



Heat and mass transfer mechanisms in nanofluids boundary layers



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ABSTRACT

Steady two-dimensional nanofluids boundary layers are studied with focus on heat and mass transfer properties. The study is conducted by numerical analysis of the nonlinear boundary layer equations in a self-similar form for the case of constant wall temperature. The density, specific heat, viscosity, conductivity, and thermal diffusion dependence on the solid-phase volumetric fraction are considered, as well as the brownian diffusion dependence on temperature. Under the assumption of dilute mixtures, the zeroth order solution is calculated as an approach to the particles distribution in the boundary layer and it is compared with the results obtained from the full equations solutions. The effects of the Schmidt number, the wall temperature, and the particle bulk volumetric fraction on the Nusselt number, the Sherwood number, and the skin-friction coefficient are elucidated and compared to the values obtained for the pure fluid and for uniform mixtures. An increase in the heat transfer performances with respect to the case of the base fluid is found for most of the cases.

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1. Introduction

Due to the promising potential for heat transfer applications, nanofluids have received a great attention worldwide in recent days [1]. These fluids are obtained by mixing nanometer-scale solid particles in a base liquid, and their applications include, among others, thermal waste heat management of new power weapons [2], increase of performances of solar collectors [3,4], or nuclear safety issues [5]. Regarding these points, the main effect of the addition of nanoparticles is the increase of the thermal conductivity much more than the Maxwell's theory [6] predicts. Additionally, the fact that nanofluids are highly stable [7] make them attractive as a solution for cooling applications. Notwithstanding the big effort made, models for heat transfer in nanofluids are nowadays under continuous revision, both to the particle size level [8] as to the continuous formulation of the nanofluid behavior [9,10].

In certain modern works, dating from approximately seven years ago, nanofluids are modeled as a uniform, homogenous mixture [11–16]. In these studies, the effect of the nanoparticles is considered only for the calculation of the average properties of the fluid for a constant, bulk volumetric fraction. This methodology is supported by the large values of Lewis and Schmidt numbers found in nanofluids [17]. Nevertheless, in recent years, the effect of the solid-phase distribution has begun to be studied in order to get a deeper knowledge of nanofluids behavior [18–20]. Most of these

works are based on the four nonlinear equations Buongiorno's model [17].

Regarding boundary layer studies, the uniform mixture model is found up to recent dates, researches in [21–25] considered only the momentum and energy equations, without taking into account the particles' dynamics. In these works, the particles presence is reduced to a modification of the transport coefficients and, consequently, the effective Reynolds and Prandtl numbers, that differ from those related to the base fluid. Kuznetsov's work [26] is a pioneering study in modeling the conservation equation for the solid phase for natural convective boundary layer flows. In this work, the thermal and brownian diffusion coefficients are considered constant. The same model is used by RamReddy [27] to study a mixed convection boundary layer with focus in the Soret effect. As a result of RamReddy's work, the Soret effect is seemed to enhance the skin friction, and heat and mass transfer performances. Avramenko [18], based on Lie group analysis, performed a selfsimilar study of convective boundary layers. Considering constant thermal and brownian diffusion factors as in previous works, the effect of the Schmidt number on boundary layers thickness and heat and mass transfer is studied. This work concludes that the local distribution of the particles has no appreciable effect. Notwithstanding, the mixed convection boundary layer study in [3] established that thermophoresis and brownian motion play a key role on both the heat transfer and the nanoparticles distribution. These phenomena result in the presence of additional nonlinear terms in the equations.

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In view of previous works, the particles fluxes, due to brownian diffusion and thermophoresis, must be considered when nanofluids are modeled, or, at least, their impact must be quantified if they are neglected or simplified in the problems under study. It must also be taken into account that brownian diffusion in typical nanofluids is much lower than thermophoresis [17]. Thus, for cooling applications, where the wall is hotter than the bulk fluid, it is expected a particles migration from the wall. This fact can lead to a very low particles volumetric fraction near the wall and, consequently, the local conductivity of the nanofluid in this zone would correspond to the conductivity of the base fluid. In this scenario, any improvement of the heat transfer would be related to a modification of the temperature field near the wall and not to the modification of thermal properties of the fluid. A resembling kind of boundary layer flow has been studied in [28] from an analytical point of view. In this work, the brownian and thermophoresis coefficients are considered to be constant; additionally, no coupling between the particles and the temperature or velocity fields is modeled. This is not the case in nanofluids, where the brownian diffusion depends on the temperature, and thermophoresis is proportional to the local particle volumetric fraction. Furthermore, the transport coefficients show a great dependency with the amount of particles [29–31], which arises nonlinear terms in the problem formulation.

This work tries to shed light into the importance of considering the solid phase distribution in the temperature and velocity fields, and, specifically, in the heat and mass transfer properties of nanofluids. To do this, the equations of self-similar boundary layers are derived in Section 2, where two models are presented: the first one considers the fully coupled nonlinear equations, while the second one is based on an expansion of the velocity and temperature fields up to first order in the bulk volumetric fraction, arising non coupled equations. The equations are solved numerically, being the numerical method briefly presented in Section 3. Results for the different effects are discussed in Section 4.

