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GRAPHENE-BASED NEWTONIAN NANOLIQUID FLOWS OVER AN INCLINED PERMEABLE MOVING CYLINDER DUE TO THERMAL STRATIFICATION

by

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Heat flux enhancement due to utilization of graphene, graphene nanoplatelets, and graphene oxides in water/ethylene-glycol based nanofluids over an inclined permeable cylinder is focused in the present study. The governing PDE are reformulated into non-linear ODE by applying similarity expressions. A shooting procedure is opted to reformulate the equations into boundary value problems which are solved by employing a numerical finite difference code in MATLAB. The effects of constructive parameters toward the model on non-dimensional velocity and temperature dissemination, reduced skin friction coefficient and reduced Nusselt number are graphically reported and discussed in details. It is observed that by increasing the thermal stratification and inclination angle, the temperature profile and Nusselt number for the selected nanofluids will be decreased.

Key words: *nanofluid, heterogeneous, inclined cylinder, thermal stratification, graphene, graphene nanoplatelets, graphene oxides*

Introductory remarks

The conventional heat transfer fluids which are used frequently in various industrial processes namely water, oil and ethylene glycol have low thermal conductivity which restrict the efficiency of heat transfer for many engineering and industrial equipment. To encounter this issue, the novel concept of nanotechnology-based heat transfer fluid was proposed by Choi [1] in the spring of 1993 to boost better heat transfer and energy power. Nanofluids made a significant remark for heat transfer applications such as in cooling and heating exchangers, microelectronics, microfluidics, biomedical, and pharmaceutical fields, food manufacturing, magma solidification, and drug delivery.

Tiwari and Das [2] analyzed the behavior of nanofluids by considering the solid nanoparticles' volume fraction where thermophysical properties of the regular base fluid and nanoparticles are heterogenously correlated. Several excellent research on related models of Tiwari and Das are now available in literatures. Dinarvand *et al.* [3] embraced homotopy analysis method (HAM) for solving an unsteady mixed convective stagnation-point flow of an electrically conducting nanofluid over a vertical moving sheet. Chen *et al.* [4] deal with heterogeneous nanofluid-flow in a porous channel with suction and chemical reaction by introducing the conservation equation of nanoparticle volume fraction. Mabood *et al.* [5] conducted the Tiwari-

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Das nanofluid model for copper and alumina saturated in water under mixed convection and unsteady luid flow condition.

Ibrahim and Gadisa [6] analyzed a double stratified mixed convective flow of couple stress nanofluid past inclined stretching cylinder using Cattaneo-Christov heat and mass flux model. Rehman *et al.* [7] scrutinized the effect of double stratification and mixed convection on a Williamson fluid-flow under a stagnation region past an inclined cylinder and they noticed that the skin friction coefficient and heat transfer rate increase for higher values of Prandtl number, curvature and thermal stratification parameters. Khashi'ie *et al.* [8] analytically modeled the thermally stratified flow process of Cu-Al_2O_3/water hybrid nanofluid past a permeable cylinder using the extended Tiwari and Das nanofluid model. Dinarvand *et al.* [9] discovered that the curvature parameter acts as one of the influential indicators on determining the inquiry of heat transfer of their selected metallic water based nanofluid.

The utilization of graphene-based nanoparticles in preparing nanofluid mixtures motivates curiosity of the science and technological researchers. Yet the research on graphene, graphene nanoplatelets (GNP) and graphene oxides (GO) as potential nanomaterials in fluid mechanics analysis is still sporadic despite of special combination of first-rate electrical and mechanical properties. Nevertheless, this study is the first attempt that examines graphene, GNP and GO nanoparticles altogether in the water and ethylene glycol (EG) base fluids for thermal stratification over an inclined permeably moving cylinder out of the long list of existing common literatures.

