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Experimental study on convective heat transfer of nanofluids in turbulent flow: Methods of comparison of their performance

Ehsan B. Haghighi [a,*], Adi T. Utomo [b], Morteza Ghanbarpour [a], Ashkan I.T. Zavareh [c], Heiko Poth [d], Rahmatollah Khodabandeh [a], Andrzej Pacek [c], Björn E. Palm [a]

[a] KTH Royal Institute of Technology, Department of Energy Technology, 100 44 Stockholm, Sweden
[b] BHR Virtual PiE, The Fluid Engineering Centre, Cranfield, MK43 0AJ, UK
[c] University of Birmingham, School of Chemical Engineering, B15 2TT Birmingham, UK
[d] ItN Nanovation AG, Untertuerkheimer Straße 25, 66117 Saarbrücken, Germany

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ABSTRACT

Turbulent convective heat transfer coefficients of 9 wt% Al_2O_3/water and TiO_2/water nanofluids inside a circular tube were investigated independently at the Royal Institute of Technology, KTH (Sweden) and at University of Birmingham (UK). The experimental data from both laboratories agreed very well and clearly show that Nusselt numbers are well correlated by the equations developed for single phase fluids with the thermophysical properties of nanofluid.

The heat transfer coefficients of nanofluids can be compared with those of the base fluids at the same Reynolds number or at the same pumping power. As the same Reynolds number requires higher flow rate of nanofluids therefore such comparison shows up to 15% increase in heat transfer coefficient. However, at equal pumping power, the heat transfer coefficient of Al_2O_3 nanofluid was practically the same as that of water while that of TiO_2 was about 10% lower. Comparing performance at equal Reynolds number is clearly misleading since the heat transfer coefficient can always be increased by increased pumping power, accordingly, the comparison between the fluids should be done at equal pumping power.

1. Introduction

In the last decade the convective heat transfer of nanofluids including turbulent flow was very frequently investigated and according to Science Direct, there were about 1000 articles investigating thermal performance of nanofluids until 2013. Whilst there is still luck of consensus among scientists whether nanofluids show unusual thermal properties majority of papers claim that the presence small amount of nanoparticles drastically increases thermal conductivity and heat transfer coefficients [1–3].

Duangthongsuk and Wongwises [4] experimentally investigated the heat transfer and pressure drop in turbulent flow of TiO_2/water nanofluids (0.2–2 vol% TiO_2) in a horizontal double tube counter-flow heat exchanger. They compared heat transfer coefficients in nanofluids with those in the base liquid at the same Re numbers (between 3000 and 18,000) and observed 20–32% enhancement at 1.0% volume fraction of nanoparticles. However as the concentration of nanoparticles was increased to 2 vol% a reduction of the heat transfer coefficients by 14% was observed compared to base liquid.

Fotukian and Nasr Esfahany [5] investigated turbulent convective heat transfer in diluted γ-Al_2O_3/water nanofluids (Al_2O_3 < 0.2 vol%) in turbulent flow in a circular tube. They showed that, at the same Re number, heat transfer coefficients and pressure drops of nanofluids were higher than of the base fluid. A maximum increase of heat transfer coefficients by 48% was observed at volume fraction of nanoparticles of 0.054% and at Reynolds number of 10,000.

Zamzamian et al. [6] investigated the effect of nanoparticles concentration and operating temperature on turbulent heat transfer coefficients in Al_2O_3/Ethylene Glycol (EG) and CuO/EG nanofluids (nanoparticles concentration between 0.1 and 1 wt%) in a double pipe and in a plate heat exchangers and reported an increase of heat transfer coefficients with the increase of particle concentration and operating temperature. They reported 3–49% enhancement of the heat transfer coefficients in nanofluids at the same Reynolds number.

Suresh et al. [7] investigated the heat transfer coefficient and friction factor in Al_2O_3/water nanofluids (0.3%, 0.4% and 0.5% Al_2O_3) in a turbulent flow through a straight pipe fitted with spiral inserts. At all Reynolds numbers, they observed almost the same

* Corresponding author. Tel.: +46 704057299.
E-mail address: ehsan.bitaraf@energy.kth.se (E.B. Haghighi).

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values of the friction factors for the nanofluids as for the base fluids, and reported 10–48% enhancement in the Nusselt number in nanofluids at the same Reynolds number.