2. Model and equations

Following Buongiorno [17], a nanofluid can be modeled as a two-component mixture of a base fluid and nanoparticles under the assumptions of incompressible flow, dilute mixture ($\phi_b \ll 1$, being ϕ_b the bulk particle volumetric fraction), and local thermal equilibrium for the nanoparticles and the base fluid. Additionally, the viscous dissipation and the radiative heat transfer are going to be neglected in this work. Under these postulates, the conservation equations [17] writes:

$$\text{Continuity: } \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (1)$$

$$\text{Momentum: } \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{1}{\rho} \nabla p + \frac{1}{\rho} \nabla \cdot (\mu [\nabla \mathbf{v} + (\nabla \mathbf{v})^T]) \quad (2)$$

$$\text{Energy: } \frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T = \frac{1}{\rho c} \nabla \cdot (k \nabla T) + \frac{\rho_p c_p}{\rho c} (D_B \nabla \phi \cdot \nabla T + D_T \frac{\nabla T \cdot \nabla T}{T}) \quad (3)$$

$$\text{Nanoparticles: } \frac{\partial \phi}{\partial t} + \mathbf{v} \cdot \nabla \phi = \nabla \cdot (D_B \nabla \phi + D_T \frac{\nabla T}{T}) \quad (4)$$

where \mathbf{v} is the velocity vector, ρ is the density, μ is the viscosity, k is the thermal conductivity, and c is the specific heat of the nanofluid; ρ_p and c_p respectively denote the density and specific heat of the solid particles, T represents the temperature, and ϕ is the particle volumetric fraction. D_B denotes the Brownian diffusion coefficient, given by the Einstein–Stokes' expression:

$$D_B = \frac{k_B T}{3\pi \mu_f d_p} \quad (5)$$

with k_B being the Boltzmann constant, and d_p the particles diameter. Additionally, D_T represents the thermal diffusion coefficient, modeled as:

$$D_T = \beta \frac{\mu_f}{\rho_f} \phi \quad (6)$$

with $\beta = \frac{0.26k_f}{2k_f + k_p}$ [32], where the subscript $()_f$ denotes that the properties are referred to the base fluid.

Considering a reference velocity U_c , a characteristic length L_c , and a bulk temperature T_b , the following non-dimensional variables can be constructed:

$$\tilde{\mathbf{v}} = \frac{\mathbf{v}}{U_c}, \quad \tilde{\mathbf{x}} = \frac{\mathbf{x}}{L_c}, \quad \chi = \frac{t}{L_c/U_c}, \quad \theta = \frac{T}{T_b}, \quad \Phi = \frac{\phi}{\phi_b}, \quad P = \frac{p}{\rho U_c^2}$$

and Eqs. (1)–(4) become:

$$\frac{\partial \tilde{\rho}}{\partial \chi} + \tilde{\nabla} \cdot (\tilde{\rho} \tilde{\mathbf{v}}) = 0 \quad (7)$$

$$\frac{\partial \tilde{\mathbf{v}}}{\partial \chi} + \tilde{\mathbf{v}} \cdot \tilde{\nabla} \tilde{\mathbf{v}} = -\frac{1}{\tilde{\rho}} \tilde{\nabla} P + \frac{1}{Re \tilde{\rho}} \nabla \cdot (\tilde{\mu} [\tilde{\nabla} \tilde{\mathbf{v}} + (\tilde{\nabla} \tilde{\mathbf{v}})^T]) \quad (8)$$

$$\begin{aligned} \frac{\partial \theta}{\partial \chi} + \tilde{\mathbf{v}} \cdot \tilde{\nabla} \theta &= \frac{1}{Re Pr} \frac{1}{\tilde{\rho} c} \nabla \cdot (k \tilde{\nabla} \theta) \\ &+ \frac{1}{\tilde{\rho} c} \frac{1}{Re Pr Le} \left(\theta \tilde{\nabla} \Phi \cdot \tilde{\nabla} \theta + \frac{1}{N_{BT}} \frac{\Phi \tilde{\nabla} \theta \cdot \tilde{\nabla} \theta}{\theta} \right) \end{aligned} \quad (9)$$

$$\frac{\partial \Phi}{\partial \chi} + \tilde{\mathbf{v}} \cdot \tilde{\nabla} \Phi = \frac{1}{Re Sc} \tilde{\nabla} \cdot \left(\theta \tilde{\nabla} \Phi + \frac{1}{N_{BT}} \frac{\Phi \tilde{\nabla} \theta}{\theta} \right) \quad (10)$$

where nanofluid properties have been referred to the mass and transport properties of the base fluid:

$$\tilde{\rho} = \frac{\rho}{\rho_f}, \quad \tilde{\mu} = \frac{\mu}{\mu_f}, \quad \tilde{k} = \frac{k}{k_f}$$

The non-dimensional parameters that appear are:

$$\text{Reynolds number: } Re = \frac{\rho_f U_c L_c}{\mu_f} \quad (11)$$

$$\text{Prandtl number: } Pr = \frac{c \mu_f}{k_f} \quad (12)$$

$$\text{Lewis number: } Le = \frac{k_f}{(\rho c)_p D_{Bb} \phi_b} \quad (13)$$

$$\text{Schmidt number: } Sc = \frac{\mu_f}{\rho_f D_{Bb}} \quad (14)$$

$$\text{Diffusivities reference ratio: } N_{BT} = \frac{D_{Bb} \rho_f}{\beta_f \mu_f} \quad (15)$$

where D_{Bb} is the brownian diffusion coefficient for the particles bulk volumetric fraction.

Under two-dimensional, steady flow assumptions with $Re \gg 1$, and $Pr, Le, Sc, LeN_{BT}, ScN_{BT}$ of order unity or greater, and being x the streamwise direction, such that $\mathbf{v}_c = (u_c, 0)$, a region close to any solid wall, known as boundary layer, can be identified [33]. The solid wall is considered to be placed at $y = 0$, being y the wall-normal coordinate. For the boundary layer approximation, the friction effects are only taken into account within this region, and Eqs. (7)–(10) can be simplified to:

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