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Accurate basis of comparison for convective heat transfer in nanofluids ☆

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ABSTRACT

Thermal conductivity and viscosity of alumina (Al_2O_3), zirconia (ZrO_2), and titania (TiO_2) nanofluids (NFs) were measured at 20 °C. All the NF systems were water based and contained 9 wt.% solid particles. Additionally, the heat transfer coefficients for these NFs were measured in a straight tube of 1.5 m length and 3.7 mm inner diameter. Based on the results, it can be stated that classical correlations, such as Shah and Gnielinski, for laminar and turbulent flow respectively, can be employed to predict convective heat transfer coefficients in NFs, if the accurate thermophysical properties are used in the calculations. Convective heat transfer coefficients for NFs were also compared with those of the base fluids using two different bases for the comparison, with contradictory results: while compared at equal Reynolds number, the heat transfer coefficients increased by 8–51%, whereas compared at equal pumping power the heat transfer coefficients decreased by 17–63%. As NFs have higher viscosity than the base fluids, equal Reynolds number requires higher volumetric flow, hence higher pumping power for the NFs. It is therefore strongly suggested that heat transfer results should be compared at equal pumping power and not at equal Reynolds number.

1. Introduction

Engineered colloids composed of particles of less than 100 nm dispersed in base fluids are called nanofluids (NFs). The addition of nanoparticles (NPs) implies different thermophysical properties for NFs compared to their base fluids. Generally, thermal conductivities of most solid particles are higher than common base fluids such as water, ethylene glycol and engine oils [1]. As a result, well-dispersed NFs are expected to have higher thermal conductivity than their base fluids, thereby also higher heat transfer coefficients. Based on the expected increase in thermal conductivity, NFs have been considered as alternative heat transfer fluids and have therefore attracted a lot of attention in the past decade [2]. The viscosity of NFs is also expected to be higher than that of their base fluids, but this increase is negative in practical applications. The increased viscosity, which acquires higher pumping power, might counterbalance the benefits of greater thermal conductivity. The trade off between increases in these two thermophysical properties is very crucial when considering NFs as heat transfer fluids.

Unlike thermal conductivity and viscosity, which are thermophysical properties, the heat transfer coefficient depends on flow rate and channel geometry. The heat transfer coefficient of NFs and their base fluids can be compared in different geometries e.g. straight tubes, intricate micro-channels and/or heat sinks. The simplest geometry is a straight tube with a clearly defined inlet velocity profile and boundary conditions. Quite a wide range of heat transfer data of NFs based on measurements in straight tubes can be found in the literature. In these reports, different bases of comparison for the heat transfer coefficient (or for the Nusselt number as a non-dimensional parameter) have been used. Most common is to compare at equal Reynolds number. A few researchers have based their results on other comparisons, such as equal velocity.

Several studies comparing laminar flow NF heat transfer with that of the corresponding base fluid can be referred. Hwang et al. [3] declared 8% enhancement for 0.3 vol.% water-based Al_2O_3 NF analysed at equal Reynolds number in the developed region in a straight tube with 1.8 mm diameter and 2502 mm length. Similarly, Anoop et al. [4] tested 4 wt.% water–Al_2O_3 NF in a straight tube with inner diameter of 4.75 mm and 1200 mm length and they reported an 11–25% increase in heat transfer coefficient comparing at equal Reynolds number. Garg et al. [5] proclaimed 32% enhancement for water-based 1 wt.% Multi-Walled Carbon Nanotubes (MWCNT) NF in a straight tube ($D = 1.55$ mm and $L/D = 590$) comparing at equal Reynolds number. Also, Liu and Yu [6] indicated up to a 19% enhancement for 5 vol.% water-based Al_2O_3 solution tested in Re = 600–4500 range. Bases of comparison for the heat transfer coefficient of NFs other than equal Reynolds number have also been reported in the literature for laminar flow. Rea et al. [7] reported a 3% increase for 1.32 vol.% water–ZrO_2 NF and a 27% enhancement for 6 vol.% water–Al_2O_3 NF in a straight tube ($D = 4.5$ mm and $L = 1008$ mm) at equal cross sectional velocity. Moreover, Vafaei and Wen [8] tested 1–7 vol.% alumina water-based

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Nomenclature

A	area, m^2
c_p	specific heat capacity, J/kgK
D	pipe diameter, m
f	friction factor, —
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	length, m
L^*	dimensionless length, $(L/D_{in})/(RePr)$
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number, hD_{in}/k
Pr	Prandtl number, $(C_p\,\mu)/k$
Re	Reynolds number, $(\rho u_m D_i)/\mu$
ΔP	pressure drop, Pa
q''	heat flux, W/m^2
P	pumping power, W
Q	heat, W
T	temperature, C
u	velocity, m/s
x	axial distance, m
$\dot{\forall}$	volume flow rate, m^3/s

Greek letters

v	*kinematic* viscosity, m^2/s
ρ	density, kg/m^3

Subscripts

ave	average
bf	base fluid
eff	effective
f	fluid
in	inner
out	outer
p	nano particle
S-in	surface-inner
S-out	surface-outer

NF in a 0.51 mm inner diameter and 306 mm length tube in flow rate of 8–20 ml/min and showed a doubled heat transfer coefficient at high flow rates for NFs, although they did not perceive any enhancement at low flow rates.

