluid [1–4].

Forced convective heat transfer effectiveness of using various water-based nanofluids in turbulent circular tube flow has been experimentally investigated intensively [5–10]. However, there exists significant disparity among these experiments. Pak and Cho [5] found that due to greatly enhanced viscosity over their base fluid, the convective heat transfer coefficients for fully turbulent flows of the γ-Al_2O_3– and TiO–water nanofluids in an iso-flux heated circular tube were lower than that of the pure water under fixed averaged fluid velocity. In contrast, the experiment by Torii and Yang [6] reported significant heat transfer enhancement for using the nanodiamond-water nanofluid in a fully turbulent tube flow. In conformity with the conclusion of Pak and Cho [5], Williams et al. [7] observed no abnormal heat transfer enhancement from using Al_2O_3– and ZrO_2–water nanofluids for a fully turbulent flow in horizontal tubes. Using water-based nanofluid containing less than 2 vol.% of γ-Al_2O_3 nanoparticles for turbulent tube flow, Fotukian and Nasr Esfahany [8] found an increase of 48% in heat transfer coefficient over that of pure water for the nanofluid of 0.054 vol.% at the Reynolds number of 10^4. Further, Chandrasekar and Suresh [9] observed an enhancement of 51% in the convective heat transfer coefficient for the thermally fully developed turbulent tube flow of Al_2O_3–water nanofluid of 0.2 vol.% over that the pure water.

Above all, the heat transfer enhancement of utilizing the water-nanofluids as the convection fluids in the turbulent tube flows was mostly attributed to their highly enhanced thermal conductivity over the pure water. Moreover, some experimental studies [10–16] show that the thermal conductivity of the nanofluids can be significantly enhanced with an increase of the fluid temperature, other than that of the nanoparticle fraction dispersed. Such temperature-dependent enhancement in thermal conductivity may serve as another potential benefit for using the nanofluids as the high-temperature coolants. In this context, the objective of the present study is to explore experimentally the efficacy in utilizing Al_2O_3–water nanofluid for turbulent forced convection in an iso-flux heated tube under various inlet fluid temperatures.

☆ Communicated by W.J. Minkowycz.
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http://dx.doi.org/10.1016/j.icheatmasstransfer.2014.08.017
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Nomenclature

c_p	specific heat, kJ/kg K
d_i	inner diameter, m
f	friction factor, $\Delta p(d_i/l)/(\rho u_b^2/2)$
FOM	figure of merit
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
l	length of tube section, m
Nu	average Nusselt number, hd_i/k
Δp	pressure drop, kPa
P	pumping power, W
Q	volumetric flow rate, cm$^{3/}$min
q_o	heat transfer rate removed by fluid, W
Re	Reynolds number, $\rho u_b d_i/\mu$
T	temperature, K
$\overline{T}$	averaged temperature, K
u_b	bulk velocity, m/s

Greek symbols

μ	dynamic viscosity, N s/m^2
ρ	density, g/cm^3
ϕ_{np}	volumetric fraction of nanoparticles
ω_{np}	mass fraction of nanoparticles

Subscripts

b	bulk mean quantity
bf	base fluid
btd	bulk temperature difference
in	inlet
itd	inlet temperature difference
mean	mean quantity
nf	nanofluid
out	outlet
w	base wall

2. Preparation and thermal properties of nanofluid

The nanometer-sized particles of alumina (γ-Al_2O_3) (Nanotech, Kanto Chemical Co. Inc., Japan) with an averaged particle size about 33 nm and 99.95% purity were dispersed in ultra-pure Milli-Q water (the base fluid) to form the alumina–water nanofluid. Nanofluids containing various mass fractions of alumina were formulated by mixing appropriate quantities of nanoparticles with the base fluid in a flask and then dispersing in an ultrasonic vibration bath for at least 24 h. The volume-mean diameters of the alumina particles in the nanofluids formulated were measured by means of laser diffraction technique to be 85–100 nm, depending on the mass fraction.

