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The effect of nanoparticle diffusion and thermophoresis on convective heat transfer of nanofluid in a circular tube

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ABSTRACT

Laminar convective heat transfer of water–alumina nanofluid in a circular tube with uniform heat flux is investigated numerically on the basis of two-component model, which takes into account nanoparticle transport by diffusion and thermophoresis. A new expression for thermophoretic mobility is suggested on the basis of existing experimental results and theoretical concepts. It is shown that thermophoresis leads to a significant reduction of nanoparticle volume fraction in the boundary layer near the wall. The corresponding viscosity reduction causes the velocity increase near the wall and flattening of velocity profile near the tube axis to keep the mass flow rate constant. The decrease of wall shear stress leads to the decrease of the required pressure drop. The calculations for two-component model provide higher values of the local and average heat transfer coefficients in comparison with the one-component model. The difference does not exceed 10% and decreases with increasing the thermal Peclet number. The calculations for one-component model show the independence of local and average Nusselt numbers on the nanoparticle volume fraction. The results for two-component model predict the increase of Nusselt number when the thermophoretic effect becomes stronger. The effectiveness of water–alumina nanofluid is analyzed by plotting the average heat transfer coefficient against the required pumping power. It is shown that the nanofluid shows better performance than the base fluid in the range of low pumping power and, correspondingly, low inlet velocity.

1. Introduction

Nanofluids are colloidal suspensions of nano-sized particles in a base fluid. The particles are typically made of oxides, metals, and carbon nanotubes. Common base fluids include water, ethylene glycol, and oil. The addition of a small amount of nanoparticles to the base fluid enhances its thermal conductivity. Thus, nanofluids can potentially be used as heat transfer fluids for cooling electronic devices, vehicle engines, nuclear reactors, laser diodes, etc. [1]. The effectiveness of nanofluids in forced convective heat transfer depends on whether the thermal conductivity enhancement can override the penalty in pumping power associated with the viscosity increase due to addition of nanoparticles [2]. The production of stable nanofluids with prescribed physical properties for commercial use still remains a challenging problem [3].

The use of nanofluids requires a clear understanding of heat transfer mechanisms, which contribute to their enhanced thermal properties. The anomalously high values of thermal conductivity reported in some studies and the contradictions between results measured by different authors (see review paper [4]) promoted the development of theoretical concepts for heat transfer in nanofluids. Several potential mechanisms were suggested: Brownian motion of nanoparticles, formation of highly conductive liquid nanolayer at liquid–particle interface, nanoparticle clustering, ballistic transfer of heat energy inside a separate nanoparticle and between nanoparticles upon contact, dispersion of nanoparticles, and thermophoresis (nanoparticle transport driven by temperature gradient) [5–7]. However, the contribution of these mechanisms to the effective thermal conductivity of nanofluids is not fully understood yet.

To describe the flow and heat transfer in nanofluids, three main approaches are used at present. The first one is *the homogeneous one-component model* based on the momentum and heat transfer equations with physical properties corresponding to nanofluids. It implies that traditional heat transfer correlations must be valid for nanofluids [3]. The second approach is *the dispersion model*, which was first proposed by Xuan and Roetzel [8]. In this model, it is assumed that the relative motion of nanoparticles with respect

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Nomenclature

r	radial coordinate (m)
z	axial coordinate (m)
R	tube radius (m)
L	heated section length (m)
u	radial velocity (m/s)
v	axial velocity (m/s)
v_0	average axial velocity (m/s)
$\boldsymbol{v}_T$	thermophoretic velocity (m/s)
T	temperature (K)
T_0	inlet temperature (K)
H	specific enthalpy (J/kg)
C_m	mass fraction of nanoparticles
C_v	volume fraction of nanoparticles
C_{m0}	inlet mass fraction of nanoparticles
C_{v0}	inlet volume fraction of nanoparticles
$\mathcal{J}$	nanoparticle flux (kg/m^2 s)
q	heat flux (W/m K)
ρ	density (kg/m^3)
ρ_0	reference density (kg/m^3)
β_T	thermal expansion coefficient (K^{-1})
μ	dynamic viscosity (Pa s)
κ	thermal conductivity (W/m K)
c_p	specific heat capacity (J/kg K)
χ	thermal diffusivity (m^2/s)
$\mathcal{D}$	diffusion coefficient (m^2/s)
$\mathcal{D}_T$	thermophoretic mobility (m^2/s K)
$\mathcal{S}_T$	Soret coefficient (K^{-1})
α	proportionality coefficient (kg m/s^2)
τ_w	wall shear stress (Pa)
h	heat transfer coefficient (W/m^2 K)
$\overline{h}$	average heat transfer coefficient (W/m^2 K)
W_p	pumping power (W)
Q	volume flow rate (m^3/s)
k_B	Boltzmann's constant (J/K)
d_a	nanoparticle diameter (m)
Π	viscous stress tensor (Pa)
E	unit tensor
ξ	dimensionless axial coordinate
Re	Reynolds number
Pe	thermal Peclet number
Pe$_c$	solutal Peclet number
Nu	Nusselt number
$\overline{\mathrm{Nu}}$	average Nusselt number