In respect to turbulent flow a number of studies found in the literature measured the heat transfer coefficient for NFs in straight tubes. Duangthongsuk and Wongwises [9] reported a 20–32% enhancement for 1.0 vol.% water–TiO_2 NF in a tube with D = 9.53 mm and L = 1500 mm while comparing at equal Reynolds number (3000–18,000 range). Fotukian and Nasr Esfehany established water-based γ-Al_2O_3 (0.054 vol.%) [10] and CuO (0.24 vol.%) [11] tests in a 5 mm inner diameter and 1000 mm length tube in Reynolds number range 6000–31,000. They declared a maximum 48% and 25% increase for Al_2O_3 and CuO NFs respectively comparing the results at equal Reynolds number. Suresh et al. [12] presented 10–48% increase in heat transfer coefficient at equal Reynolds number for water–Al_2O_3 (0.3–0.5 vol.%) in a tube with 4.85 mm inner diameter and 800 mm length. Sajadi and Kazemi [13] reported a 22% enhancement at Re = 5000 for water-based TiO_2 (0.25 vol.%) in a 5 mm inside diameter and 1800 mm length tube. Also, Kayhani et al. [14] reported 8% increase in the heat transfer coefficient at Re = 11,800 for 2 vol.% of TiO_2 NPs in water measured in 2000 mm length straight tube with 5 mm inner diameter. Few studies comparing the heat transfer coefficient of NFs and their base fluids used other parameters than Reynolds number. Pak and Cho [15] reported a 12% decrease in the heat transfer coefficient for Al_2O_3–water (2.78 vol.%) compared with its base fluid at the same velocity. Similar results were reported by Yu et al. [16] for 3.7 vol.% water-SiC NFs, giving a 7% decrease compared with the base fluid at identical velocity. However, Xuan and Li [17] showed an improvement in the convective heat transfer coefficient of the Cu–water (0.3–2 vol.%) NF compared with its base fluid with the same flow velocity.

As highlighted, the vast majority of studies in the NF field compare the heat transfer coefficient with their base fluids at equal Reynolds number, although a few studies can be found with other basis of comparison. As a matter of fact NFs, which naturally have a higher viscosity, must be run in higher volume flow rates to have a Reynolds number equal to that of their base fluid. Consequently, at equal Reynolds number NFs must have a higher velocity than their base fluid, which requires greater pumping power to compensate for the extra volumetric flow. Hence, comparing NFs and base fluids at equal Reynolds number is iniquitous. Heat transfer of the base fluid could be enhanced by increasing the flow rate up to the point where the pumping powers would be equal. Comparing heat transfer coefficients of NFs and base fluids at equal pumping power is therefore the most reasonable method. Basically it is the pumping power that keeps the flow condition in the cooling systems and it is the most important characteristic value that operators pay for.

In this study the thermal conductivity and viscosity of water-based Al_2O_3, ZrO_2 and TiO_2 NFs (all with 9 wt.%) at 20 °C were measured. The convective heat transfer coefficient of all NFs and of distilled water was measured in a 1.5 m long, 3.7 mm diameter tube in both laminar and turbulent flow. Unlike many studies, the experimental convective heat transfer coefficient was compared not only at equal Reynolds number but also at equal pumping power. The study was completed in EC FP7 project called Nanohex and few important findings in this article are being presented.

2. Experiments

2.1. Materials, synthesis and characterisation

As noted above, in this work, three different NF systems were investigated. All the samples contained pure water as the base fluid. Al_2O_3 NF was manufactured and supplied by Dispersia Ltd, UK. The pH of this NF was adjusted to 3.6 with base. The NF contained some surfactant and pH adjustment base solvent to increase the stability of the suspension. The type and amount of these components were not revealed, as this is the intellectual property of the company. Two other types of water-based NFs, containing 9 wt.% solid content of ZrO_2 and TiO_2 respectively, were prepared and provided by ItN Nanovation AG, Germany. According to the supplier, the ZrO_2 and TiO_2 NFs were stabilised with ammonium polyacrylate (molar weight 3000) while ZrO_2 NF was adjusted to pH 8.4 and TiO_2 NF was adjusted to pH 8.1 to increase electrostatic stability by addition of NH_4OH.

Dynamic light scattering (DLS) and scanning electron microscopy (SEM) were used to determine wet and dry particle size. Both techniques are important in understanding the NF's agglomeration behaviour. DLS analysis provides the details of NPs dispersed in the base fluid while SEM analysis reports the morphology and dry particle size. It is significant to correlate DLS vs SEM particle size to determine the interaction of NPs with the base fluid. DLS was measured using the Beckman Coulter instrument Delsa Nano C and SEM was performed using the Zeiss Gemini Ultra 55. Fig. 1(a–c) presents the DLS curves from Al_2O_3, ZrO_2 and TiO_2 suspensions. For DLS measurements all samples were diluted to at least 1 wt.% and SEM samples were prepared by drying few ml of NFs in an oven at 60 °C overnight. Fig. 1(a) presents the hydrodynamic particle size of Al_2O_3 NF. The wide range of distribution shows that particles are polydispersed in this system. Most of the particles are lying between 50 and 100 nm and the average particle size