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Influence of particle size and shape on turbulent heat transfer characteristics and pressure losses in water-based nanofluids

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ABSTRACT

We carry out extensive experimental studies of turbulent convective heat transfer of several water-based Al_2O_3, SiO_2, and MgO nanofluids with a nanoparticle volume fraction up to 4%. The experimental setup consists of an annular tube, where sub-atmospheric condensing steam is used to establish a constant wall temperature boundary condition, with nanofluid forced through the inner tube. To unravel the influence of particle shape and size to heat transfer we also present a detailed characterization of the nanofluids using Dynamic Light Scattering and Transmission Electron Microscopy techniques *in situ*. In agreement with previous studies, we find that the average convective heat transfer coefficients of nanofluids are typically enhanced by up to 40% when compared to the base fluid on the basis of constant Reynolds number in the turbulent regime, where $Re = 3000–10,000$. However, the increase of the dynamic viscosity of nanofluids leads to significant pressure losses as compared to the base fluids. To account for this, the convective heat transfer efficiency η is determined by comparing the enhanced heat transfer performance to the increased pumping power requirement. When this has been properly taken into account, only the SiO_2 based nanofluid with smooth spherical particles (of average size 6.5 ± 1.8 nm) shows noticeable improvement in heat transfer with a particle volume fraction of 0.5–2%. Increasing the nanoparticle volume fraction beyond 2% enhances the heat transfer coefficient but at the same time lowers heat transfer efficiency η due to pressure losses, which result from the increased fluid density and viscosity. Through our nanoparticle size and shape analysis we find that in general small, spherical and smooth particles (less than 10 nm in size) are best in enhancing heat transfer and keeping the increase of pressure losses moderate. Our results show that the nanoscale properties of the particle phase must be carefully considered in heat transfer experiments.

1. Introduction

One of the most exciting novel directions of research in nanosciences concerns nanofluids [1]. They can be considered as a new class of solid–liquid composite materials consisting of solid nanoparticles, with sizes typically in the order of 1–100 nm, suspended in a liquid (solvent). Typical solutes in water-based nanofluids are metals, oxides such as SiO_2 or Al_2O_3, or even C nanotubes and graphene [2]. A remarkable feature of nanofluids is that the small particle size prevents phase separation and sedimentation under typical experimental conditions and renders the nanofluid dramatic new properties [3]. For example, some nanofluids have been demonstrated to conduct heat an order of magnitude better than predicted by conventional theories [4,5]. Other exciting results in this rapidly evolving field include a surprisingly strong temperature dependence of the thermal conductivity and a threefold higher critical heat flux than that of base fluids [6]. A spectacular example of reported enhanced thermal conductivity is the observation that a small amount (less than 1% volume fraction) of copper nanoparticles or carbon nanotubes dispersed in ethylene glycol or oil can increase their inherently poor thermal conductivity by 40% and 150%, respectively [5–9]. A comprehensive comparison between all the published data indicates, however, that the details of enhancement of thermal conductivity cannot be currently explained [5].

Convective heat transfer in nanofluids has been under intense scrutiny, too [1,4,6–9]. However, there exist significant discrepan-

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Nomenclature

c_p	specific heat capacity, J/(kg K)
d	diameter, m
f	friction factor
G	conductance, W/K
G'	conductance per unit length, W/(m K)
h	heat transfer coefficient, W/(m^2 K)
k	thermal conductivity, W/(m K)
K	ball constant, m^2/s^2
L	length, m
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number ($Nu = hd/k$)
p	pressure, Pa
P	pumping power, W
Pr	Prandtl number ($Pr = c_p\mu/k$)
Re	Reynolds number ($Re = \rho ud/\mu$)
t	time, s
T	temperature, K
u	flow velocity, m/s
$\dot{V}$	volumetric flow rate, m^3/s
ε	absolute surface roughness, m
η	convective heat transfer efficiency
θ_{ln}	logarithmic temperature difference, K
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
φ	volume fraction
ϕ	heat transfer rate, W