Nomenclature

A	area, m^2
c_p	specific heat capacity, J/kg K
d	pipe diameter, m
DW	distilled water
EG	ethylene glycol
f	friction factor, –
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	length, m
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number, hd/k
Pe	Peclet number, Re × Pr
Pr	Prandtl number, $(C_p\mu)/k$
Re	Reynolds number, $(\rho ud)/\mu$
Δp	pressure drop, Pa
q''	heat flux, W/m^2
P	pumping power, W
T	temperature, C
t	thickness, mm
u	velocity, m/s
x	axial distance, m
$\dot{\forall}$	volume flow rate, m^3/s
Greek letters	
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
α	thermal diffusivity, m^2/s
$\emptyset$	solid particle volume concentration, –
μ	dynamic viscosity, cP
Subscripts	
bf	base fluid
eff	effective
f	fluid
w	wall
in	inner
out	outer
p	nanoparticle
x	axial direction

Fotukian and Nasr Esfahany [8] reported enhancement of the heat transfer coefficients by 25% and 20% increase of pressure drop in a turbulent flow of diluted CuO/water nanofluids (solid concentration larger than 0.3% v/v) in a circular tube comparing with water at the same Re number. They also found that the enhancement of heat transfer coefficient at all investigated Reynolds number was practically independent of the concentration of nanoparticles.

Sajadi and Kazemi [9] measured turbulent heat transfer coefficient and pressure drop in TiO_2/water nanofluid (TiO_2 volume fraction < 0.25%) in a circular tube and reported approximately 22% enhancement of the heat transfer coefficient and 25% increase in the pressure drop at Re = 5000.

Turbulent convective heat transfer of the suspensions of γ-Al_2O_3, TiO_2 and CuO nanoparticles in aqueous solutions of carboxymethyl cellulose were investigated by Hojjat et al. [10]. They reported that the convective heat transfer coefficients in the nanofluids were higher than those in the base fluid when compared at equal Peclet numbers (Pe = Re × Pr) and that the heat transfer coefficient increases with the increase of Peclet number and nanoparticles concentration.

On the other hand, when compared at the same average velocity, the heat transfer coefficients of nanofluids were lower than those of the base fluids [11,12]. The early work from Pak and Cho [11] showed that the heat transfer coefficient of alumina/water was up to 75% higher than the base fluid at the same Reynolds number, but it was 12% lower at the same average velocity. They argued that since the viscosity of nanofluids was higher than that of the base fluid, the Reynolds numbers of the nanofluids were lower than that of water at the same average velocity and consequently the heat transfer coefficient was lower. The results of Pak and Cho [11] clearly indicated that the heat transfer coefficient enhancements of nanofluids depended on the method of comparing them with those of base fluids. Yu et al. [13] also reported the same conclusion.

Table 1 summarises some works investigating turbulent heat transfer in nanofluids.

Some of the reported enhancement of heat transfer coefficient (compared at the same Re) plotted against concentration of nanoparticles summarised in Fig. 1 and clearly show that there is no correlation between the two.

It is well known that there is no theory enabling explanation of unusual enhancement of thermal properties of nanofluids. Therefore in the great majority of the papers discussed above the experiments carried out by one research group are analysed and the results are presented as a graphs showing enhancement coefficients as a function of Re number or pumping power. In such a type of research there is very difficult, if possible at all, to verify experimental results.

In this paper we exploit the fact that the heat transfer in nanofluids was investigated in an EU sponsored project (NanoHex, Ref: 228882) by the consortium comprising universities, research establishment and companies. As it was already mentioned the bulk of experiments were carried out in B-ham and in Stockholm but all the results were heavily scrutinised by other members of the consortium during research meetings. This approach gives extra level of confidence as all the data presented in this paper were at least double/triple checked. Therefore the conclusions indicating that heat transfer coefficient in turbulent flow of nanofluid can be correlated by standard equations developed for ordinary fluids and that there is nothing unusual in thermal behaviour of nanofluids are sound.

2. Materials and methods

2.1. Materials

The Al_2O_3 and TiO_2 nanofluids were supplied as concentrated suspensions (40 wt% for both) by ItN Nanovation AG (Germany) and Evonik AG (Germany), respectively. The concentrated suspensions were diluted to 9 wt% with distilled water (DW). Fig. 2 shows the TEM micrographs of Al_2O_3 and TiO_2 nanoparticles and Fig. 3 shows size distributions of nanoparticles/aggregates in the diluted suspension measured by dynamic light scattering (DLS). The physical properties of nanoparticles/nanofluids including pH, crystal phase, hydrodynamic particle size, average dry particle size (measured by TEM), and the concentration of additives (additives/surfactant) are summarised in Table 2.