



# Implementation of diffusion and electrostatic forces to produce a new slip velocity in the multiphase approach to nanofluids

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## ABSTRACT

Due to the improvement of heat transfer by nanofluids, an understanding of the interactions between nanoparticles and the base fluid is essential for simulation. The relative or slip velocity between nanoparticles and the base fluid is one of the main factors in choosing the multiphase mixture model approach. In this paper, a new slip velocity is proposed and used to compare the simulation result to the experimental results of natural convective flow in a cavity filled with an alumina nanofluid. Therefore, the ANSYS-Fluent 15.0 software is employed and the new slip velocity is applied as a user-defined function. The new slip velocity is a result of the combination of Brownian and thermophoretic diffusions, lift, buoyancy and centrifugal forces, virtual mass, pressure gradient, Van der Waals attraction and electric double layer repulsion forces. The comparison between these forces and induced drag force will provide the corresponding slip velocity. The simulation results were in good agreement with the flow pattern and heat transfer features of the experimental studies in the literature. It was found that thermophoretic and electrostatic slip mechanisms should essentially be considered in simulations, as well as buoyancy force. The major effects of electrostatic slip velocity are mainly seen in concentration higher than 1 vol.%, while thermophoresis could not be ignored in any concentration. Therefore, the implemented slip velocity reveals some critical aspects of nanoparticle and base fluid interactions compared to an algebraic velocity.

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## 1. Introduction

The applicability of nano-sized materials suspended in liquids for the enhancement of heat transfer has been a source of much interest in recent years. The improvement of thermal conductivity and the possibility of uniform distribution are considered to be advantages of nanoparticles, especially for small ranges of volume concentrations [1–5]. On the other hand, the negative effects on the mixture's total viscosity may improve or deteriorate the heat transfer, particularly for natural convection [6–9].

Many experimental studies on nanofluids have been conducted in a wide range of flow regimes [10–15], but none of the available theoretical and modelling approaches can fully explain the entire phenomena inside the nanofluid. One of the most applicable approaches is the mixture model where there is a continuum of both the nanoparticles and the base fluid. The main interaction between phases in the mixture model occurs by implementing relative velocity. Goodarzi et al. [16], Xuan and Roetzel [17] and Maiga et al. [18] assumed no drift or slip velocity between the nanoparticles and continuous phase, which contradicts the observation of other researchers.

Zero slip velocity supports the idea of homogenous distribution or a lack of particle diffusion inside the base fluid. The abovementioned

authors explained the nanofluid mixture properties as the dominant factor to determine the heat transfer features of the flow. Akbarinia and Laur [19], Bianco et al. [20], Rashidi et al. [21] and some more in recent years [22–26] considered centrifugal and gravitational forces as the main reason for the accelerating particle with respect to the base fluid.

Therefore, they discussed the possibility of non-homogeneity of nanoparticle concentration distribution inside the mixture. However, they only employed the default algebraic slip velocity available in the ANSYS-Fluent software without any development for nanoscale application. Buongiorno [27], Hwang et al. [28] and others [29–34] stated that the diffusion flux due to the gradient of concentration and thermophoretic force can be the dominant interaction phenomena between two phases. This idea can be mainly followed by the scale analysis of Buongiorno [27] and Hwang et al. [28], while comparing it to other mechanisms such as gravity, inertia, diffusiophoresis, the magnus effect, fluid drainage, viscosity gradient and non-uniform shear rate. However, it was shown that the influences of slip mechanism between particles and fluid on flow field cannot be ignored.

The literature review shows that, despite the reasonable prediction of the Nusselt number in most of the cases, the results of disturbed flow patterns and concentration distribution could only be reliable when the roles of all the slip mechanisms are considered. Therefore, a new slip velocity equation is developed for the mixture model in this study with the assumption that the resulting drag force is induced by each interaction force.

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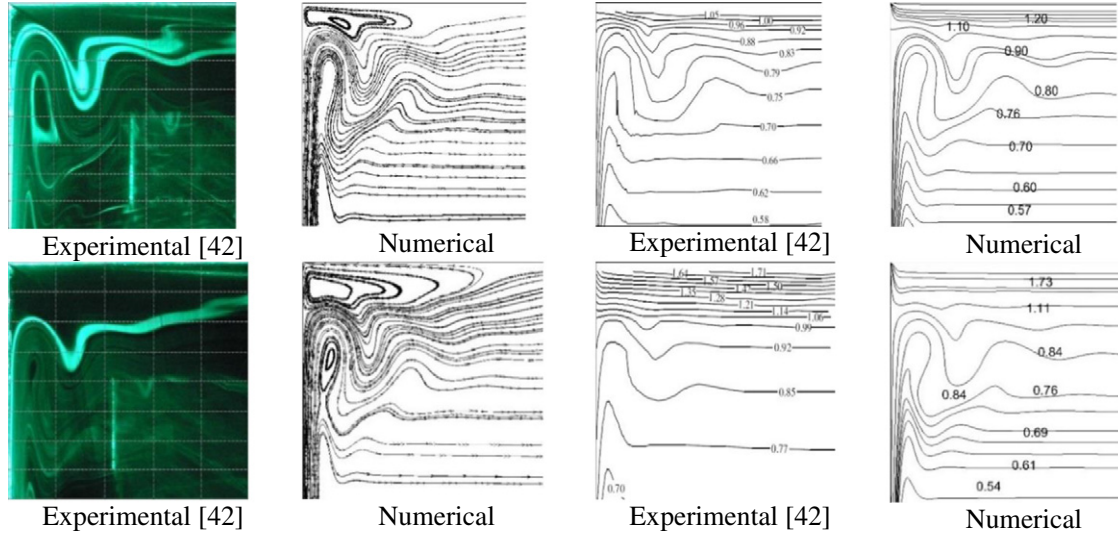