Remarks on the model's governing equations

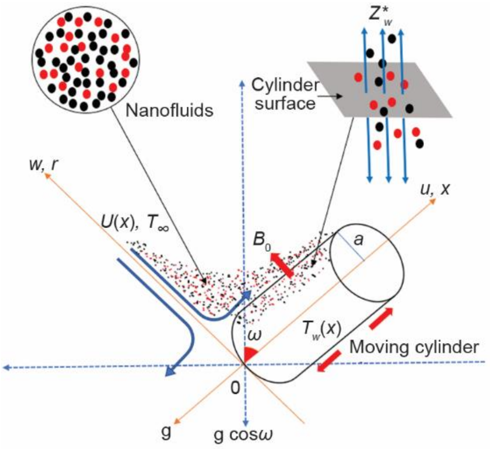

Figure 1. Diagrammatic for the current problem with geometrical coordinates

Consider the heterogeneous nanofluid model with radius, *a*, as in fig. 1. We assume $U_e(x) = U_0(x/l)$ as the stagnation flow velocity within the cylindrical co-ordinates (x, r). Hence, we have:

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

$$u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial r} = U_e\frac{\partial U_e}{\partial x} + \nu_{\text{nf}}\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r}\right) + \frac{\sigma B_0{}^2}{\rho_{\text{nf}}}(U_e - u) + \frac{[\phi(\rho\beta_T)_{\text{s}} + (1-\phi)(\rho\beta_T)_f]}{\rho_{\text{nf}}}\cdot \text{g}(T - T_\infty)\cos\omega \tag{2}$$

$$u\frac{\partial T}{\partial x} + w\frac{\partial T}{\partial r} = \frac{\kappa_{\text{nf}}}{(\rho c_p)_{\text{nf}}}\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \tag{3}$$

$$u(x,r) = U(x) = sx, \quad w(x,r) = Z_{\text{w}}^*, \quad T(x,r) = T_{\text{w}}(x) = T_0 + \frac{mx}{l} \quad \text{at } r = a$$

$$u(x,r) \to U_e(x) = Sx, \quad T(x,r) \to T_\infty(x,r) \to T_0 + \frac{nx}{l} \quad \text{at} \quad r \to \infty \tag{4}$$

The nanofluid's thermophysical properties and similarity transformations are exemplified:

$$\nu_{\rm nf} = \frac{\mu_f}{(1-\phi)^{2.5}\rho_{\rm nf}}, \quad \rho_{\rm nf} = (1-\phi)\rho_f + \phi\rho_{\rm s}, \quad \alpha_{\rm nf} = \frac{\kappa_{\rm nf}}{(\rho c_p)_{\rm nf}}$$

$$(\rho c_p)_{\rm nf} = (1-\phi)(\rho c_p)_f + \phi(\rho c_p)_{\rm s}, \quad \frac{\kappa_{\rm nf}}{\kappa_f} = \frac{(\kappa_{\rm s} + 2\kappa_f) - 2\phi(\kappa_f - \kappa_{\rm s})}{(\kappa_{\rm s} + 2\kappa_f) + \phi(\kappa_f - \kappa_{\rm s})} \tag{5}$$

$$u = U_0\left(\frac{x}{l}\right)\breve{f}'(\eta), \quad w = -\frac{a}{r}\left(\frac{U_0\nu_f}{l}\right)^{\frac{1}{2}}\breve{f}'(\eta), \quad \eta = \frac{r^2 - a^2}{2a}\left(\frac{U_0}{\nu_f l}\right)^{\frac{1}{2}}$$

$$\psi = \left(\frac{U_0\nu_f x^2}{l}\right)^{\frac{1}{2}} a\breve{f}'(\eta), \quad \breve{\theta}(\eta) = \frac{T - T_\infty}{T_{\rm w} - T_0} \tag{6}$$

By substituting eq. (6) into eqs. (2) and (3), we obtain the dimensionless system of non-linear ODE:

$$\breve{f}\breve{f}'' - \breve{f}'^2 + S^{*2} + \frac{1}{(1-\phi)^{2.5}\left(1-\phi+\phi\dfrac{\rho_{\rm s}}{\rho_f}\right)}\left[(1+2\gamma\eta)\breve{f}''' + 2\gamma\breve{f}''\right] +$$

$$+\frac{M}{1-\phi+\phi\dfrac{\rho_{\rm s}}{\rho_f}}(S^* - \breve{f}') + \frac{1-\phi+\phi\dfrac{(\rho\beta_T)_{\rm s}}{(\rho\beta_T)_f}}{1-\phi+\phi\dfrac{\rho_{\rm s}}{\rho_f}}\lambda\breve{\theta}\cos\omega = 0 \tag{7}$$

