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Heat transfer properties of nanoparticle-in-fluid dispersions (nanofluids) in laminar flow

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Abstract

The convective heat transfer coefficients of several nanoparticle-in-liquid dispersions (nanofluids) have been measured under laminar flow in a horizontal tube heat exchanger. The nanoparticles used in this research were graphitic in nature, with aspect ratios significantly different from one ($l/d \approx 0.02$). The graphite nanoparticles increased the static thermal conductivities of the fluid significantly at low weight fraction loadings. However, the experimental heat transfer coefficients showed lower increases than predicted by either the conventional heat transfer correlations for homogeneous fluids, or the correlations developed from the particle suspensions with aspect ratios close to one. New correlations on heat transfer need to be developed for nanofluid systems.

Keywords: Nanoparticles; Dispersions; Thermal conductivity; Heat transfer coefficient; Laminar flow

1. Introduction

Heat transfer fluids provide an environment for adding or removing energy to systems, and their efficacies depend on their physical properties, such as thermal conductivity, viscosity, density, and heat capacity. Low thermal conductivity is often the primary limitation for heat transfer fluids. Recently, there has been interest in using nanoparticles as additives to modify heat transfer fluids to improve their performance [1–12]. Dispersion or suspension of nanoparticles of high thermal conductivities in heat transfer fluids (the so-called "nanofluids") is one of the methods for improving the thermal conductivity of the mixtures [1–5], and thus increasing their heat transfer coefficient in various applications. Some examples of nanofluids with improved thermal conductivity include metal nanoparticle suspensions as working fluids in microchannel heat exchangers [1], copper oxide particles suspended in water [3], and silicon carbide nanoparticles in water or ethylene glycol [9,12]. Compared with millimeter- or micrometer-sized particle suspensions, nanofluids possess better long-term stability and rheological properties, and can have dramatically higher thermal conductivities. Current efforts have mainly been focused on low aspect ratio nanoparticle

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Nomenclature

A	area
C_P	heat capacity
d	diameter of particle
D	diameter of test tube
g	acceleration due to gravity
h	heat transfer coefficient
k	thermal conductivity
l	thickness of particle
L	length of test tube
$\dot{m}$	mass flow rate
n	shape factor
q	heat transfer rate
T	temperature
U	overall heat transfer coefficient
W	weight flow of fluid

Greek symbols

β	coefficient of expansion
μ	viscosity
v	kinematic viscosity
ρ	density
ϕ	volume fraction of nanoparticles
Gr	Grashoff number
Gz	Graetz number
Nu	Nusselt number
Pe	Peclet number
Pr	Prandtl number
Re	Reynolds number

Subscripts

b	bulk
e	equivalent
eff	effective
f	fluid
hf	heating fluid
i	inside
in	inlet
o	outside
out	outlet
p	particle
w	wall

dispersions (disks), since controlling the thickening effect of the high aspect ratio particles (rods) is still a very challenging task [10,13].

A model has long been established by Hamilton and Crosser [14] to estimate the effective thermal conductivity, k_{eff}, of macroscopic solid–liquid mixtures, which is given in the following equation:

$$\frac{k_{\text{eff}}}{k_{\text{f}}} = \frac{k_{\text{p}} + (n-1)k_{\text{f}} - (n-1)\phi(k_{\text{f}} - k_{\text{p}})}{k_{\text{p}} + (n-1)k_{\text{f}} + \phi(k_{\text{f}} - k_{\text{p}})} \tag{1}$$

in which k_{f} and k_{p} are the thermal conductivities of the fluid and particles, respectively. ϕ is the volume fraction of the particles, and n is the empirical shape factor. Large aspect ratio particles, such as carbon nanotubes [10], have high values of n in Eq. (1), and therefore more potential for thermal conductivity enhancement. However, the addition of large aspect ratio particles into a liquid may result in huge increase in viscosity as compared to the continuous phase [13].

Recent work by Choi and colleagues [4,5,8,10] indicates that the thermal conductivity increase caused by the addition of nanometer-sized particles is much higher than predicted by the above equation. For example, the addition of 0.3 vol% of copper nanoparticles increases the thermal conductivity of ethylene glycol by 40% [8], and 1 vol% carbon nanotubes lead to a 150% increase of the thermal conductivity of a synthetic poly(α-olefin) oil [10].

Keblinski et al. [15] explored the mechanisms of heat transfer in nanofluids, and proposed four possible reasons for the contribution of the nanometer-sized particles to the increase of the thermal conductivity of the system: Brownian motion of the particles, molecular-level layering of the liquid at the liquid/solid interface, the nature of the heat transport in the nanoparticles, and the effects of nanoparticle clustering. The authors of the current communication believe there may be a synergistic effect of several above-mentioned mechanisms, among which the percolation effect may be favored for particles with high or low aspect ratios.

Nanofluids are multicomponent systems, and the morphology and orientation of the dispersed solids is complex. That is probably the reason that very few correlations have been developed for their convection heat transfer coefficients [16,17]. Considering the small size and the low volume fraction of the particles in most nanofluids, it might be reasonable to treat nanofluids as pure liquids in certain cases. Under these circumstances, the conventional correlations for homogeneous liquids might be applied to these systems. Three such correlations are the Seider–Tate equation for convective heat transfer of laminar flow in tubes [18], the Oliver correlation [19], and the Eubank and Proctor correlation [20].

The Seider–Tate equation is [18]

$$Nu = 1.86 Re^{1/3} Pr^{1/3} \left(\frac{D}{L}\right)^{1/3} \left(\frac{\mu_{\text{b}}}{\mu_{\text{w}}}\right)^{0.14} \tag{2}$$

in which Nu is the Nusselt number, Re is the Reynolds number, and Pr is the Prandtl number. $(\frac{\mu_{\text{b}}}{\mu_{\text{w}}})^{0.14}$ repre-