Review of Magnetohydrodynamics flow in Nanofluids

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Abstract. This paper review some of the available nanofluids physical properties models and focuses on presenting the various research work done on MHD convection of nanofluids in various geometries and application. Analysis has been carried out in the presence of applied magnetic field and chemical reaction. Heat and mass transfer characteristics are studied using heat and mass convective conditions. The governing partial differential equations are transferred to the nonlinear ordinary differential equations. In this research paper we have disussed about the Lorentz forces which helped the velocity and temperature to decrease, but the concentration increased with an increase of the magnetic field. Convergent series solutions are obtained from fluid velocity, temperature and concentration fields.

1. Introduction
Nanofluids are used to enhance the thermal conductivity of base fluids like water, ethylene glycol, propylene glycol etc. They have several engineering and biomedical applications in cooling, cancer therapy and process industries. The enhancement of thermal conductivity of conventional heat transfer fluids through suspensions of solid particles is a relatively recent development in engineering technology. The resulting effect of these suspensions is to increase the coefficient of heat transfer. The suspended particles are able to increase the thermal conductivity and heat transfer performance since the thermal conductivity of solid metals is higher than base fluids. Major advantages of nanofluids are that they are more stable, have direct impact on viscosity depends upon the parameters of nanoparticles and better wetting, spreading and dispersion properties of solid surface even for modest nanoparticle concentrations. The MHD laminar boundary layer flow with heat and mass transfer of an electrically conducting water-based nanofluid over a nonlinear stretching sheet with viscous dissipation effect is investigated numerically.

2. Theory
When describing the flow of an electrically and/or magnetically conducting fluid of velocity, say, electrolytes, charged particle/magnetic suspensions and/or liquid metals, the Navier-Stokes equation carries additional body force terms, summarized as the electromagnetic force. Assuming that the externally imposed magnetic field is unperturbed by the flow, i.e., Re<<1, we have (Griffith, 1999):

\[ f_{EM} = f_{electrostatics} + f_{magnetic} + f_{magnetic\ phoretic} = f_{Lorenz} + f_{m-p} \]  

(1)

By definition, the Lorentz force is the force on a point charge of a moving particle due to electromagnetic fields, i.e., caused by the induced current density J and external fields B and E:

\[ f_L = J \times B; J = \sigma (-\nabla \phi + v \times B); -\nabla \phi = E_{ext} \]  

(2)

In case the ions or fluid particles are magnetic, we have to consider:
Where $\Delta \chi = \chi_{\text{particles}} - \chi_{\text{fluid}}$ is the difference in magnetic susceptibilities and permeability

\[ \mu_0 = 4\pi \times 10^{-7} \text{ Tm/A} \]

Evaluation of the electrostatic (i.e., Coulomb) force for an electrolyte solution with n ionic species of concentrations requires first the solution of the Nernst-Planck equation

\[ f_{\text{Coulomb}} = F \nabla \phi \cdot \sum_{i=1}^{n} Z_i C_i \]

Here $Z_i$ is the valence of the $i_{th}$ ion species, $F$ is the Faraday constant, and $\phi$ is the applied electric potential. Clearly, the applied electric potential and magnetic field are uniform, $f_{\text{Coulomb}}$ and $f_{mp}$ are zero, respectively.

In summary, the system of the extended Navier-Stokes equations read:

\[ \nabla \cdot \mathbf{v} = 0 \\
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{v} + f_{\text{EM}} \\
\rho_c \left[ \frac{\partial T}{\partial t} + (\mathbf{v} \cdot \nabla) T \right] = k \nabla^2 T + \frac{1}{\sigma_{\text{el}}} \mathbf{J} \cdot \mathbf{J} + \mu \Phi \]

Where, $\sigma_{\text{el}}$ is the electric conductivity of the solution, $\mathbf{v}$ is the flow velocity, the term $\frac{1}{\sigma_{\text{el}}} \mathbf{J} \cdot \mathbf{J}$ indicates possible Joule heating, and $\mu \Phi$ is the viscous dissipation function.

MHD Applications. Various dimensionless groups, e.g., the magnetic Reynolds number, $R_{em}$, the Hartmann number, $Ha$, and the interaction parameter, IP, with their value ranges determine dominant forces in MHD. For example, in micromagneto fluids:

\[ Re_m = \frac{vl}{\lambda} = O(10^{-8}) \]

Where $v$ is the average velocity, $l$ the characteristic length scale and $\lambda = (\varepsilon \sigma_{\text{el}})^{-1}$ is the magnetic field diffusivity with $\varepsilon$ being the permittivity and $\sigma_{\text{el}}$ the electric conductivity. Typically microchannel flow values are $v=100\mu m/s$, $l=100\mu m$ and $\lambda=lm^2/s$ which is much higher than momentum ($10^{-6} m^2/s$) and species ($10^{-9} m^2/s$) diffusivity. An important dimensionless group in MHD the Hartman number

\[ Ha = Bl \sqrt{\frac{\sigma_{\text{el}}}{\mu}} \]

where $(Ha)^2$ is the Lorentz force over the viscous force and is the dynamic viscosity. Clearly, as a microchannel’s $D_h \rightarrow 0$, $f_{\text{Lorenz}} \rightarrow 0$ and the liquid flow ceases. A basic application of the extended momentum equation, assuming constant properties, is Poiseuille-type flow between parallel plates a distance 2d apart. In the absence of an electric field, the N-S equation reads:

\[ \rho \frac{D \mathbf{v}}{Dt} = -\nabla p + \mu \nabla^2 \mathbf{v} + \rho g + f_{\text{Lorenz}} \]

