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Axisymmetric mixed convective stagnation-point flow of a nanofluid over a vertical permeable cylinder by Tiwari-Das nanofluid model

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ABSTRACT

In this article, the steady axisymmetric mixed convective stagnation-point flow of an incompressible electrically conducting nanofluid over a vertical permeable circular cylinder in the presence of transverse magnetic field is investigated. The mathematical model has been formulated based on Tiwari-Das nanofluid model. In this study, the water as the base fluid and three different types of nanoparticles; copper, aluminum oxide (alumina) and titanium dioxide (titania) are considered. Using appropriate transformations, the system of partial differential equations is transformed into an ordinary differential system of two equations, which is solved analytically by the well-known homotopy analysis method (HAM) and numerically using the fourth-order Runge–Kutta method with shooting technique. The present analytical and numerical simulations agree closely with the previous studies in the especial cases. The effects of the five key thermophysical parameters governing the flow; the nanoparticle volume fraction (ϕ), the magnetic parameter (M), the wall permeability parameter (V_w), the mixed convection parameter (λ) and the curvature parameter (γ) on dimensionless velocity and temperature distributions, skin friction coefficient and local Nusselt number are presented graphically and discussed in details. Our results demonstrate that, the enhancement of heat transfer is a function of particle concentration, small fraction of metallic particles leading to significant changes in both skin friction coefficient and local Nusselt number. The results illustrate that selecting alumina and copper as the nanoparticle leads to the minimum and maximum amounts of skin friction coefficient value, and also copper and titania nanoparticles have the largest and lowest local Nusselt number. In addition, our computation shows that the curvature parameter has a strong additive effect on the skin friction coefficient and local Nusselt number. Moreover, it is observed that the highest velocity and thermal boundary layer thickness are related to the opposing flow, while the smallest one is for assisting flow.

1. Introduction

Working fluids have great demands placed upon them in terms of increasing or decreasing energy release to systems, and their influences depend on thermal conductivity, heat capacity and other physical properties in modern thermal and manufacturing processes. A low thermal conductivity is one of the most remarkable parameters that can limit the heat transfer performance. Suspending the ultrafine solid metallic particles in technological fluids causes an increase in the thermal conductivity. This is one of the most modern and appropriate methods for increasing the coefficient of heat transfer. It is expected that the ultrafine solid particle is able to increase the thermal conductivity and heat transfer performance, since the thermal conductivity of solid metals is higher than that of base fluids [1–3]. Some numerical and experimental studies on nanofluids include application to convective heat transfer (Maiga et al. [4], Tiwari and Das [5], Dinarvand et al. [6], and Oztop and Abu-Nada [7]).

Free convection is caused by the temperature difference of the fluid at different locations and forced convection is the flow of heat due to the cause of some external applied forces. The combination of free convection and forced convection is called as mixed convection. The phenomenon of mixed convection flow near a stagnation-point has attracted several investigators during the recent past because of its wide range of applications in many industrial devices such as atmospheric boundary layer flows, heat exchangers, solar collectors, nuclear reactors and electronic equipments etc. Ramachandran et al. [8] studied the steady laminar mixed convection in two-dimensional stagnation flows around vertical surfaces by considering both cases of an arbitrary wall temperature and arbitrary surface heat flux variations. This work was then continued by Devi et al. [9] for the unsteady flow, Lok et al. [10] for a vertical surface immersed in a micropolar fluid, Ishak et al. [11,12] for MHD mixed convection flow on a vertical surface, Ishak et al. [13] for the mixed convection on the stagnation-point flow toward a vertical,

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continuously stretching sheet, and Dinarvand et al. [14] for mixed convective boundary layer flow of a nanofluid over a vertical circular cylinder with prescribed surface temperature. Later on, Makinde et al. [15] studied their problem for a convectively heated stretching/shrinking sheet under the influence of magnetic field. Their model included the combined effects of Brownian motion and thermophoresis. Recently, Tamim et al. [16] studied the MHD mixed convection stagnation-point flow of a nanofluid over a vertical permeable surface. As a completive study, they also investigated the unsteady mixed convection flow of a nanofluid near orthogonal stagnation-point [17].

Some of strongly nonlinear equations used to describe physical systems in the form of mathematical modeling do not have the exact solutions. The numerical or analytical methods can be applied to solve these nonlinear equations [18–24]. Despite all the benefits, there are some disadvantages for the numerical methods in comparison with the analytical methods. One of the most known and reliable techniques to solve nonlinear problems is homotopy analysis method (HAM). The HAM was employed by Liao, for the first time, to offer a general analytical method for nonlinear problems [25–27].

The main purpose of the current article is to study the steady MHD axisymmetric mixed convective stagnation-point flow of a nanofluid over a vertical permeable cylinder through Tiwari-Das nanofluid model. The well-known HAM and the fourth-order Runge–Kutta method with shooting technique is employed to study the effects of flow thermophysical parameters such as the nanoparticle volume fraction, the magnetic parameter, the wall permeability parameter, the mixed convection parameter and the curvature parameter on the fluid velocity component, temperature distribution, skin friction coefficient and local Nusselt number for three different types of nanoparticles as listed in Table 1.

2. Nanofluid flow analysis and mathematical formulation

Let us consider the steady axisymmetric mixed convective stagnation-point flow of an incompressible electrically conducting nanofluid over a vertical permeable cylinder in the presence of transverse magnetic field as shown in Fig. 1. We choose the cylindrical coordinates (x, r) such that x and r-axes are along the cylinder surface (vertically) and radial directions, respectively. Symmetric nature of the flow is assumed with respect to the transverse coordinate. It is assumed that the mainstream velocity is $U(x)$ and the temperature of the ambient nanofluid is T_∞, while the temperature of the cylinder is $T_w(x)$ Under these assumptions and using the model of the nanofluid proposed by Tiwari and Das [5], the boundary layer equations governing the flow can be written as follows [28];

$$\frac{\partial}{\partial x}(ru)+\frac{\partial}{\partial r}(rw)=0, \tag{1}$$

$$u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial r}=-\frac{1}{\rho_{nf}}\frac{dp}{dx}+\nu_{nf}\left(\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}\right)-\frac{\sigma B_0^2}{\rho_{nf}}u+\frac{\phi\rho_s\beta_s+(1-\phi)\rho_f\beta_f}{\rho_{nf}}g(T-T_\infty), \tag{2}$$

$$u\frac{\partial T}{\partial x}+w\frac{\partial T}{\partial r}=\alpha_{nf}\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right). \tag{3}$$

The corresponding boundary conditions are

$$\begin{aligned} &u=0, \quad w=V_w^*, \quad T=T_w(x)=T_\infty+\Delta T\left(\frac{x}{\ell}\right), \quad \text{at} \quad r=a,\\ &u=U(x)\to U_\infty(x/\ell), \quad T\to T_\infty, \quad \text{as} \quad r\to\infty. \end{aligned} \tag{4}$$

By employing the generalized Bernoulli's equation, in free-stream, Eq. (2) becomes

$$U\frac{\partial U}{\partial x}=-\frac{1}{\rho_{nf}}\frac{dp}{dx}-\frac{\sigma B_0^2}{\rho_{nf}}U. \tag{5}$$

Substituting Eq. (5), Eq. (2) can be written as

$$u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial r}=U\frac{\partial U}{\partial x}+\nu_{nf}\left(\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}\right)+\frac{\sigma B_0^2}{\rho_{nf}}(U-u)+\frac{\phi\rho_s\beta_s+(1-\phi)\rho_f\beta_f}{\rho_{nf}}g(T-T_\infty). \tag{6}$$

Here, V_w^* is the uniform surface mass flux, where $V_w^*<0$ corresponds to suction and $V_w^*<0$ corresponds to injection, B_0 is the uniform magnetic field and σ is the electrical conductivity. Further, u and w are the velocity components along x and r directions, T is the temperature of the nanofluid, β is the coefficient of thermal expansion, and ρ_f and ρ_s are the densities of the fluid and of the solid fractions, respectively. Here, ν_{nf} is the kinematic viscosity of nanofluid and α_{nf} is the thermal diffusivity of nanofluid, which are given by [7]

$$\nu_{nf}=\frac{\mu_f}{(1-\phi)^{2.5}\left[(1-\phi)\rho_f+\phi\rho_s\right]}, \tag{7}$$

$$\rho_{nf}=(1-\phi)\rho_f+\phi\rho_s, \tag{8}$$

$$\alpha_{nf}=\frac{k_{nf}}{(\rho C_p)_{nf}}, \tag{9}$$

$$(\rho C_p)_{nf}=(1-\phi)(\rho C_p)_f+\phi(\rho C_p)_s, \tag{10}$$

$$\frac{k_{nf}}{k_f}=\frac{(k_s+2k_f)-2\phi(k_f-k_s)}{(k_s+2k_f)+\phi(k_f-k_s)}, \tag{11}$$

where ϕ is the nanoparticle volume fraction, k_{nf} is the thermal conductivity of the nanofluid, k_f and k_s are the thermal conductivities of the fluid and of the solid fractions, respectively, $(\rho C_p)_{nf}$ is the heat capacity of the nanofluid.

Table 1
Thermophysical properties of the base fluid and the nanoparticles [7].

Base fluid and nanoparticles	Molecular formula	Cp (J/kgK)	ρ (kg/m^3)	k (W/mK)	$\alpha\times10^7$(m^2/s)	$\beta\times10^{-5}$ (1/K)
Water	H_2O	4179	997.1	0.613	1.47	21
Aluminum oxide (alumina)	Al_2O_3	765	3970	40	131.7	0.85
Titanium dioxide (titania)	TiO_2	686.2	4250	8.954	30.7	0.9
Copper	Cu	385	8933	400	1163.1	1.67