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Numerical study of forced convective heat transfer of Nanofluids: Comparison of different approaches ☆

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ABSTRACT

Forced convective of a nanofluid that consists of water and Al_2O_3 in horizontal tubes has been studied numerically. Computed results were validated with existing well established correlation. Two-phase Eulerian model has been implemented for the first time to study such a flow field. A single-phase model and two-phase mixture model formulations were also used for comparison. The comparison of calculated results with experimental values shows that the mixture model is more precise. It is illustrated that the single-phase model and the two-phase Eulerian model underestimates the Nusselt number. Effects of nanoparticles concentration on the thermal parameters are also discussed.

1. Introduction

Fluids are essential for heat transfer in many engineering equipments. Although various techniques are applied to enhance the heat transfer, the low heat transfer performance of these conventional fluids obstructs the performance enhancement and the compactness of heat exchangers. The use of solid particles as an additive suspended into the base fluid is a technique for the heat transfer enhancement. The enhancement of thermal conductivity of conventional fluids by the suspension of solid particles, such as millimeter- or micrometer-sized particles, has been well known for more than 100 years. However, they have not been of interest for practical applications due to problems such as sedimentation, erosion, fouling and increased pressure drop of the flow channel. The recent advance in materials technology has made it possible to produce nanometer-sizes particles that can overcome these problems. Innovative heat transfer fluids suspended by nanometer-sized solid particles are called 'nanofluids'. These suspended nanoparticles can change the transport and thermal properties of the base fluid.

Xuan and Li [1] studied the single-phase flow and heat transfer performance of nanofluids under turbulent flow in tubes. Their experimental results showed that the convective heat transfer coefficient and the Nusselt number of nanofluids increase with the Reynolds number and the volume fraction of nanoparticles under turbulent flow. Compared with water, the Nusselt number of the nanofluids with a 2.0 vol.% of Cu nanoparticles is more increased than 39%. Wen and Ding [2] focused on the entry region under laminar flow condition using nanofluids containing γ-Al_2O_3 nanoparticles of various concentrations. It is shown that the enhancement increases with the Reynolds number as well as the volume concentration of nanoparticle. Heris et al. [3,4] investigated the convective heat transfer coefficient of Al_2O_3–water and CuO–water nanofluids for laminar flow in annular tube under a constant wall temperature boundary condition. The thermal and physical properties of the nanofluids were calculated using the following formulas: the Einstein equation for viscosity, the Xuan and Roetzel [5] equation for specific heat, and Yu and Choi [6] correlation for thermal conductivity and Hamilton and Crosser [7] model. The results showed that the heat transfer coefficient increased with an increasing Peclet number and increasing volume fraction while Al_2O_3–water nanofluid showed larger enhancement than CuO–water nanofluids. Yang et al. measured the convective heat transfer coefficients of graphitic nanoparticle-in-liquid dispersions (nanofluids) with aspect ratios of 0.02 under laminar flow in a horizontal tube heat exchanger [8]. It has been showed the effect of particle concentration is more considerable in the turbulent flow regime than the laminar flow [9]. Rea et al. showed when the experimental data are plotted using dimensionless numbers, based on the measured properties of the nanofluids, there is a good agreement with the predictions of the traditional models/correlations for laminar flow [10]. In a comparison between particle sizes it was observed that nanofluid with smaller particles show higher heat transfer coefficient than that with larger particles [11].

Despite so many papers published in the field of nanofluids, this field is still open-ended. Some different areas of research worked in recent years include: flow of nanofluid in micro-nano channels [12–16], boiling of nanofluids [17], nanofluid flow in heat exchangers [18,19] and nanofluid oscillating heat pipe [20]. Also as an interesting application of

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Nomenclature

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})
L	Length of tube (m)
Nu	Nusselt number ($=hD/\lambda$)
Pr	Prandtl number ($=\mu C_p/\lambda$)
q_w	uniform heat flux at the solid–fluid interface (W m^{-2})
Re	Reynolds number ($=V_0D/\nu$)
x	distance from the inlet (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

eff	effective
f	fluid, primary phase
k	the kth phase
m	mean
p	particle, secondary phase
t	turbulent
w	wall

nanofluids, Kleinstreuer et al. investigated the concentration uniformity of nanomedicine (nanofluid) delivery system with eight microchannels [15]. On the other hand, in addition to the experimental works some numerical studies have been done to investigate the effect of nanofluids in thermal enhancement of fluids [13,15,21–30].