Fig. 1. Comparison of experimental flow pattern and non-dimensional temperature with numerical results. The first row is the Grashof number ( $Gr$ ) =  $1.39 \times 10^8$  and the second row is  $Gr = 1.44 \times 10^8$ .

## 2. Description of the numerical approach

### 2.1. Mixture model theory

The main assumption of the mixture model is based on the validity of the continuum theory in a binary mixture. It can easily be verified by checking the Knudsen number less than 0.1 for nanoparticles inside the liquid, as  $Kn = \lambda/d_p$ , where  $\lambda$  and  $d_p$  indicate the mean free path of the liquid phase (0.3 nm for water) and nanoparticle mean diameter (normally from 50 to 200 nm), respectively. The momentum and energy equations of both phases are combined to form one set of equations with a mixture of thermophysical properties. The mixture continuity, momentum and energy equations for steady conditions are as follows [35]:

$$\nabla \cdot (\rho_m \vec{V}_m) = 0 \quad (1)$$

$$\nabla \cdot (\rho_m \vec{V}_m \vec{V}_m) = -\nabla P_m + \nabla \cdot \tau_m + \rho_m \mathbf{g} - \nabla \cdot \left( \frac{\alpha_p \rho_p \rho_m}{(1-\alpha_p) \rho_c} \vec{V}_{pm} \vec{V}_{pm} \right) \quad (2)$$

$$\nabla \cdot (\rho_m \vec{V}_m H_m) = -\nabla \cdot q_m - \nabla \cdot (\alpha_p \rho_p \vec{V}_{pm} (H_p - H_c)), \quad (3)$$

where  $\alpha_p$ ,  $h_p$ ,  $h_c$  and  $\vec{V}_m$  represent the particle volume fraction, particle enthalpy, fluid enthalpy and mixture velocity respectively. The mixture shear stress ( $\tau_m$ ) is similar to the single-phase, except that the viscosity of the nanofluid is replaced. The important parameter in the equations is drift velocity  $\vec{V}_{pm}$  [35]:

$$\vec{V}_{pm} = \vec{V}_p - \vec{V}_m \quad (4)$$

$$\vec{V}_m = \frac{\sum_{k=1}^2 \alpha_k \rho_k \vec{V}_k}{\rho_m} \quad (5)$$

The drift and slip velocity are correlated as [35]:

$$\vec{V}_{pm} = \vec{V}_{slip} - \frac{\alpha_p \rho_p}{\rho_m} \vec{V}_{slip} = \frac{\alpha_c \rho_c}{\rho_m} \vec{V}_{slip} \quad (6)$$

The concentration field of nanoparticles is computed from the modified continuity equation for the second phase as follows [35]:

$$\nabla \cdot (\alpha_p \vec{V}_m) = -\nabla \cdot (\alpha_p \vec{V}_{pm}) \quad (7)$$

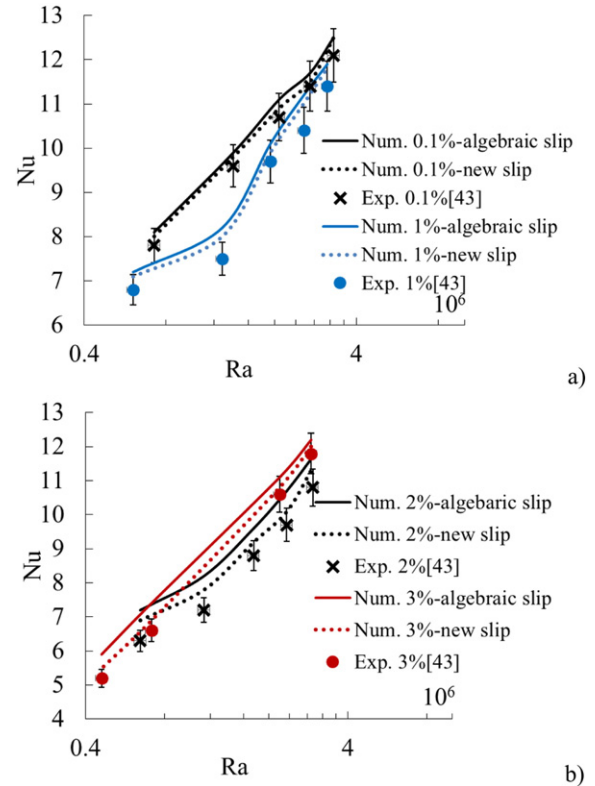


Fig. 2. Comparing the Nusselt number estimated by the conventional algebraic and the proposed slip velocity with the experimental measurements for alumina nanofluid.

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