The effective thermal properties of the water-based nanofluid formulated pertinent to the present experiment, including the density ρ, the specific heat c_p, the thermal conductivity k, and the dynamic viscosity μ, were measured using various techniques as described in [17,18] and are tabulated in Table 1. An overview of the data in Table 1 clearly reveals that for the pure water as well as the Al_2O_3–water nanofluid formulated, an increasing trend with temperature prevails for the thermal conductivity and the specific heat; while an opposite trend for the viscosity and density. Specifically, the results for the density and the specific heat in Table 1 can be seen rather insensitive to temperature variation, in comparison with those for the thermal conductivity and viscosity. In particular, with temperature decreasing from 20 °C down to 60 °C for the pure water, and the water-based nanofluid of $\omega_{np} = 2\%$, 5% and 10%, the dynamic viscosity/thermal conductivity appears to reduce/increase more than 52%/8%, 50%/10%, 47%/12%, and 35%/12%, respectively. The measured results of these thermal properties generally demonstrate the benefit of the nanofluid, leading to significant increases in thermal conductivity with temperature, in comparison with water, as shown by the increasing trend with temperature for the thermal conductivity ratio, k_{nf}/k_{bf}, of the nanofluid containing various particle fractions over the water in Fig. 1(a) together with the results from the previous studies [19,20]. Moreover as illustrated in Fig. 1(b), the results for the ratio of effective dynamic viscosity of the nanofluid relative to water, μ_{nf}/μ_{bf}, feature nevertheless a somewhat increase trend with increasing temperature, which can be attributed to the relatively lower decreasing rate with temperature for the nanofluid in comparison with that for the pure water.

Table 1
Measured data for thermal properties of pure water and water–Al_2O_3 nanofluid formulated.

ω_{np} (wt.%)	T (°C)	ρ (kg/m^3)	c_p (kJ/kg K)	k (W/m K)	μ ($\times 10^3$) (N s/m^2)
0	20	997.73	4.180	0.603	0.973
	30	993.78	4.178	0.617	0. 801
	40	991.81	4.178	0.632	0. 655
	50	984.97	4.181	0.643	0. 542
	60	981.10	4.185	0.653	0. 464
2	20	1012.54	4.116	0.604	1.160
	30	1010.10	4.110	0.607	0.936
	40	1006.58	4.110	0.631	0.785
	50	1002.65	4.112	0.644	0.655
	60	997.81	4.116	0.654	0.573
5	20	1035.30	4.012	0.620	1.230
	30	1032.80	4.006	0.624	1.020
	40	1029.28	4.007	0.644	0.876
	50	1025.29	4.008	0.682	0.736
	60	1020.38	4.012	0.721	0.642
10	20	1075.60	3.839	0.656	1.145
	30	1073.20	3.834	0.685	1.117
	40	1069.48	3.834	0.732	0.980
	50	1065.40	3.836	0.750	0.840
	60	1000.37	3.839	0.783	0.740

Based on the measured results obtained in the present study, the dependences of the thermal conductivity and the dynamic viscosity of the alumina–water nanofluid formulated can be correlated well with parameters, including the nanoparticle Reynolds number, Re_{np}; the Prandtl number, Pr_{bf}; the fluid temperature T; the freezing temperature of base fluid, $T_{fr,bf}$; the thermal conductivity ratio of the nanoparticle over the base fluid, k_{np}/k_{bf}; and the mass fraction of nanoparticles dispersed, ω_{np} , as follow:

$$\frac{k_{nf}}{k_{bf}} = 1 + 7.814\mathrm{Re}_{np}^{1/2}\,\mathrm{Pr}_{bf}^{1.713}\left(\frac{T}{T_{fr,bf}}\right)^{11.307}\left(\frac{k_{np}}{k_{bf}}\right)^{0.282}\omega_{np}^{1.925} \quad (1)$$

with an averaged and maximum deviation of 1.62% and 4.17%, respectively, from the measured data for k_{nf}/k_{bf}; and

$$\frac{\mu_{nf}}{\mu_{bf}} = \left(1 + 2.0908\omega_{np}^{0.7285}\right)\left(\frac{T}{T_{fr,bf}}\right)^{0.3658} \quad (2)$$

with an averaged and maximum deviation of 2.13% and 3.86%, respectively, from the measured data for μ_{nf}/μ_{bf}. The nanoparticle Reynolds number Re_{np} in Eq. (1) is defined as

$$\mathrm{Re}_{np} = \frac{2\rho_{bf}\kappa_b T}{\pi\mu_{bf}^2 d_{np}} \quad (3)$$

where κ_b ($=1.281 \times 10^{-23}$ J/K) is the Boltzmann constant.

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