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Original Research Paper

Effects of nanoparticle migration on force convection of alumina/water nanofluid in a cooled parallel-plate channel

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ABSTRACT

Force convective heat transfer of alumina/water nanofluid inside a cooled parallel-plate channel in the creeping flow regime and the presence of heat generation is investigated theoretically. A modified two-component four-equation non-homogeneous equilibrium model is employed for the alumina/water nanofluid that fully accounts for the effects of nanoparticles volume fraction distribution. To impose the temperature gradients across the channel, the upper wall is subjected to a prescribed wall heat flux while the bottom wall is kept adiabatic. Moreover, due to the nanoparticle migration in the fluid, the no-slip condition of the fluid–solid interface at the walls is abandoned in favor of a slip condition that appropriately represents the non-equilibrium region near the interface. The results indicated that nanoparticles move from the adiabatic wall (nanoparticles depletion) toward the cold wall (nanoparticles accumulation) and construct a non-uniform nanoparticle distribution. Moreover, the anomalous heat transfer rate occurs when the Brownian motion takes control of the nanoparticle migration (smaller nanoparticles).

1. Introduction

Enhancing the performance of conventional heat transfer became a critical challenge for scientists and engineers. Generally, the enhancement techniques can be divided into two groups: (a) active techniques which require external forces such as electrical field and (b) passive techniques which require special surface geometries [1] or fluid additives. Concerning the second method, Aiming to improve the thermal conductivity of the most common fluids such as water, oil, and ethylene–glycol mixture, the idea of adding particles to the heat transfer fluids emerged, in 1873 [2]. Later, many researchers studied the influence of solid–liquid mixture on the possible heat transfer enhancement. But, they were confronted with some problems such as abrasion, clogging, fouling and additional pressure loss of the system which is not suitable for heat transfer systems. In 1995, the word "nanofluid" was proposed by Choi [3] to identify dilute suspensions formed by functionalized nanoparticles smaller than 100 nm in diameter which had already created (Al_2O_3–water) by Masuda et al. [4]. These nanoparticles are fairly close in size to the molecules of the base fluid and, thus, can realize extremely stable suspensions with slight gravitational settling over long periods. Likewise, Lee et al. [5] in 1999 measured the thermal conductivity of Al_2O_3 and CuO nanoparticle suspensions in water and ethylene glycol. In 2001, Eastman et al. [6] and Choi et al. [7] found an anomalous thermal conductivity enhancement of Cu and nanotube dispersions in ethylene glycol and oil respectively. In the light of these pioneering works, a numerous experimental investigation on the behaviors of nanofluids has been carried out which can be found in literature such as Fan and Wang [8].

Meanwhile, theoretical studies emerged to model the behaviors of nanofluid. At the outset, the proposed models were twofold: the homogeneous flow models and the dispersion models. Buongiorno [9] in 2006 indicated that the homogeneous models tend to underpredict the nanofluid heat transfer coefficient, and because of the nanoparticle size, the dispersion effect is completely negligible. Therefore, Buongiorno developed an alternative model to explain the anomalous convective heat transfer in nanofluids and eliminate the shortcomings of the homogeneous and dispersion models. He declared that the anomalous heat transfer occurs due to particle migration in the fluid. Investigating the nanoparticle migration, he considered seven slip mechanisms—inertia, Brownian diffusion, thermophoresis, diffusiophoresis, Magnus, fluid drainage, and gravity—and maintained that, of these seven, only Brownian diffusion and thermophoresis are important slip mechanisms in nanofluids. With this finding as his basis, he proposed a two-component

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Nomenclature

c	specific heat (m^2/s^2 K)
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
h	heat transfer coefficient (W/m^2 K)
H	height of the channel (m)
k	thermal conductivity (W/m K)
k_{BO}	Boltzmann constant (= $1.3806488 \times 10^{-23}$ m^2kg/s^2 K)
Nu	Nusselt number
N_{BT}	ratio of the Brownian to thermophoretic diffusivities
p	pressure (Pa)
q_w	surface heat flux (W/m^2)
T	temperature (K)
u	axial velocity (m/s)
x, y	coordinate system

Greek symbols

ϕ	nanoparticle volume fraction
γ	heat generation parameter
η	transverse direction
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
λ	slip parameter

Subscripts

B	bulk mean
bf	base fluid
p	Nanoparticle
w	condition at the wall

Superscripts

$*$	dimensionless variable

four-equation non-homogeneous equilibrium model for convective transport in nanofluids. The model has been used by Kuznetsov and Nield [10], Malvandi et al. [11–13], Sheikholeslami et al. [14–18], Hatami et al. [19–21], Yang et al. [22,23], Matin and Pop [24,25], Malvandi et al. [26], Servati et al. [27], Malvandi and Ganji [28,29], Ding et al. [30], and Mahian et al. [31].

