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Impact of Marangoni convection in the flow of carbon–water nanofluid with thermal radiation

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ABSTRACT

This article mainly addresses the influence of carbon nanotubes in the Marangoni convection boundary layer flow of viscous fluid. Formulation and analysis have been made for both single-wall (SWCNTs) and multi-wall (MWCNTs) carbon nanotubes. Thermal radiation effect is considered in the energy expression. Transformation method reduces the partial differential systems into the ordinary differential systems. Convergent series solutions are established for the resulting differential systems. Velocity and thermal fields are focused for the outcome of sundry variables through the problems statement. Nusselt number is also analyzed. It is found that Nusselt number is more effective for larger radiation and nanoparticle volume fraction parameters.

1. Introduction

In recent years "new energy resources" is the hot topic of research amongst the scientists and engineers in order to fulfill the rapid energy demand in the advanced industrial and technological processes. Having such industrial demands in mind, the scientists and engineers are interested to develop some new devices with high rate of cooling or heating that could result in large amount of energy saving and storage. Further these devices could more suitable economically and environmentally. Solar energy is the most free available source of renewable energy in the universe. For the storage of large amount of solar energy radiation, the scientists designed the solar thermal collectors having conventional fluids as a heat transfer medium. Mostly these fluids have the property of low thermal conductivity and are inadequate to heat up more efficiently which badly affect the performance and efficiency of solar collectors. Investigators are thus forced to improve the thermal properties of these fluids. First step in this direction was taken by Choi [1] for enhancement of thermal conductivity and energy storage of the fluids via nanoparticles. Combination of homogeneously dispersed nanoparticles within the base fluid is known as nanofluid. Mostly water, ethylene, glycol oil etc. having low thermal conductivity are used frequently in various industrial processes. Therefore nano-sized metallic particles (copper, titanium, iron, gold and their oxides) are homogeneously dispersed in these base fluids for enhancement of thermal conductivity. Rashidi et al. [2] investigated entropy generation in the magnetohydrodynamic (MHD) flow of nanoliquid by an impermeable rotating disk. Hayat et al. [3] presented the characteristics of stagnation point flow of carbon–water nanofluid with homogenous-heterogeneous reactions and Newtonian heating. Turkyilmazoglu [4] examined unsteady heat transfer characteristics of nanoliquid induced by a vertical plate. Battacharyya and Layek [5] discussed MHD boundary layer flow of nanofluid created by an exponentially stretching sheet. Sheikholeslami et al. [6] studied heat transfer characteristics in the flow of nanofluid by a porous wall. Here porous medium is also considered. Sheikholeslami et al. [7] examined the combined effects of thermophoresis and Brownian motion in mixed convection flow of nanofluid. Impacts of variable heat flux and thermal radiation in the flow of nanofluid saturating porous medium is presented by Zhang et al. [8]. Lin et al. [9] studied unsteady magnetohydrodynamic pseudo-plastic nanofluid in a thin film with heat generation. Hayat et al. [10] discussed the melting heat transfer in boundary layer flow of carbon–water nanofluid past a variable surface thickness.

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Phenomenon of Marangoni convection has attracted the attention of researchers and scientists in view of its widespread applications. Marangoni convection is produced by the variation of gradients of surface tension having the applications in the fields of crystal growth and welding, soap film stabilization, drying silicon wafers and convection in obligatory. The phenomenon of Marangoni convection is extensively used in the art works like dyeing on the ground. In such technique the dye or pigment is floated on the surface of the fundamental medium (i.e., water or any other viscosity liquid). Further surface is covered by cloth or paper to take a print. Lin et al. [11] examined the characteristics of magnetohydrodynamic Marangoni convection flow of power-law fluid induced by a power law temperature gradient. Gangadharaiah [12] examined double diffusive Marangoni convection in superposed fluid and porous layers. Ibrahim [13] discussed the phenomenon of radiative Marangoni convection phenomenon in the flow of viscous fluid over a permeable sheet with Joule heating. Sreenivasulu et al. [14] analyzed the magnetohydrodynamic thermosolutal Marangoni convection flow of viscous fluid by considering viscous dissipation and Joule heating. Lin et al. [15] examined the characteristics of radiative Marangoni convection flow of pseudo-plastic nanofluid with temperature dependent thermal conductivity. Hayat et al. [16] explored Marangoni mixed convective flow of Casson fluid in presence of nonlinear thermal radiation.

Aforementioned literature survey shows that most of the researchers have investigated the characteristics of Marangoni convection in flow of viscous non-Newtonian fluids. However such phenomenon is not investigated in the flow of nanofluid via single and multi-wall carbon nanotubes. Hence our main objective is to analyze the behavior of Marangoni convection in the flow of carbon–water nanofluid. Thermal radiation is also considered. Convergent series solutions are developed for the governing equations via homotopy analysis method [17–34]. Influences of numerous pertinent parameters on the Nusselt number are discussed.

