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Scrutiny of mixed convection flow of a nanofluid in a vertical channel

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ABSTRACT

The laminar fully developed nanofluid flow and heat transfer in a vertical channel are investigated. By means of a new set of similarity variables, the governing equations are reduced to a set of three coupled equations with an unknown constant, which are solved along with the corresponding boundary conditions and the mass flux conservation relation by the homotopy perturbation method (HPM). We have tried to show reliability and performance of the present method compared with the numerical method (Runge–Kutta fourth-rate) to solve this problem. The effects of the Grashof number (*Gr*), Prandtl number (*Pr*) and Reynolds number (*Re*) on the nanofluid flows are then investigated successively. The effects of the Brownian motion parameter (N_b), the thermophoresis parameter (N_t), and the Lewis number (L_e) on the temperature and nanoparticle concentration distributions are discussed. The current analysis shows that the nanoparticles can improve the heat transfer characteristics significantly for this flow problem.

1. Introduction

Mixed convection flows or combined free and forced convection flows occur in many technological and industrial applications in nature, e.g., solar receivers exposed to wind currents, electronic devices cooled by fans, nuclear reactors cooled during emergency shutdown, heat exchangers placed in a low-velocity environment, flows in the ocean and in the atmosphere and so on. The comprehensive reviews of convective flows are given in the monograph by Gebhart et al. [1] and Martynenko and Khramtsov [2]. A technique for improving heat transfer uses solid particles in the base fluids, which has been used recently in some studies. The term nanofluid refers to fluids in which nano-scale particles are suspended in the base fluid, which was initially suggested by Choi [3]. The comprehensive references on nanofluids have been done by Yu and Lin [4], Das et al. [5], Buongiorno [6], Daungthongsuk and Wongwises [7], Ding et al. [8], Wang and Mujumdar [9,10], and Kaka and Pramuanjaroenkij [11]. In most heat transfer studies, the base fluid has a low thermal conductivity, which limits the heat transfer enhancement. However, the continuing miniaturization of electronic devices requires further heat transfer improvements from an energy saving viewpoint. An innovative technique for adding nanoparticles to the base fluid was introduced by Choi [3] for heat transfer enhancement of pure fluids. The resulting mixture of the base fluid and nanoparticles has unique physical and chemical properties. It is expected that the presence of nanoparticles in the

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Table 1
The result of HPM and numeric method for U, θ and φ.

y	HPM(U)	NUM(U)	HPM(θ)	NUM(θ)	HPM(φ)	NUM(φ)
−1.0	0.00000007	0.0000000000	0.0000000078	1.0000000000	−0.0000000069	0.0000000000
−0.8	0.0015258029	0.0015322789	0.0353431520	0.0353488532	−0.0415288519	−0.0414708272
−0.6	0.028889823	0.0029013226	0.0627668542	0.0627767997	−0.0745248639	−0.0744174086
−0.4	0.0039582922	0.0039752697	0.0823183873	0.0823313032	−0.0984913012	−0.0983461175
−0.2	0.0046384449	0.0046583907	0.0940340772	0.0940487521	−0.1130375452	−0.1128687272
0.0	0.0048716232	0.0048925940	0.0979367194	0.0979519717	−0.1179147516	−0.1177378758
0.2	0.0046384449	0.0046583907	0.0940340772	0.0940487521	−0.1130375452	−0.1128687272
0.4	0.0039582922	0.0039752697	0.0823183873	0.0823313032	−0.0984913012	−0.0983461175
0.6	0.0028889823	0.0029013226	0.0627668542	0.0627767997	−0.0745248639	−0.0744174086
0.8	0.0015258029	0.0015322789	0.0353431520	0.0353488532	−0.0415288519	−0.0414708272
1.0	0.0000000007	0.0000000000	0.0000000078	0.0000000000	−0.0000000069	0.00000000000

