IMPACTS OF HEAT SOURCE/SINK AND ELECTROMAGNETIC FIELD ON HEAT TRANSFER IN FERROFLUID FLOW

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ABSTRACT. The inspiration driving this article is to explore the impacts of electromagnetic field and heat source/sink on two dimensional nanofluid flow over a stretching cylinder. The effectively controlled nanofluid model utilized in the current assessment incorporates the nanoparticle fraction model. The nanoparticles specified here are Cobalt Co and Gadolinium Gd. Cobalt, Co is a shunt material in the thermomagnetic generator. Gadolinium, Gd is the material first used practically in the thermomagnetic generator. Motor Oil has taken as a base fluid. The governing system of equations solved numerically utilizing MATLAB. The effect of electric field parameter on velocity profile, Heat source/sink on temperature and heat transfer profile, has examined. Further, we noticed that Gadolinium is the most suitable material for the thermomagnetic generator. Its temperature is close to room temperature.

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2020 Mathematics Subject Classification. 76, 80.

Key words and phrases. Heat transfer, Magnetohydrodynamics, Electric field, Heat Source/sink.

Submitted: 11.03.2021; Accepted: 01.04.2021; Published: 14.04.2021.
1. INTRODUCTION

The thermomagnetic generator is an active device that used to convert heat energy into electrical energy. It is one of the solid-state thermal energy harvesters, and it works with no fuel and doesn't give any destructive discharge. Ferrofluid is a colloidal mix of engaging nanoparticles in a transporter liquid, conventionally water, or oil. Ferrofluid has utilized in numerous applications, for example, loudspeakers, rotational seals and pumps, and so on. Gholinia et al. [1] inquired about ethylene glycol with two nanofluids flow on a vertical porous cylinder in the presence of a magnetic field. They discovered that the velocity distribution enhances for more substantial nanoparticle volume fraction, mixed convection parameter, permeability parameter, and curvature parameter. Guestal et al. [2] examined the impacts of heat transfer by buoyancy convection of nanofluids in a partially heated closed cylinder. In their examinations, they discovered that as the nanoparticle volume fraction increases, heat transfer increases. Nagaraju and Mahesh [3] analyzed the impact of magnetized couple stress, heat mass transfer, cross-diffusion, and chemical reaction on a stretching cylinder with the convective boundary condition. They found that with an ascent in curvature parameter, velocity, temperature, and concentration profiles enhanced. Qasim et al. [4] inspected MHD boundary layer ferrofluid slip flow and heat transfer with prescribed thermal flux along a stretching cylinder. They found that surface shear stress and coefficient of heat transfer at the surface increases as the curvature parameter enhances. Hayat et al. [5] inspected the hydromagnetic boundary layer flow of Williamson fluid in the presence of ohmic dissipation and thermal radiation. They found that the local nusselt number raises for a larger electric parameter, suction parameter, Prandtl number and unsteadiness parameter.

An enormous number of the evaluations gave a record on Heat Source/Sink. Elbashbeshy et al. [6] studied numerically the boundary layer steady flow on a stretching horizontal cylinder under the effect of uniform magnetic field with suction/injection and heat source/sink. They found that, their results indicate that the shear stress at the surface can be minimized by increasing the stretching cylinder radius, the suction/injection velocity and decreasing the magnetic field strength.Dash and Behera [7] explored the heat transfer characteristics of laminar natural convective viscoelastic liquid from an isothermal cylinder with
heat source/sink. They graphically compared the difference between the heat transfer coefficient of combined momentum and single momentum equation for viscoelastic liquids.

Disregarding of the Heat source/sink, it’s essential to consider the electric field impact on the stretching cylinder is significant in Thermomagnetic generator. Feng et al. [8] studied numerical examination on simulated pool boiling curves with heat transfer in the presence of a uniform applied electric field by using the lattice Boltzmann (LB) model. They deduced that increasing gradually the electric field strength, intensity could enhance the heat transfer of boiling liquid. Based on the above showed assessments, at present, we assessed the consolidated impacts of the magnetic field, electric field, and heat source/sink effects on ferrofluid fluid over-stretching cylinder with convective heat transfer. We consider here, Cobalt, Co and Gadalonium, Gd nanoparticles with base fluid as motor oil. The combined effects of all the parameters in this study are significant in the thermomagnetic generator.

2. Mathematical Formulation

A steady, two dimensional, laminar, viscous incompressible nanofluid flow over-stretching cylinder with radius \( r_0 \) is presented in Fig. 1. The coordinate system is chosen, such that \( z \) axis is measured along the axis of the tube and \( r \) axis is measured in the radial direction. The velocity components in the directions of \( r, z \) are \( u, w \), \( p \) is fluid pressure. The constant and ambient temperatures at the cylinder’s surface are \( T_w, T_\infty \) such that \( T_w > T_\infty \). It is assumed that the uniform magnetic field with intensity of \( B = (0, B_0, 0) \) acts in the radial direction and the effect of the induced magnetic field is negligible, which is valid only for small Reynolds number. The electromagnetic body force or Lorentz force is
given by $J \times B$, where $J = \sigma (E + V \times B)$ is the Joul current, $\sigma$ is the electrical conductivity, $V = (u, v)$ is the fluid velocity and $E = (0, 0, -E_0 z)$ is electric field vector. Under the above considerations, the governing equations can be expressed as (Tiwari and Das [9])