$$\frac{\dfrac{\kappa_{\rm nf}}{\kappa_f}}{1-\phi+\phi\dfrac{(\rho c_p)_{\rm s}}{(\rho c_p)_f}}[(1+2\gamma\eta)\breve{\theta}'' + 2\gamma\breve{\theta}'] + \Pr(\breve{f}\breve{\theta}' - \breve{f}'\breve{\theta} - \varepsilon\breve{f}') = 0 \tag{8}$$

depending on the following boundary conditions:

$$\breve{f}(\eta) = Z_{\rm w}, \quad \breve{f}'(\eta) = \varpi, \quad \breve{\theta}(\eta) = 1-\varepsilon, \quad \text{at} \quad \eta = 0$$

$$\breve{f}'(\eta) \to S^*, \quad \breve{\theta}(\eta) \to 0, \quad \text{at} \quad \eta \to \infty \tag{9}$$

The emerged parameters are all described mathematically as:

$$s = \frac{U_0}{l}, \quad \gamma = \frac{1}{a}\left(\frac{\nu_f}{s}\right)^{1/2}, \quad M = \frac{\sigma B_0^2 l}{\rho_f U_0}, \quad \Pr = \frac{\mu c_p}{\kappa}, \quad S^* = \frac{S}{s}, \quad \varepsilon = \frac{n}{m}$$

$$Z_{\rm w} = -\frac{r}{a}\left(\frac{l}{\nu_f U_0}\right)^{1/2} Z_{\rm w}^*, \quad \lambda = \frac{{\rm Gr}_x}{{\rm Re}_x^2} \tag{10}$$

where opposing and assisting flows occur when $\lambda < 0$ and $\lambda > 0$, respectively. Invoking eq. (6) gives:

$$C_f \operatorname{Re}^{\frac{1}{2}} = \frac{1}{(1-\phi)^{2.5}} \bar{x} \breve{f}''(0), \quad \operatorname{Nu} \operatorname{Re}^{-\frac{1}{2}} = -\frac{\kappa_{\mathrm{nf}}}{\kappa_f} \bar{x} \breve{\theta}'(0) \tag{11}$$

where $\bar{x} = x/l$.

Methodology towards solution

Equations (7) and (8) under the boundary conditions (9) are first reformulated by performing a shooting technique. The selected limit for η is 10 and the initial values for $\breve{f}_{(3)}$ and $\breve{f}_{(5)}$ are assumed to be 0. The resulting boundary value problem is further solved using the MATLAB package (bvp4c) under the residual tolerance of 10^{-6}.

Analytical insights

The nanoparticle volume fraction parameter, $\phi = 0.4$ is simulated for this current problem. The comparison between present and the previous outcomes [9] in tab. 1 yields a very good agreement. The numerical results are demonstrated in figs. 2 and 3 for various values of thermal stratification, ε, inclination angle, ω, stretching/shrinking, ϖ, and wall permeability, Z_w, for clear physical insights. Figure 2(a) shows that both velocity and temperature profiles decrease when ε is increased from 0 to 0.8. Clearly, GNP-water and graphene-water have the highest velocity profile, while GO-ethylene glycol has the highest temperature profile at $\varepsilon = 0.8$. Figure 2(b) confirms the velocity increment with the inclination angle, ω. However, the opposite trend is displayed for the temperature profile when increasing the value of inclination angle up to 45°. The result shows that GNP-water the highest velocity and temperature profiles at $\omega = 45°$.

Table 1. Effects of ϕ and λ on skin friction coefficient and Nusselt number for Cu-water nanofluid when Pr = 6.2, $\gamma = 1$, M = 0, and $\nu_w = 0$

λ	ϕ	$1/xC_f\operatorname{Re}^{1/2}$			$1/x\operatorname{Nu}\operatorname{Re}^{1/2}$		
		[9]		Present	[9]		Present
		HAM	RK4	bvp4c	HAM	RK4	bvp4c
0.0	0.0	1.70764	1.70762	1.70766	2.15177	2.15173	2.15175
	0.1	2.51216	2.51214	2.51213	2.69664	2.69666	2.69667
	0.2	3.46826	3.46828	3.46829	3.26935	3.26939	3.26938
1.0	0.0	1.99210	1.99215	1.99218	2.21366	2.21362	2.21363
	0.1	2.79276	2.79273	2.79271	2.74838	2.74831	2.74831
	0.2	3.75691	3.75698	3.75700	3.31539	3.31532	3.31533
5.0	0.0	3.02007	3.02004	3.02005	2.40937	2.40936	2.40935
	0.1	3.83616	3.83608	3.83609	2.92289	2.92285	2.92286
	0.2	4.84849	4.84840	4.84841	3.47660	3.47668	3.47668