nanofluid increases the thermal conductivity and therefore substantially enhances the heat transfer characteristics of the nanofluid. Eastman et al. [12] and Xie et al. [13] showed that higher thermal conductivity can be achieved in thermal systems using nanofluids. Moreover, it is well-known that conventional heat transfer fluids, including oil, water, and ethylene glycol mixture, are poor heat transfer fluids, since the thermal conductivity of these fluids plays an important role on the heat transfer coefficient between the heat transfer medium and the heat transfer surface. Researchers have tried to increase the thermal conductivity of base fluids by suspending micro- or larger-sized solid particles in fluids, since the thermal conductivity of solid is typically higher than that of liquids, as seen from Table 1 in the paper by Oztop and Abu-Nada [14]. Nanofluids consist of very small-sized solid particles. Therefore, in a low solid concentration, it is reasonable to consider the nanofluid as a single phase flow (Xuan and Li [15]). There are many numerical studies about heat and mass transfer of nanofluids in enclosures. In contrary, the number of studies on natural and mixed convection of nanofluids in vertical and horizontal channels is very small [16]. However, several researches on nanofluid flows in pipes and bends have been available in the literature, as shown by Lin et al. [17] and Lin and Lin [18]. We mention to this end the very interesting paper by Lavine [19] on steady fully developed opposing mixed convection between inclined parallel plates filled by a viscous and incompressible fluid (a regular fluid). The present paper considers the steady fully developed mixed convection flow in a vertical channel filled with nanofluids, which is driven by an external pressure gradient and also by a buoyancy force using the mathematical nanofluid model proposed by Buongiorno [6]. The paper may be regarded as the extension of the problem considered by Chen and Chung [20] on the mixed convection of a viscous (Newtonian) fluid in a vertical channel with linear variation of the wall temperature. Using similarity variables, the governing partial differential equations are transformed to ordinary differential equations, which are solved along with the corresponding boundary conditions and the mass flux conservation relation by the homotopy perturbation method (HPM) [22–25]. To our best knowledge, this problem has not been considered before so that the results are new and original.

2. Describe problem and mathematical formulation

In the present study the laminar fully developed nanofluid flow and heat transfer in a vertical channel are investigated which is driven by an external pressure gradient and also by a buoyancy force. Fig. 1 shows the physical model. As can be seen in this figure the origin of coordinates is considered at the center of the channel. The gravitational acceleration vector g is perpendicular to the y-axis. The parameters u and v are the velocity components in x and y directions, respectively. The temperature distribution at the both of the walls and the nanoparticle volume fraction on the walls are defined as follows: $T_w(x)=T_0+A_1x$, $C_w(x)=C_0+A_2x$; where T_0 is a reference temperature at the channel entrance and A_1 is a constant and C_0 denotes the nanoparticle volume fraction at far field and A_2 is a positive constant. Equations of the conservation of total mass, momentum, thermal energy, and nanoparticle volume fraction with considering the nanofluid model proposed by Buongiorno [6] and introducing the Oberbeck–Boussinesq approximation by Kuznetsov and Nield [21] can be presented

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \tag{1}$$

$$\frac{\partial p}{\partial x}=\mu\frac{\partial^2 u}{\partial y^2}+\left[(1-C_0\,\rho_f\,\beta(T-T_w)-(\rho_s-\rho_f)(C-C_w)\right]g, \tag{2}$$

$$\alpha\frac{\partial^2 T}{\partial y^2}+\tau\left\{D_B\left(\frac{\partial C}{\partial x}\frac{\partial T}{\partial x}+\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}\right)+\left(\frac{D_T}{T_0}\right)\left[\left(\frac{\partial T}{\partial x}\right)^2+\left(\frac{\partial T}{\partial y}\right)^2\right]\right\}=u\frac{\partial T}{\partial x}, \tag{3}$$

$$D_B\frac{\partial^2 C}{\partial y^2}+\left(\frac{D_T}{T_0}\right)\left(\frac{\partial T}{\partial y}\right)^2=u\frac{\partial C}{\partial x}, \tag{4}$$