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Original Research Paper

A novel thermal dispersion model to improve prediction of nanofluid convective heat transfer

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ABSTRACT

This study numerically investigates the hydrothermal characteristics of the nanofluid in a laminar flow inside a straight tube. A new model is proposed for dispersion thermal conductivity while a theoretical approach is adopted to predict the particle distribution at the tube cross section considering the effects of non-uniform shear rate, Brownian diffusion and viscosity gradient on particle migration. It is observed that nanoparticles are not distributed uniformly at the tube cross section such that the values of concentration are higher at central regions of the tube and this non-uniformity intensifies at higher mean concentrations and Reynolds numbers. The particle distribution is applied in the proposed dispersion model. The findings show that this dispersion model presents more accurate results than traditional homogenous one. For dispersion model, the velocity profile is flatter than that obtained from the homogenous model. In addition, in the vicinity of the wall, the value of temperature and its gradient obtained from the dispersion model are respectively lower and higher than those from the homogenous model. Increasing the mean concentration results in convective heat transfer enhancement, while causing not much penalty in pressure drop. This indicates that application of nanofluids can result in energy efficiency improvement.

1. Introduction

Most conventional heat transfer fluids such as water and ethylene glycol show relatively poor thermal properties which can restrict their application in industrial heat transfer equipment such as heat exchangers and micro channels. On the other hand, most solids, especially metals, have much higher thermal conductivity in comparison with these fluids. Therefore, fluids containing suspended solid particles are expected to provide better heat transfer characteristics than the conventional heat transfer fluids.

Application of suspensions with particles of millimeter or micrometer size causes some difficulties, such as sedimentation of particles and extra penalty of pressure drop in the flow channel [1,2]. However, new advancements in nanotechnology have paved the way to producing a new kind of suspensions called nanofluid. Nanofluid contains nanoparticles (usually less than 100 nm) which are uniformly dispersed in a liquid. The dispersion of a small amount of solid nanoparticles within conventional fluids will increase their thermal conductivity remarkably [3–5].

Regarding superior features of nanofluids, numerous studies, both experimental and numerical, have been conducted on their hydrothermal characteristics and a review on different studies in this field has been presented in some articles such as [6–8].

There are two distinct methods for investigating flow and thermal fields of nanofluids, namely single-phase and two-phase. The former assumes that the fluid and particles are in thermal equilibrium and move with similar velocity [9,10]. In fact, the effect of particles existence is considered only in effective properties. But in the latter model, effect of Brownian motion, thermophoresis and other interactions between fluid and particles are taken into account [11,12]. Homogenous model is one of the single-phase models in which effective properties of nanofluid is applied in the continuity, momentum and energy equations. Therefore, accuracy of the model will depend on applied effective properties. However, effective properties which are proposed for one nanofluid may be inappropriate for another one. This seems to be one major limitation of the homogenous single-phase model.

A new single-phase model, called dispersion model which was first proposed by Xuan and Roetzel [13] for nanofluids, employs an additional heat transfer mechanism. In this model, the effect of relative velocity between nanoparticle and base fluid is regarded

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Nomenclature

c_p	specific heat, J/kgK
D_b	Brownian diffusion coefficient, m^2/s
d	particle diameter, m
J	total flux of particles, m/s
J_b	particle flux due to Brownian motion, m/s
J_c	particle flux due to shear rate, m/s
J_μ	particle flux due to viscosity gradient, m/s
k	thermal conductivity, W/mK
k_b	Boltzmann constant, J/K
P	pressure, Pa
q''	wall heat flux, W/m^2
R	radius of tube, m
r	radial coordinate
T	temperature, K
T'	temperature perturbation, K
t	time, s
V	volume, m^3
$\mathbf{v}$	velocity, m/s
$\mathbf{v}'$	velocity perturbation, m/s
x	axial coordinate

Greek symbols

$\dot{\gamma}$	shear rate, 1/s
μ	dynamic viscosity, kg/m s
ρ	density, kg/m^3
φ	volume concentration of nanoparticles

Subscripts

d	dispersion
eff	effective
f	fluid
p	particle

as a perturbation on energy equation. Thus, this model is known as an advanced version of the previously mentioned single-phase method.