\[
\frac{\partial}{\partial r} (ru) + \frac{\partial}{\partial z} (rw) = 0
\]

\[
u \frac{\partial u}{\partial r} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho_{nf}} \frac{\partial p}{\partial r} + \frac{\mu_{nf}}{\rho_{nf}} \left( \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} - \frac{u}{r^2} \right)
\]

\[
u \frac{\partial T}{\partial r} + w \frac{\partial T}{\partial z} = \frac{k_{nf}}{(\rho C_p)_{nf}} \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) + \frac{Q}{(\rho C_p)_{nf}} (T - T_\infty).
\]

The boundary conditions for Eqns. (2.1)-(2.4) are

\[
u = 0, \quad w = w_e = \frac{U_0 z}{l}, \quad T = T_w, \quad \text{at} \quad r = R
\]

\[
u \to 0, \quad T \to T_\infty, \quad p \to p_\infty, \quad \text{as} \quad r \to \infty.
\]

The effective dynamic viscosity, density and thermal diffusivity of nano fluid are

\[
u_{nf} = \frac{\mu_f}{(1 - \phi)^2}, \quad \rho_{nf} = (1 - \phi) \rho_f + \phi \rho_s, \quad \alpha_{nf} = \frac{k_{nf}}{(\rho C_p)_{nf}}.
\]

The heat capacitance of the nano fluid is given by

\[(\rho C_p)_{nf} = (1 - \phi) (\rho C_p)_f + \phi (\rho C_p)_s.
\]

The thermal conductivity of the nano fluids is approximated by the Maxwell-Garnetss (MG) model (\[10\] and \[11\])

\[
u_{nf} = \frac{k_s + 2k_f - 2\phi (k_f - k_s)}{k_s + 2k_f + \phi (k_f - k_s)}.
\]

Here, the subscripts $nf$, $f$, and $s$ represent the thermophysical properties of the nano fluid, base fluid, and nanosolid particles, respectively (Table I). Then introduce the new variable $\eta = \sqrt{\frac{U_0}{\nu_f} \left( \frac{r^2 - R^2}{2R} \right)}$. Then, the velocity and temperature components are

\[
u = -\sqrt{\nu_f U_0 \frac{R}{r}} f(\eta), \quad w = \frac{U_0 z}{l} f'(\eta), \quad T = T_\infty + \Delta T \theta(\eta).
\]
Substituting Eqns. (2.6)-(2.9) in Eqns. (2.2)-(2.5), we get

\[(1 + 2\gamma \eta) f''' + 2\gamma f'' + \frac{\phi_1}{\phi_2} M (E_1 - f') - \phi_1 \left( f'^2 - f f'' \right) = 0 \]  
(2.10)

\[(1 + 2\gamma \eta) \left( P' - \frac{\phi_2}{\phi_1} f'' \right) + \phi_2 \frac{R^2}{r^2} \gamma f^2 - \phi_2 f f' = 0 \]  
(2.11)

\[(1 + 2\gamma \eta) \theta'' + 2\gamma \theta' + \left( \frac{k_f}{k_{nf}} \right) Pr \left( \phi_3 f \theta' + \delta \theta \right) = 0 \]  
(2.12)

\[f (0) = 0, \ f'(0) = 1, \ f'(\infty) \to 0 \]  
(2.13)

\[\theta (0) = 1, \ \theta (\infty) \to 0 \]  
(2.14)

\[P (\infty) \to 0 \]  
(2.15)

The non-dimensional constants in Eqns. (2.10)-(2.12) are the curvature parameter \(\gamma\), magnetic parameter \(M\), electric parameter \(E_1\), Prandtl number \(Pr\), heat source/sink parameter \(\delta_1\) and pressure term \(p\). These parameters are defined as follows:

\[\gamma = \sqrt{\frac{\nu_f l}{U_0 R^2}} , \ M = \frac{\sigma B_0^2 l}{\rho_f U_0} , \ E_1 = \frac{E_0 l}{B_0 U_0} , \ Pr = \frac{\nu_f (\rho C_p)_f}{k_f} , \]

\[\delta_1 = \frac{Q l}{(\rho C_p)_f U_0} , \ p = p_\infty - \rho_f \frac{U_0}{l} \nu_f P (\eta) , \ \phi_1 = (1 - \phi)^{2.5} \left[ 1 - \phi + \phi \left( \frac{\rho_s}{\rho_f} \right) \right] , \]

\[\phi_2 = 1 - \phi + \phi \left( \frac{\rho_s}{\rho_f} \right) , \ \phi_3 = 1 - \phi + \phi \left( \frac{(\rho C_p)_s}{(\rho C_p)_f} \right) . \]

The Skin friction and dimensionless nusselt modulus coefficients are characterized as

\[C_f (1 - \phi)^{2.5} \sqrt{Re_z} = f''(0) , \ \ Nu_z Re_z^{-1/2} \left( \frac{k_f}{k_{nf}} \right) = -\theta'(0) , \]  
(2.16)

where \(Re = \frac{U_0}{\nu_f}\).

**Table 1.** Thermo-physical properties of motor oil, Cobalt and Gadolinium nanoparticles are

<table>
<thead>
<tr>
<th>Properties →</th>
<th>(\rho \ (kg/m^3))</th>
<th>(C_p \ (J/kgK))</th>
<th>(k \ (W/mK))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil (Motor Oil 10W30)</td>
<td>856</td>
<td>1990</td>
<td>0.158</td>
</tr>
<tr>
<td>Cobalt (Co)</td>
<td>8860</td>
<td>423</td>
<td>84.935</td>
</tr>
<tr>
<td>Gadolinium (Gd)</td>
<td>7870</td>
<td>230</td>
<td>8.786</td>
</tr>
</tbody>
</table>
3. PRESSURE GRADIENT EQUATION

The pressure gradient equation is partially decoupled from the momentum equation

\[
P' (\eta) = \frac{\phi_2}{\phi_1} f'' + \phi_2 \frac{R^2}{r^2} f f' - \phi_2 \frac{R^4}{r^4} \gamma f^2
\]

4. VALIDATION OF RESULTS

In pursuance of confirming the precision of the current numerical results, we’ve examined our outcomes with those of Elbashbeshy et al. [6], Ishak and Nazar [12], Grubka and Bobba [13]. The outcomes of these comparisons are as shown in Table 2.

<table>
<thead>
<tr>
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<tbody>
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<tr>
<td>10</td>
<td>2.3080</td>
<td>2.3080</td>
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</tr>
</tbody>
</table>

5. DISCUSSION OF RESULTS

Figure 2 addresses the impact of the electric field parameter \( E_1 \) on the velocity profile. From the figure, we presume that the velocity decrease when it enhances the electric field parameter, because of Lorentz force acts perpendicular to the nanoparticles, and the drag force on the nanofluids reduces fluid flow motion. The density of Cobalt \( \text{Co} \) is more than Gadolinium \( \text{Gd} \). It is more attracted by an electric field so that the velocity profile is diminishing more in Gadolinium \( \text{Gd} \) nanoparticles compare to Cobalt \( \text{Co} \) nanoparticles.

Figure 3 displays the fluctuations of heat source parameters on the temperature profile. A heat source produces thermal energy that carries the working substance to a high-temperature state. If the heat source parameter \( \delta_1 \) enhances, the temperature of nanoparticles also increases. We see that the temperature profile enhances more in Gadolinium \( \text{Gd} \) than Cobalt \( \text{Co} \) with an enhance in the heat source parameter. It can be clarified that, Gadolinium \( \text{Gd} \) nanoparticles heat
rapidly in the light of the fact that it has the least value of specific heat and low density than Cobalt Co nanoparticles.

Figure 4 illustrates the impact of the heat sink parameter on the temperature profile. A heat sink parameter used to transfer heat from a device to the surroundings, to prevent the device from overheating. If the heat sink parameter enhances, then the temperature profile also increases. Because of high thermal conductivity, Cobalt Co nanoparticles have minimal temperature than Gadolinium Gd nanoparticles.

Figure 5 displays the effect heat source/sink parameter $\delta_1$ on the heat transfer coefficient with increasing the nanoparticle volume fraction. This figure shows that the heat transfer coefficient $-\theta'(0)$ diminishes very high in Gadolinium Gd nanoparticles than Cobalt Co nanoparticles for increasing values of heat source/sink parameter. From Figs. 3 and 4 we observe that the temperature gradient increases more in Gadolinium Gd nanoparticles compared to Cobalt Co nanoparticles with heat source/sink. Furthermore, with an increase in nanoparticle volume fraction, temperature increases in both cases of nanofluids. That’s why the heat transfer coefficient decreases for both the nanofluids.

**Figure 2.** Variations of velocity profile for different values of $E_1$, Co, and Gd nanoparticles, when $Pr = 1531.92, M = 0.5, \gamma = 1.2, \delta_1 = 0.2, \phi = 0.1$
**Figure 4.** Variations of temperature profile for different values of $\delta_1$ (negative), Co, and Gd nanoparticles, when $M = 0.5$, $Pr = 1531.92$, $\gamma = 1.2$, $E_1 = 10^{-3}$, $\phi = 0.1$

**Figure 3.** Variations of temperature profile for different values of $\delta_1$ (positive), Co, and Gd nanoparticles, when $M = 0.5$, $Pr = 1531.92$, $\gamma = 1.2$, $E_1 = 10^{-3}$, $\phi = 0.1$
Figure 5. Heat transfer coefficient as a function of nanoparticle volume fraction $\phi$ for different values of heat source/sink parameter $\delta_1$, Co, and Gd nanoparticles, when $Pr = 1531.92, \gamma = 1.2, E_1 = 10^{-3}, M = 0.5$

References