In the present study forced convective of a nanofluid consists of water and Al_2O_3 in a horizontal circular tube has been studied numerically. Three different approaches for simulating nanofluids, which are a single-phase model and two-phase mixture model, have been implemented. Two-phase Eulerian model has been implemented for the first time to study such a flow field. The comparison of calculated results with experimental values shows that the mixture model is more precise than the other two models.

2. Mathematical modeling

2.1. Physical properties of the nanofuids

By assuming the nanoparticles are well dispersed within the base fluid, the effective physical properties of the mixtures studied can be evaluated using some classical formulas as well known for two-phase fluids.

$$\rho_{\text{eff}} = (1-\phi)\rho_f + \phi\rho_p \tag{1}$$

$$\left(C_p\right)_{\text{eff}} = (1-\phi)\left(C_p\right)_f + \phi\left(C_p\right)_p \tag{2}$$

$$\frac{\lambda_{\text{eff}}}{\lambda_f} = 4.97\phi^2 + 2.72\phi + 1 \tag{3}$$

$$\frac{\mu_{\text{eff}}}{\mu_f} = 123\phi^2 + 7.3\phi + 1 \tag{4}$$

Eqs. (1) and (2) are general relationships used to compute the density and specific heat for a classical two-phase mixture. Eq. (3) for calculating the thermal conductivity of the nanofluid has been obtained by Hamilton and Crosser [7] by the use of spherical particles assumption. Although this model was first developed based on millimeter and micrometer size particles, it is believed that its use with nanofluids is acceptable. So despite its probable underestimation with nanofluids, because of its simplicity, this model has been adapted for this study. It should be noted that for the case of 1% volume concentration of Al_2O_3 in water, the experimental result of Wen and Ding [2] is used for calculating the thermal conductivity of nanofluids to have a unique input for comparison. The dynamic viscosity of nanofluids has been calculated through Eq. (4), which is obtained, by Maiga et al. [31] performing a least-square curve fitting of some experimental data available for the mixtures considered.

As it will be shown in next sections, in this paper it is concluded that the mixture approach in comparison with single-phase and Eulerian approaches, shows more reliable results for numerical simulation of nanofluids. So in the next section the mathematical formulation of the mixture model is discussed.

2.2. Mixture model

The mixture model, based on a single fluid two-phase approach, is employed in the simulation by assuming that the coupling between phases is strong, and particles closely follow the flow. The two-phases are assumed to be interpenetrating, meaning that each phase has its own velocity vector field, and within any control volume there is a volume fraction of primary phase and also a volume fraction of the secondary phase. Instead of utilizing the governing equations of each phase separately, the continuity, momentum and energy equations for the mixture are employed. A nanofluid composed of water and Al_2O_3 nanoparticles flowing in a long tube with uniform heating at the wall boundary is considered. Therefore, the dimensional equations for steady state mean conditions are

Continuity,

$$\nabla.(\rho_m V_m) = 0 \tag{5}$$

Momentum and,

$$\nabla.(\rho_m V_m V_m) = -\nabla p_m + \nabla.[\tau - \tau_t] + \rho_m g + \nabla.\left(\sum_{k=1}^{n} \phi_k \rho_k V_{dr,k} V_{dr,k}\right) \tag{6}$$

Energy,

$$\nabla.(\phi_k V_k(\rho_k h_k + p)) = \nabla.\left(\lambda_{\text{eff}}\nabla T - C_p\rho_m\overline{vt}\right) \tag{7}$$

while considering Φ is the volume fraction of phase k, we have:

$$\rho_m = \sum_{k=1}^{n} \phi_k\rho_k \tag{8}$$

$$\mu_m = \sum_{k=1}^{n} \phi_k\mu_k \tag{9}$$