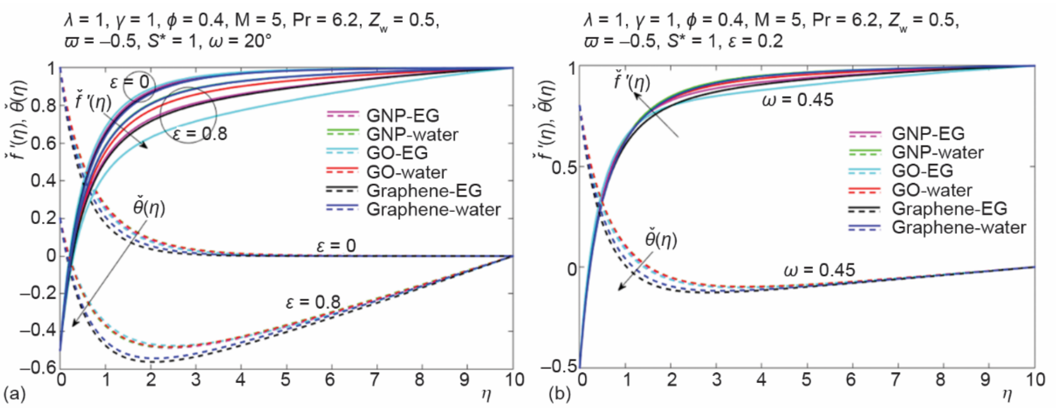

Figure 2. Effect of thermal stratification parameter (a) and inclination angle (b) on velocity and temperature profile for shrinking cylinder