In this paper, the laminar creeping flow of alumina/water nanofluid in two-dimensional cooling channels is investigated theoretically. The modified two-component four-equation non-homogeneous equilibrium model [13,22] is employed for nanofluid to fully account for the effects of nanoparticle volume fraction on continuity, momentum and energy equations. The mentioned model is one of the most important techniques that consider nanoparticles' migration due to the thermophoretic and Brownian motion forces. To the best of the author's knowledge, no study thus far has looked at the effects of cooling on nanoparticles migration, flow, and thermal fields. It is hoped that the current theoretical findings will motivate more researchers to conduct experiments on nanofluids in the heat transfer system involving cooling channels.

2. Problem description and governing equations

Consider the steady, incompressible, and laminar flow of the alumina/water nanofluid in a two-dimensional parallel-plate channel: the geometry of the problem is shown in Fig. 1, where the lower wall stayed adiabatic and the upper wall is subjected to a constant heat flux (cooled). A two-dimensional coordinate frame has been selected in which the x-axis is aligned horizontally and the y-axis is normally aligned with the walls. The nanofluid is treated as a two-component non-homogeneous mixture, and it includes the base fluid and nanoparticles as introduced by Buongiorno [9], but this was modified according to Yang et al. [22] to fully account for the effects of the nanoparticles' migration. This modification was also employed by Malvandi et al. [13] for the theoretical investigation of the mixed convective flow of nanofluids inside vertical annuli. Consequently, the basic incompressible conservation equations of the mass, momentum, thermal energy, and nanoparticle volume fraction can be expressed in the following manner

$$\partial_i(\rho u_i) = 0 \tag{1}$$

$$\partial_t(\rho u_i) + \partial_j(\rho u_i u_j) = -\partial_i p + \partial_j \mu(\partial_i u_j + \partial_j u_i) \tag{2}$$

$$\partial_t(\rho cT) + \partial_i(\rho c u_i T) = \partial_i(k\partial_i T) + \rho_p c_p\left(D_B\partial_i\phi + \frac{D_T}{T_C}\partial_i T\right)\partial_i T + Q_0(T - T_w) \tag{3}$$

$$\partial_t(\phi) + \partial_i(u_i\phi) = \partial_i\left(D_B\partial_i\phi + \frac{D_T}{T_C}\partial_i T\right) \tag{4}$$

where u_i represents the velocity components; T is the local temperature; p is the pressure, and D_B and D_T are the Brownian diffusion and thermophoretic diffusion coefficients respectively, which can be obtained as

$$D_B = \frac{k_{BO}T}{3\pi\mu_{bf}d_p} \tag{5}$$

and

$$D_T = 0.26\frac{k_{bf}}{2k_{bf}+k_p}\frac{\mu_{bf}}{\rho_{bf}}\phi \tag{6}$$

where k_{BO} is the Boltzmann constant and d_p is the nanoparticle diameter. Further, ρ, μ, k, c are the density, dynamic viscosity, thermal conductivity, and specific heat capacity of the alumina/water nanofluid, respectively, which depend on the nanoparticle volume fraction as follows

$$\mu = \mu_{bf}(1 + 39.11\phi + 533.9\phi^2),\ \rho = \phi\rho_p + (1-\phi)\rho_{bf}$$
$$c = \frac{\phi\rho_p c_p + (1-\phi)\rho_{bf}c_{bf}}{\rho},\ k = k_{bf}(1 + 7.47\phi) \tag{7}$$

and the thermophysical properties of the alumina nanoparticles and base fluid (water) are also as follows:

$$c_{p_{bf}} = 4182,\quad \rho_{bf} = 998.2,\quad k_{bf} = 0.597,\quad \mu_{bf} = 9.93\times10^{-4}\ \mathrm{kg/(m\,s)}$$
$$c_{p_p} = 773\ \mathrm{J/(kg\,K)},\quad \rho_p = 3380\ \mathrm{kg/m^3},\quad k_p = 36\ \mathrm{W/(m\,K)} \tag{8}$$

where bf stands for the base fluid and p for the particle. Considering Eqs. (1)–(4), it is evident that the modified version includes the nanofluid density (ρ) variation in mass, momentum and energy conservations. Since ρ strongly depends on the nanoparticle volume fraction (ϕ), the modified model entirely considers the effects of the nanoparticle concentration distribution.

In the creeping flow regime, the Reynolds number is very small (Re<<1), such that the inertia effects can be ignored compared with the viscous resistance. This is an accepted situation in flows where