Superscript

T	transpose

Subscripts

b	bulk
w	water
a	alumina nanoparticles
f	fluid
p	particle

to the base fluid introduces a perturbation to the energy equation. The latter is modeled by the dispersion coefficient, which is added to the thermal conductivity to describe the heat transfer enhancement. Finally, the third approach suggested by Buongiorno [9] is known as *non-homogeneous two-component model*. It treats nanofluid as a mixture of the base fluid and nanoparticles, which is described by the equations of momentum, heat and mass transfer. According to [9], the main mechanisms that induce variations of nanoparticle concentration are Brownian diffusion and thermophoresis. In general, further experimental and theoretical studies are needed to verify the applicability of existing models to the description of nanofluids.

Extensive research has been performed on convective heat transfer in nanofluids. In most studies, nanofluids are pumped trough a circular tube with uniform heat flux. A large amount of experimental data on forced convective heat transfer can be found in the review papers by Yu et al. [10] and Terekhov et al. [11]. The enhancement in heat transfer coefficient with respect to base fluids ranges from a few percents for oxide nanoparticles up to 350% for carbon nanotubes [12]. In some studies, the measured Nusselt numbers followed classical heat transfer correlations such as Shah correlation for laminar flows and Dittus–Boelter correlation for turbulent flows as well as their modifications for temperature-dependent physical properties [13–16]. At the same time, the experimental results for water–alumina nanofluid showed anomalous heat transfer enhancement in laminar regime [17,18]. It was conjectured that particle migration due to non-uniform shear rate, viscosity gradient, or thermophoretic migration of nanoparticles were responsible for this enhancement. Measurements of the Nusselt number for water–Cu nanofluid in turbulent regime [19] provided a 30% increase in comparison with the Dittus–Boelter correlation for 2% volume fraction of nanoparticles. These results cannot be explained on the basis of homogeneous flow model. Note that in most studies, comparison between heat transfer coefficients of the base fluids and nanofluids was made at the same Reynolds number. Yu et al. [2] and Utomo et al. [15] showed that it distorts the physical situation since nanofluids require higher average velocity than the base fluids to achieve the same Reynolds number due to viscosity increase. From engineering point of view, the comparison must be performed at the same pumping power, which determines the cost of transferring the heat.

The effect of particle migration on convective heat transfer of nanofluids in laminar regime has been studied in a number of works. Wen and Ding [20] considered three mechanisms leading to non-uniform concentration of particles in radial direction: non-uniform shear rate, viscosity gradient, and Brownian diffusion. It was concluded that particles migrate to the tube center leading to the higher values of the Nusselt number. This study was continued in [21], where a numerical simulation on the basis of combined Euler and Lagrange approach was performed. Using the order-of-magnitude analysis, Sohn and Kihm [22] showed that thermophoresis and Brownian diffusion are the most important mechanisms of particle migration, while the effects of viscosity gradient and non-uniform shear rate can be neglected. Numerical simulations on the basis of homogeneous model showed that the Nusselt number for laminar flow is independent of nanoparticle concentration. When the non-homogeneous model is used, the Nusselt number increases (decreases) with increasing nanoparticle concentration when the tube wall is heated (cooled). Na et al. [23,24] investigated laminar convective heat transfer in water–alumina nanofluid. They found that the dynamic thermal conductivity of nanofluid increases (decreases) with increasing the Reynolds number in the wall heating (cooling) regime. It was attributed to the thermophoretic migration of nanoparticles. However, the dynamic thermal conductivity was calculated either from both experimental and numerical data [23] or under the assumption of fully developed temperature profile [24]. Thus, the entrance region that can be rather large for high Reynolds numbers was neglected. Numerical