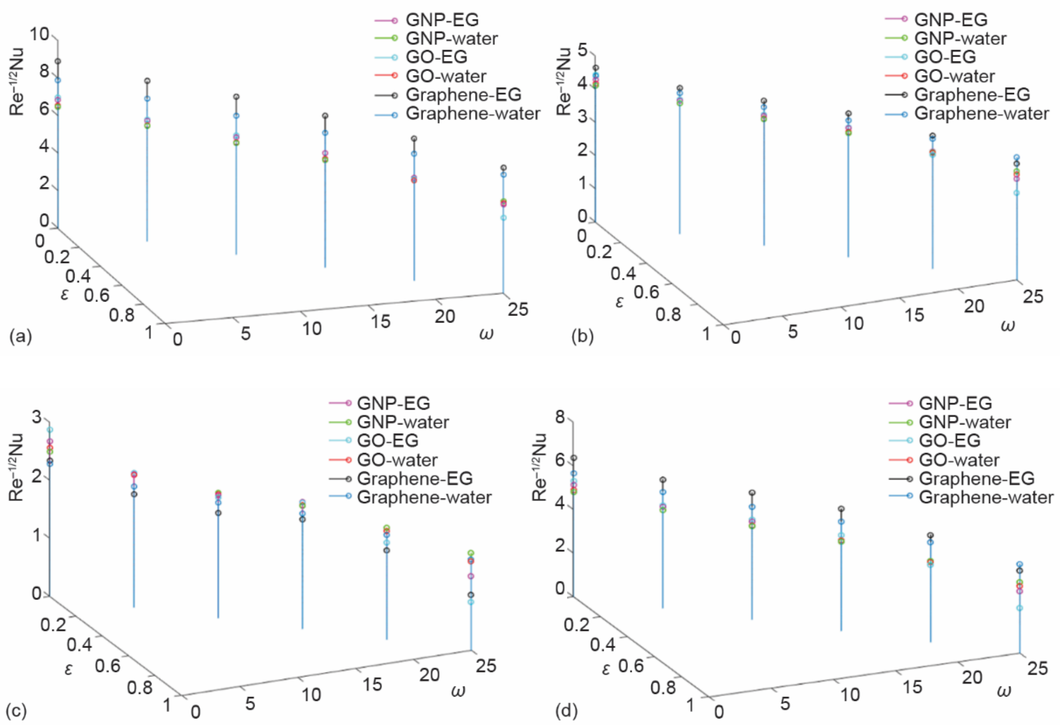

Figure 3. Effect of inclination angle and thermal stratification parameters on Nusselt number; (a) for stretching and injection case, (b) for stretching and suction case, (c) for shrinking and injection case, and (d) for shrinking and suction case; λ = 1, γ = 1, ϕ = 0.4, M = 5, Pr = 6.2, Z_w = 0.5, ϖ = –0.5, S^* = 1 (*for color image see journal web site*)

Figures 3(a)-(d) represent the effects of ω and ε on Nusselt number for four different cases where the Nusselt number decrease for all cases when increasing the value of ω and ε.

Figure 3(a) shows that graphene-EG has the highest Nusselt number compared to other nanofluids when imposing an injection stretching cylinder. Similar outcome was recorded for the next case of suction stretching and injection shrinking cylinder in figs. 3(b) and 3(c), respectively in which graphene-EG has the highest value of Nusselt number when increasing the value of ω from 0° to 20° and ε form 0° to 0.8°. However, the highest Nusselt number is rendered by graphene/water at ω = 25° and ε = 1 based on both corresponding figures. Figure 3(d) shows that GNP-water strongly dominates the Nusselt number when increasing the value of ε and ω from 15° to 25° and 0.6 to 1, respectively. It is worth to notify that GO-EG nanofluid has the lowest Nusselt number at ω = 25° and ε = 1 for all cases.

Conclusive remarks

This study examined the variant graphene based nanofluids due to thermal stratification over an inclined permeable moving cylinder. Temperature profiles and Nusselt numbers for all selected nanofluids decrease with increasing values in thermal stratification parameter, ε, and inclination angle, ω. The GO-EG and GNP-water have the highest temperature profiles at ε = 0.8 and ω = 45°, respectively. Moreover, graphene-EG nanofluid excellently dominates over Nusselt number, while GO-EG nanofluid tends to have the lowest Nusselt number at ω = 25° and ε = 1 for all cases.

Nomenclature

B_0 – uniform magnetic field, [T]
C_f – skin friction coefficient [= $\tau_w/(\rho_f U_0^2)$], [–]
c_p – specific heat capacity, [Jkg^{-1}K^{-1}]
g – gravitational acceleration, [ms^{-2}]
Gr – Grashof number [= $g\beta_T(T_w - T_0)x^3/\nu_f^2$], [–]
l – reference length, [m]
m, n – positive constants, [–]
M, Pr – Hartmann and Prandtl numbers, [–]
Nu – Nusselt number {$=xq_w/[\kappa_f(T_w - T_0)$}, [–]
q_w – heat flux [= $\kappa_f(\partial T/\partial r)_{r=a}$], [Wm^{-2}]
Re – Reynolds number(= $U_0 l/\nu_f$), [–]
S^* – stagnation velocity parameter, [–]
T – temperature, [κ]
u, w – components of velocity, [ms^{-1}]
U_0 – free stream velocity, [ms^{-1}]
Z_w – permeability parameter, [–]
Z_w^* – uniform surface mass flux, [kgm^{-2}s^{-1}]

Greek symbols

α – thermal diffusivity, [m^{2}s^{-1}]
β_T – coefficient of thermal expansion, [K^{-1}]
γ – curvature parameter, [–]
ε – thermal stratification parameter [-]
κ – thermal conductivity, [Wm^{-1}K^{-1}]
λ – mixed convection parameter, [–]
ν – kinematic viscosity, [m^{2}s^{-1}]
ϖ – stretching/shrinking parameter, [–]
ρ – density, [kgm^{-3}]
σ – electrical conductivity, [Sm^{-1}]
ϕ – nanoparticle volume fraction parameter,[–]
τ_w – shear stress [= $\mu_{nf}(\partial u/\partial r)_{r=a}$], [Pa]
ω – inclination angle, [°]

Subscripts

s – solid nanoparticles
w – surface of cylinder
0 – initial or reference
∞ – ambient

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