In the conventional homogeneous approach, effective properties of nanofluid which are obtained in the stagnant state ($u_{bulk} = 0$) are included into the conservation equations, whereas movement of the fluid can considerably affect the interaction between fluid and particles. However, in the thermal dispersion method, it is tried to add a virtual term to the thermal conductivity of nanofluid in order to take into account the effects associated with chaotic movements of the particles which were being neglected in the thermal conductivity thus far.

Xuan and Roetzel [13] suggested a model for dispersion thermal conductivity. They considered dispersion thermal conductivity as a function of density, specific heat, velocity and volume fraction of nanofluid. A few researchers followed Xuan and Roetzel's model and claimed that it can properly predict the hydrothermal characteristics of nanofluids [14–17].

Kumar et al. [14] adopted non-dimensional form of the transport equations including thermal dispersion effect and examined water–Cu nanofluid features through a driven cavity. They showed that Nusselt number increases with particle volume fraction. Meanwhile, it was demonstrated that thermal conductivity of the nanofluid increases with shape factor. Duangthongsuk and Wongwises [15] used the dispersion model for predicting the heat transfer performance of the TiO_2–water nanofluid flowing under a laminar regime and constant heat flux. Their results revealed that the heat transfer coefficient increases with increasing Reynolds number and particle concentration. Moreover, they showed that the heat transfer coefficient decreases with increasing length of the test tube. Laminar convective heat transfer of nanofluid in a tube was investigated by Heris et al. [16] applying a dispersion model. Numerical predictions were in agreement with experimental results for different particles. Their results showed that addition of nanoparticles to base liquid produces considerable enhancement of heat transfer. Ozerinc et al. [17] evaluated thermal features of the Al_2O_3–water nanofluid based on the thermal dispersion model. Their assessment showed that the associated enhancement, which is the result of the thermal dispersion, constitutes a relatively smaller portion of the heat transfer coefficient enhancement obtained with nanofluids, the larger portion being the result of the thermal conductivity enhancement.

In the models which have been applied to predict the dispersion thermal conductivity for nanofluids so far, the average concentration has been used and the particle distribution has not been taken into account. In this study, a new mathematical model is proposed for dispersion thermal conductivity based on distribution of particle concentration at the cross section of the tube. The effect of non-uniform particle concentration on thermal dispersion and heat transfer characteristics is considered and investigated.

2. Governing equations

Water/Al_2O_3 nanofluid flowing in a circular tube is investigated. The conservation equations in dispersion model are similar to those of pure fluid, except that thermophysical properties will be replaced by nanofluid effective properties. The dimensional conservation equations for steady state conditions are listed below:

Continuity equation:

$$\nabla \cdot (\rho \mathbf{v}) = 0 \quad (1)$$

Momentum equation:

$$\nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla P + \nabla \cdot (\mu \nabla \mathbf{v}) \quad (2)$$

Energy equation:

$$\nabla \cdot (\rho c_p \mathbf{v} T) = \nabla \cdot (k \nabla T) \quad (3)$$

where ρ, c_p, k and μ represent density, specific heat, thermal conductivity and viscosity of the nanofluid, respectively. Also, P is pressure, T denotes temperature, and $\mathbf{v}$ refers to velocity.

Effective density and specific heat of the nanofluid are calculated based on nanoparticle volume concentration as follows:

$$\rho = \varphi \rho_p + (1 - \varphi)\rho_f \quad (4)$$

$$c_p = \varphi c_{p,p} + (1 - \varphi) c_{p,f} \quad (5)$$

where subscripts p and f refer to particle and base fluid, respectively, and φ denotes concentration. Thermal conductivity of the nanofluid is computed using this equation:

$$k = k_{nf} + k_d \quad (6)$$

where k_d is dispersion thermal conductivity and will be introduced later. Moreover, k_{nf} is the stagnant thermal conductivity and can be calculated using Hamilton–Crosser model [18]: