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Original Research Paper

Effect of aligned magnetic field on liquid thin film flow of magnetic-nanofluids embedded with graphene nanoparticles

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A R T I C L E I N F O

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A B S T R A C T

Nowadays graphene is emanating as one of the most encouraging nanomaterial due to its continuous electrical conducting behaviour even at zero carrier concentration. With this initiation, we investigate the flow and heat transfer nature of liquid film flow of magnetic-nanofluids over a stretching surface by considering the aligned magnetic field with non-uniform source/sink and thermal radiation. For this study, we considered the graphene (GP) nanoparticles embedded in water and water-ethylene glycol (EG) mixtures (i.e. 70%water + 30%EG and 50%water + 50%EG). With the assistance of similarity transformations, governed equations are transferred as ordinary differential equations. Numerical results are determined by applying the Runge-Kutta and Newton's methods. Graphs are exhibited and explained for important parameters. The influence of non-dimensional parameters on reduced Nusselt number, flow and heat transfer is discussed with the assistance of graphs. It is found that aligned magnetic field regulates the local Nusselt number. It is also found that rising the volume fraction of nanoparticles effectively boosts the thermal conductivity of water + 50%EG + GP nanofluid when compared with water + GP and water + 30%EG + GP nanofluids.

1. Introduction

The momentum and thermal behaviour of liquid film flow caused by a stretching surface has numerous applications in polymer extrusion, paper production, wire thinning and foodstuff processing, etc. Nanofluids are the fluids embedded with nanometer sized effective thermal conductivity metals. The major applications of nanofluids are applicable in cooling industry, fluidization of reactors and heat exchangers, etc. Magnetic-nanofluids have various applications in metallurgical process that can be regulate by an extrinsic magnetic field. Graphene has a unique property that is ideal for future generation electronics such as high electrical conductivity and solar cells and chemical stability, Wang [1] was the first person who discussed about the thin film flow past a stretching surface. Further, Andersson et al. [2,3] extended the previous work by considering power-law fluid with various physical parameters (i.e. unsteadiness parameter, power-law parameter, Prandtl number, film thickness parameter etc.). In continuation of this, the researchers [4–7] studied the liquid film flow past a stretched sheet by considering different fluids with variable physical properties.

The thermophysical properties of magnetite and its applications were experimentally studied by Blaney [8]. He found that magnetic water treatment is best way to reduce the MBR wasting difficulties. Liang et al. [9] produced an electrically conducting graphene paper and concluded that the hybrid graphene paper is very useful for data storage, batteries and magnetic controlling devices. An experimental investigation for enhanced thermal conductivity of nanofluids embedded with graphene nanoparticles was done by [10] and found that about 16% hike in thermal conductivity at 25 °C and 75% enhancement at 50 °C. Balandin [11] illustrated the thermal properties of graphene nanoparticles and highlighted that at room temperature, the thermal conductivity of graphene nanoparticles is more than 2000 $W\,m\,K^{-1}$. Convective heat transfer in graphene immersed nanofluids was studied by Kumar and Gowd [12].

Experimental investigation on enhanced thermal conductivities of graphene and graphene oxide was presented by Mahanta and Abramson [13] and found that graphene oxide is having better thermal conductivity when compared with graphene. The thermal properties and its applications for the real world problems were discussed by the researchers [14–16]. Gul et al. [17] analysed the heat transfer behaviour of second grade thin film flow. A technical review on graphene based composite catalysts and its applications were reported by Li et al. [18] and concluded that graphene-NP

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Nomenclature

u, v	velocity components along x and y (m/s)
ρ_{nf}	density of the nanofluid (kg/m^3)
μ_{nf}	dynamic viscosity of the nanofluid (kg/ms)
σ_{nf}	electrical conductivity of nanofluid (S/m)
B_0	magnetic field strength (–)
T	fluid temperature (K)
k_{nf}	thermal conductivity (W/m K)
$(\rho c_p)_{nf}$	heat capacitance of the nanofluid (kg/m^3 K)
k^*	mean absorption coefficient (–)
γ	aligned angle (degrees)
σ^*	Stefan–Boltzmann constant (–)
A^*, B^*	non-uniform heat source/sink parameters (–)
ϕ	volume fraction of the nano particles (nm)
ρ_f, ρ_s	densities of the base fluid and solid nano particles (kg/m^3)
k_f, k_f	thermal conductivities of the base fluid and solid nanoparticles (W/m K)
σ_f, σ_s	electrical conductivities of the base fluid and solid nano particles (S/m)
$(c_p)_f$, $(c_p)_s$	specific heat capacity of the base fluid and solid nano particles (J/Kg K)
ζ	similarity variable (–)
Pr	Prandtl number (–)
M	magnetic field parameter (–)
R	radiation parameter (–)
S	unsteadiness parameter (–)
λ	film thickness parameter (–)
T_0, T_r	slit and reference temperatures (K)
v_f	kinematic viscosity (m^2/s)
α, b	constants (–)

doping is very useful in electrochemical energy applications. In continuation of this, the researchers [19–21] investigated the applications of graphene doped materials by considering the boron and nitrogen. A functional investigation of graphene and magnetite nanoparticles on oil spilling was studied by the researchers [22,23] and found that graphene nanoparticles effectively enhances the thermal conductivity of the regular base fluid. A potential environmental application of graphene/magnetite nano composites was experimentally studied by Farghali et al. [24] and concluded that graphene particles are highly influenced by the external magnetic fields. Numerical and experimental analysis of heat transfer nature of graphene nanofluid under turbulent conditions was studied by Sadeghinezhad et al. [25]. Liquid film flow of nanofluids in the presence of various physical conditions was numerically studied by the researchers [26–29]. Recently, Malvandi et al. [30–33] studied the heat transfer characteristics of thin film flow of magnetic-nanofluids by considering Brownian motion, thermophoresis and thermal radiation effects. Very recently, the researchers [34,35] discussed the heat transfer behaviour of nanofluids by considering various geometries. They highlighted that flow geometry plays a major role in heat transfer performance of the nanofluid.

Goodarzi et al. [36] investigated the heat transfer performance of graphene based nanofluid past a double-pipe heat exchanger. Heat transfer performance of kerosene based nanofluid past a oscillating pipe was studied by Goshayeshi et al. [37]. Heat transfer nature of graphene based nanofluid under turbulent conditions was illustrated by Safaei et al. [38]. Further, Goshayeshi et al. [39,40] experimentally investigated the heat transfer behaviour of ferrous nanofluid under magnetic conditions. Natural convective heat transfer of MHD nanofluid over cylindrical annulus was studied by Afrand et al. [41]. Boundary layer behaviour of water based nanofluid past a plate was studied by Safaei et al. [42]. Very recently, the researchers [43–45] analyzed the heat transfer nature of magnetohydrodynamic flows over various geometries. The detailed description about the energy distribution due to particle-particle interactions are explained by Russell et al. [46].

In all the above mentioned studies, authors discussed the heat or heat and mass transfer behaviour of Newtonian or non-Newtonian thin film flows over a stretching surface with/without considering the transverse magnetic field. To the best knowledge of author's no studies has been reported yet on flow and heat transfer characteristics of liquid film flow of magnetic-nanofluids over the vicinity of a thin elastic sheet by considering the variable directional magnetic field with non-uniform heat source/sink by considering the graphene nanoparticles.

2. Mathematical formulation

We consider an unsteady, electrically conducting radiative nano-liquid film flow past a stretching sheet. The sheet is located at origin of a coordinate system (x, y) as shown in Fig. 1. Here x-axis is measured along the surface with stretched velocity $u_w(x,t) = bx/(1-\alpha t)$, where b, α constants and y-axis are is opposite to it. The wall temperature is considered as $T_s(x,t) = T_0 - T_r(bx^2/2v_f)(1-\alpha t)^{-1.5}$, where T_0, T_r are the slit and reference temperatures. A variable magnetic field $B(t) = B_0(1-\alpha t)^{-0.5}$ is applied along the stretching sheet with an aligned angle γ.

It is assumed that the nanoparticles are spherical shaped and that no slip occurs between them. With the stream function ξ such that $u = \xi_y$ and $v = -\xi_x$, the governing conservation equations can be expressed as (see Ref. [14])

$$\frac{\partial^2 \xi}{\partial x \partial y} - \frac{\partial^2 \xi}{\partial y \partial x} = 0, \tag{1}$$

$$\rho_{nf}\left(\frac{\partial^2 \xi}{\partial t \partial y} + \frac{\partial \xi}{\partial y}\frac{\partial^2 \xi}{\partial x \partial y} - \frac{\partial \xi}{\partial x}\frac{\partial^2 \xi}{\partial y^2}\right) = \mu_{nf}\frac{\partial^3 \xi}{\partial y^3} + \sigma_{nf} B^2(t)\frac{\partial \xi}{\partial y}\cos^2\gamma, \tag{2}$$

$$(\rho c_p)_{nf}\left(\frac{\partial T}{\partial t} + \frac{\partial \xi}{\partial y}\frac{\partial T}{\partial x} - \frac{\partial \xi}{\partial x}\frac{\partial T}{\partial y}\right) = \left(k_{nf} + \frac{16 T_\infty^3 \sigma^*}{3k^*}\right)\frac{\partial^2 T}{\partial y^2} + q''', \tag{3}$$

with the boundary conditions

$$\begin{aligned} &u = u_w,\ \ v = 0, \quad T = T_s \quad \text{at } y = 0, \\ &u_y = 0,\ \ v = h_t, \quad T_y = 0, \quad \text{at } y = h(t), \end{aligned} \tag{4}$$

where u and v are the velocity components along x and y directions respectively.

The time and temperature dependent heat source/sink q''' is given by

$$q''' = \frac{k_f u_w (T_s - T_0)}{x v_f}\left(A^* f' + B^* \frac{(T - T_0)}{(T_s - T_0)}\right), \tag{5}$$

The nanofluid parameters are given as

$$\left.\begin{aligned} &\rho_{nf} = \rho_f - \phi\rho_f + \phi\rho_s, (\rho c_p)_{nf} = (\rho c_p)_f - \phi(\rho c_p)_f + \phi(\rho c_p)_s, \\ &\tfrac{k_{nf}}{k_f} = \tfrac{k_s + 2k_f - 2\phi k_f + 2\phi k_s}{k_s + 2k_f + \phi k_f - \phi k_s},\ \ \mu_{nf} = \tfrac{\mu_f}{(1-\phi)^{2.5}}, \\ &\sigma_{nf} = \sigma_f\left[1 + \tfrac{3\sigma\phi - 3\phi}{\sigma + 2 - \sigma\phi + \phi}\right],\ \ \sigma = \tfrac{\sigma_s}{\sigma_f}, \end{aligned}\right\} \tag{6}$$

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