Subscripts

bf	base fluid
f	fluid
in	inner
nf	nanofluid
o	outer
p	particle
s	surface
st	steam

cies between different experiments. For example, influence of particle size cannot be properly explained. Normally it is expected that the Brownian motion of nanoparticles results in higher thermal conductivity and thus in higher convective heat transfer coefficient when the particle size decreases. There exist reports [10] where opposite results are claimed. It is assumed that these results are mainly affected by particle clustering leading to an undefined and increased mean particle size. It has also been shown that the increase in the thermal conductivity cannot alone explain the increase in convective heat transfer coefficients [4,11]. There exist reports where enhancement of the heat transfer with cylindrical particles is much higher than with spherical particles. Also, differences in particle size distribution, pH and temperature give conflicting results [1,9]. For heat transfer, it is also imperative to understand the behavior of the (dynamic) viscosity of the nanofluid, especially its temperature dependence, because a large increase in viscosity can cancel out the benefit obtained from increased heat transfer coefficient.

The experimentally reported significant enhancement of thermal conductivity and convective heat transfer for many nanofluids even for very small concentrations of the nanoparticles need to be understood on theoretical grounds. However, conventional theories for heat conduction of colloidal particles completely fail to describe the anomalous transport properties observed in the experiments [1,4,5,9]. Theories of the Maxwell–Garnett type [12] are based on an effective medium picture of the particle–liquid composite, *i.e.* they are mean-field like. Attempts to improve upon such theories by adopting *e.g.* two-phase fluid models and including various additional parameters have not been quantitatively successful [4,13]. This line of reasoning has culminated in purely phenomenological fitting forms based of regression analysis of experimental data [14], for which no theoretical justification exists. According to Buongiorno [15], the convective heat transfer enhancement is mostly due to enhanced particle–fluid slip due to Brownian diffusion and thermophoresis.

A major shortcoming in most reported experiments, which may in part explain the contradictory results, is the almost total lack of characterization of the particle phase *in situ* in nanofluids. The solubility of nanoparticles (and colloids) can be augmented by controlling the zeta potential. However, this is often not delineated in most publications. A low value of the zeta potential together with irregular particle size and shape may lead to significant aggregation, which can seriously affect the experiments. In addition, the viscosity increase of the nanofluid and increased pressure losses in heat transfer experiment have not been properly discussed.

In the present study, we have undertaken an extensive experimental effort to clarify some of the open issues in nanofluid based heat transfer. To this end, we consider here water-based aluminum oxide, silicon oxide and magnesium oxide nanofluids and their convective heat transfer properties (MgO nanofluids have only been studied previously by Xie et al. [16,17]). Convective heat transfer coefficients and pressure losses in turbulent flow (Re = 3000–10,000) are measured in an experimental setup consisting of a long annular tube, where the nanofluid flows inside the inner tube and saturated steam enters the annular section creating a constant surface temperature boundary condition. The flow loop of the nanofluid contains measuring devices for temperature, pressure difference and flow rate. An ultrasonic disperser is incorporated in the flow loop to maintain the dispersion of nanoparticles. To properly characterize the particle phase in the nanofluids, we employ Dynamical Light Scattering and Transmission Electron Microscopy techniques to measure the size distributions and particle shapes *within the nanofluid*. Thus we can state that the nanofluids used here are well characterized, and the results are quantitative enough to identify trends and magnitudes in convective heat transfer enhancement in turbulent flow.

Another important objective here is to properly account for the dynamic viscosity of nanofluids experimentally, since it directly affects the Reynolds number and thus the convective heat transfer analysis. The resulting higher pressure losses in convective heat transfer are measured and analyzed in detail here. This issue is neglected in several studies although it directly influences the usefulness of the fluid in applications. This is because heat transfer coefficients could be improved by simply increasing the flow velocity of the base fluid, which requires additional pumping power due to the increased pressure losses. Any attempt to enhance heat transfer results in increased pressure losses. Also by adding nanoparticles to the base fluid, a competition between the heat transfer augmentation and increased pressure losses is present. Therefore, the true measure of effectiveness of a heat transfer fluid is not the convective heat transfer coefficient alone – the pressure losses need to be incorporated into the evaluation. One of our main new