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Prediction of turbulent forced convection of a nanofluid in a tube with uniform heat flux using a two phase approach

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Abstract

Turbulent forced convection heat transfer in a circular tube with a nanofluid consisting of water and 1 vol.% Cu is studied numerically. Two phase mixture model has been implemented for the first time to study such a flow field. A single phase model formulation, which has been used frequently in the past for heat transfer with nanofluids, is also used for comparison with the mixture model. The comparison of calculated results with experimental values shows that the mixture model is more precise than the single phase model. The axial evolution of the flow field and fully developed velocity profiles at different Reynolds numbers are also presented and discussed.

Keywords: Nanofluids; Mixture model; Two phase flow; Single phase model; Turbulent forced convection

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1. Introduction

Low thermal conductivity of conventional heat transfer fluids such as water, oil, and ethylene glycol mixture is a serious limitation in improving the performance and compactness of many engineering equipments such as heat exchangers and electronic devices. To overcome this disadvantage, there is strong motivation to develop advanced heat transfer fluids with substantially higher conductivity.

An innovative way of improving the thermal conductivities of fluids is to suspend small solid particles in the fluid. Various types of powders such as metallic, non-metallic and polymeric particles can be added into fluids to form slurries. The thermal conductivities of fluids with suspended particles are expected to be higher than that of common fluids (Mansoori et al., 2002). An industrial application test was carried out by Liu et al. (1988) and the effects of flow rates on the slurry pressure drop and heat transfer behavior was investigated. In conventional cases the suspended particles are of μm or even mm dimensions. However, such large particles may cause severe problems such as abrasion and clogging. Therefore, fluids with suspended large particles have little practical application in heat transfer enhancement.

Nanofluids are a new kind of heat transfer fluid containing a small quantity of nanosized particles (usually less than 100 nm) that are uniformly and stably suspended in a liquid. The dispersion of a small amount of solid nanoparticles in conventional fluids changes their thermal conductivity remarkably. Compared to the existing techniques for enhancing heat transfer, the nanofluids show a superior potential for increasing heat transfer rates in a variety of cases. Choi (1995) quantitatively analyzed some potential benefits of nanofluids for augmenting heat transfer and reducing size, weight and cost of thermal apparatuses, while incurring little or no penalty in the pressure drop.

Researchers have demonstrated that oxide ceramic nanofluids consisting of CuO or Al_2O_3 nanoparticles in water or ethylene glycol exhibit enhanced thermal conductivity (Lee et al., 1999). A maximum increase in thermal

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Nomenclature

a	acceleration
C_f	skin friction coefficient ($=\tau_w/0.5\rho V_0^2$)
C_p	fluid specific heat (J kg^{-1} K^{-1})
D	tube internal diameter (m)
g	acceleration of gravity (m s^{-2})
I	turbulent intensity
k	turbulent kinetic energy (m^2 s^{-2})
Pr	Prandtl number ($=\mu C_p/\lambda$)
q_w	uniform heat flux at the solid–fluid interface (W m^{-2})
r	radial coordinate (m)
Re	Reynolds number ($=V_0 D/\nu$)
T, t	time–mean and fluctuating temperature (K)
V, v	time–mean and fluctuating velocity (m s^{-1})
Z	axial coordinate (m)

Greek letters

ε	dissipation of turbulent kinetic energy (m^2 s^{-3})
Φ	volume fraction
λ	thermal conductivity (W m^{-1} K^{-1})
μ	dynamic viscosity (N s m^{-2})
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})

Subscripts

b	buoyancy
c	centerline
eff	effective
f	primary phase
k	the kth phase
m	mean
p	particle, secondary phase
s	solid
t	turbulent
w	wall
0	inlet condition
r	radial direction
z	axial direction
θ	tangential direction

Superscript

–	mean

conductivity of approximately 20% was observed in that study, having 4 vol.%. CuO nanoparticles with mean diameter 35 nm dispersed in ethylene glycol. A similar behavior has been observed in Al_2O_3/water nanofluid. For example, using Al_2O_3 particles having a mean diameter of 13 nm at 4.3% volume fraction increased the thermal conductivity of water under stationary conditions by 30% (Masuda et al., 1993). On the other hand, larger particles with an average diameter of 40 nm led to an increase of less than 10% (Lee et al., 1999). Furthermore, the effective thermal conductivity of metallic nanofluid increased by up to 40% for the nanofluid consisting of ethylene glycol containing approximately 0.3 vol.%. Cu nanoparticles of mean diameter less than 10 nm (Choi, 1995). Recently, a multi-wall nanotube in oil suspension (MWNT) yielded an extremely large increase in thermal conductivity (up to a 150% over the conductivity of oil) at approximately 1 vol.% nanotubes (Choi et al., 2001). This is the highest thermal conductivity enhancement ever achieved in a liquid.

Different concepts have been proposed to explain this enhancement in heat transfer. Xuan and Li (2000) and Xuan and Roetzel (2000) have identified two causes of improved heat transfer by nanofluids: the increased thermal dispersion due to the chaotic movement of nanoparticles that accelerates energy exchanges in the fluid and the enhanced thermal conductivity of nanofluids considered by Choi (1995). On the other hand Keblinski et al. (2002) have studied four possible mechanisms that contribute to the increase in nanofluid heat transfer: Brownian motion of the particles, molecular-level layering of the liquid/particle interface, heat transport in the nanoparticles and nanoparticles clustering. Similarly to Wang et al. (1999), they showed that the effects of the interface layering of liquid molecules and nanoparticles clustering could provide paths for rapid heat transfer.

Numerous theoretical and experimental studies have been conducted to determine the effective thermal conductivity of nanofluids. Most of these have been confined to liquids containing micro and milli-sized suspended solid particles. However, studies show that the measured thermal conductivity of nanofluids is much larger than the theoretical predictions (Choi et al., 2001). Many attempts have been made to formulate efficient theoretical models for the prediction of the effective thermal conductivity, but there is still a serious lack in this domain (Xue, 2003; Xuan et al., 2003).

As nanofluids are rather new, relatively few theoretical and experimental studies have been reported on convective heat transfer coefficients in confined flows. Pak and Cho (1998), Li and Xuan (2002) and Xuan and Li (2000, 2003) obtained experimental results on convective heat transfer for laminar and turbulent flow of a nanofluid inside a tube. They produced the first empirical correlations for the Nusselt number using nanofluids composed of water and Cu, TiO_2 and Al_2O_3 nanoparticles. The results indicate a remarkable increase in heat transfer performance over the base fluid for the same Reynolds number.

Convective heat transfer with nanofluids can be modeled using the two phase or single phase approach. The first provides the possibility of understanding the functions of both the fluid phase and the solid particles in the heat transfer process. The second assumes that the fluid phase