2. Formulation

Consider the steady flow of carbon–water nanofluid past an impermeable stretching sheet. Single and multi-wall carbon nanotubes are homogeneously distributed in base fluid (water). Further thermal equilibrium exists between base fluid and carbon nanotubes. Characteristics of heat transfer are analyzed with Marangoni convection phenomenon. Nanofluid is confined in semi-infinite domain. Temperature at the surface of plate is assumed variable. Under the consideration of such analysis the conservation laws are presented as follows:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu_{nf}\frac{\partial^2 u}{\partial y^2}, \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\frac{\partial^2 T}{\partial y^2}+\frac{1}{(\rho c_p)_{nf}}\frac{16\sigma^* T_\infty^3}{3K^*}\frac{\partial^2 T}{\partial y^2}. \tag{3}$$

The subjected boundary conditions are [22]

$$\mu_{nf}\frac{\partial u}{\partial y}=-\frac{d\sigma}{dT}\frac{\partial T}{\partial x}, v=V_w, T=T_w=T_0+Ax^{n+1} \text{ at } y=0, \tag{4}$$

$$u\to 0, T\to T_0 \quad as\ y\to\infty. \tag{5}$$

In above equations σ^* indicate the Stefan–Boltzman constant, K^* the mean absorption coefficient, u and v the components of horizontal and vertical velocity corresponds in x- and y- directions respectively, $V_w<0$ the suction velocity and $V_w>0$ corresponds to the injection velocity, ν_{nf} the kinematic viscosity of nanofluid, ρ_{nf} the density of nanofluid, $(c_p)_{nf}$ the specific heat, α_{nf} shows the thermal diffusivity of the nanofluid, T and T_0 the fluid temperature and external flow temperature respectively, μ_{nf} the dynamic viscosity of nanofluid, σ the surface tension and $\sigma=\sigma_0+\frac{\gamma_T}{2}(T-T_\infty)$ where $\gamma_T=(-\frac{\partial\sigma}{\partial T})_{T=T_\infty}$, Here n is an exponent constant and A the positive dimensional constant.

Xue [23] analyzed that previous proposed nanofluid models are valid only for spherical shape or elliptical rotational shape particles with small axial ratio. Such models do not describe space distribution properties of thermal conductivity of the CNTs. To overcome this difficulty, Xue [23] existing theoretical model is based on Maxwell theory considering rotational elliptical nanotubes with very large axial ratio and compensating the effects of space distribution on CNTs. Here

$$\begin{aligned}\mu_{nf}&=\frac{\mu_f}{(1-\phi)^{2.5}}, \nu_{nf}=\frac{\mu_{nf}}{\rho_{nf}}, \rho_{nf}=(1-\phi)\rho_f+\phi(\rho_s)_{CNT},\\ \alpha_{nf}&=\frac{k_{nf}}{\rho_{nf}(c_p)_{nf}}, \frac{k_{nf}}{k_f}=\frac{(1-\phi)+2\phi\frac{k_{CNT}}{k_{CNT}-k_f}\ln\frac{k_{CNT}+k_f}{2k_f}}{(1-\phi)+2\phi\frac{k_f}{k_{CNT}-k_f}\ln\frac{k_{CNT}+k_f}{2k_f}},\\ (\rho c_p)_{nf}&=(1-\phi)(\rho c_p)_f+\phi(\rho c_p)_{CNT},\end{aligned} \tag{6}$$

where ϕ is the nanoparticle volume fraction, ρ_f and ρ_s the density of fluid and solid particles respectively and k_{nf} and k_f the thermal conductivities of nanomaterial and base fluid respectively.

Transformations are considered as follows:

$$\begin{aligned}&\eta=C_2x^{(n-1)/3}y, \psi=C_1x^{(2+n)/3}f(\eta), \theta(\eta)=\frac{T-T_\infty}{Ax^{n+1}},\\ &A=\frac{\Delta T}{L^{n+1}}, C_1=\sqrt[3]{\frac{\sigma_T A\mu_f}{\rho_f^2}}, C_2=\sqrt[3]{\frac{\sigma_T A\rho_f}{\mu_f^2}}.\end{aligned} \tag{7}$$

Here σ_T denotes the rate of change of surface tension with temperature, ΔT is constant characteristic temperature and C_1 and C_2 represents the constant quantities.

Incompressibility condition is satisfied automatically and Eqs. (2)–(5) are reduced to

$$\left(\frac{1}{(1-\phi)^{2.5}(1-\phi+\phi\frac{\rho_{CNT}}{\rho_f})}\right)f'''+\frac{2+n}{3}ff''-\frac{1+2n}{3}(f')^2=0, \tag{8}$$

$$\left(\frac{\frac{k_{nf}}{k_f}+\frac{4}{3}R}{(1-\phi+\phi\frac{(\rho c_p)_{CNT}}{(\rho c_p)_f})}\right)\theta''+\frac{2+n}{3}\Pr f\theta'-(1+n)\Pr f'\theta=0. \tag{9}$$

The boundary conditions take the form

$$f(0)=\alpha, \frac{1}{(1-\phi)^{2.5}}f''(0)=-1,\ \theta(0)=1,\ f'(\infty)\to 0,\ \theta(\infty)\to 0, \tag{10}$$

where α is the suction ($\alpha>0$) /injection ($\alpha<0$) parameter, Pr the Prandtl number and R the thermal radiation parameter. These are given as follows:

$$\alpha=-C_2V_w, \Pr=\frac{\mu_f(c_p)_f}{k_f}, R=\frac{4\sigma^* T_\infty^3}{k^* k_f}. \tag{11}$$

Local Nusselt number is

$$Nu_x=\frac{xq_w(x)}{k_f(T_w-T_0)}, q_w=-\left(k_{nf}+\frac{16\sigma^* T_\infty^3}{3k^*}\right)\left(\frac{\partial T}{\partial y}\right)_{y=0}. \tag{12}$$

Dimensionless local Nusselt number is expressed as follows:

$$Nu_x=-\left(\frac{k_{nf}}{k_f}+\frac{4}{3}R\right)C_2x^{(2+n)/3}\theta'(0), \tag{13}$$