Where here $f_{\text{Lorenz}} = f_{\text{magnetic}} = J \times B$. At low magnetic Reynolds number, ie $Re_{\text{mag}} = \varepsilon \sigma_{\text{el}}$

Hayat et al. [1] investigated on Magnetohydrodynamic (MHD) three-dimensional boundary layer flow of viscous nanofluid induced by an exponentially stretching surface. It was resulted that there is an increase in the temperature $\theta(\zeta)$ and concentration $\phi(\zeta)$ fields for larger Hartman number (Ha) and an increment in Prandtl number Pr lead to lower temperature $\theta(\zeta)$ and concentration $\phi(\zeta)$ fields. Concentration field reduced for larger Brownian motion parameter (Nb). Skin-friction coefficients enhanced for higher values of ratio parameter ($\alpha$) and Hartman number (Ha). Effects of Brownian
motion parameter (Nb) on the local Nusselt and Sherwood numbers were quite reversed. Sheikholeslami et al. [2] investigated on the effect of melting heat transfer on the nanofluid flow in the presence of Lorentz forces two phase model. Researchers revealed that Nu augmented with a rise of Lorentz forces, but it diminished with augmented Re, Ec. As the magnetic field was applied, back flow occurred, and the nanofluid flow was retarded. Lorentz forces helped the velocity and temperature to decrease, but the concentration increased with an increase of the magnetic field. The temperature and velocity of the nanofluid increased with a rise in δ and φ. Öztöp et al. [3] investigated on the effects of mixed convection of MHD flow in nanofluid filled and partially heated wavy walled lid-driven enclosure. Observers gave that (t) the rate of heat transfer decreases with increasing the Hartmann number. The rate of heat transfer can be enhanced or reduced by increasing the volume fraction of nanoparticles based on Hartmann and Richardson numbers. In this numerical work, finite volume method is used to solve governing equations of sinusoidal shaped partial heater in a nanofluid filled cavity under magnetic field. Hayat et al. [4] investigated on the effects of viscoelasticity on three-dimensional nonlinear convective flow. Researchers analysed that the velocities f (g) and g’ (g) had opposite behaviour for larger d, while skin friction coefficient along x- and y-directions were enhanced. The temperature Θ (η) and thickness of boundary layer were higher for higher magnetic parameter M. The variations of thermophoresis (Nt) and Brownian motion (Nb) on Θ (η) were qualitatively similar to each other. With an increase in Brownian motion (Nb) there was reduction in Ψ(η) and its related boundary layer thickness. Higher Schmidt number (Sc) resulted in lower concentration field and larger Sherwood number. Sergeenko et al. [5] investigated on field induced proximity type behavior in based ferromagnetic nanofluid. Researchers analysed that by increasing an applied magnetic field to the saturation level, a second transition started to develop at lower temperature. The so-called finite temperature size effects could significantly reduce the amount of the ordered phase and the corresponding value of the Curie temperature.

Sheikholeslami et al. [7] investigated on the influence of Lorentz forces on nanofluid free convection inside a porous cavity. Simulations have been done via Lattice Boltzmann Method (LBM). Koo-Kleinstreuer-Li (KKL) model is applied in order to consider Brownian motion impact on nanofluid properties. They resulted that temperature gradient reduced with increasing Ha while it increased with augment of permeability of porous media and buoyancy forces. Sheikholeslami et al. [8] investigated on the magnetic field impact on nanofluid natural convection inside a porous enclosure with four square heat sources. Brownian motion impact on nanofluid properties was assumed. Impacts of shapes of nanoparticle, Rayleigh number (Ra), Darcy number (Da), nanofluid volume fraction (δ/δ), Hartmann number δHaΦ on heat transfer treatment were showed. Observers found that convective heat transfer reduced with increasing Ha but it augments with increasing Da & Ra. Sucharitha et al. [9] investigated on the the influence of wall flexibility and Joule heating on the peristaltic transport of a conducting nanofluid in uniform/non-uniform porous channel. The exact solutions were obtained for stream function and velocity. Further, R-K-Fehlberg integration scheme was applied to solve the energy and concentration equations. Researchers observed that the fluid velocity was greater in the diverging channel when compared to the uniform channel, while the situation was reversed for temperature and concentration fields. An increase in the magnetic parameter (M) and permeability parameter (σ) decreased the velocity and temperature.

Ghasemi et al. [6] investigated on the MHD natural convection of Cu-water nanofluid in a square porous enclosure. Researchers analysed that entropy generation study resulted in low and high Ra values the thermal and frictional entropy generation are respectively dominant, while for moderate Ra they have the same order of magnitude. Begum et al. [12] investigated on the fully developed mixed convective heat transfer of Cu-water nanofluid flow inside a rectangular enclosure saturated with porous medium in the presence of inclined magnetic field. Researchers observed that the thermal and flow field characteristics of the mixed convection flow in a rectangular lid-driven porous enclosure filled with Cu-water nanofluid subjected to the influence of an inclined uniform magnetic field.
Ghasemi et al. [17] investigated on the MHD natural convection of Cu-water nanofluid in a square porous enclosure. Researchers observed that entropy generation study performed and results state that in low and high Ra values the thermal and frictional entropy generation are respectively dominant, while for moderate Ra they have the same order of magnitude. Reddy et al. [38] investigated on MHD boundary layer flow, heat and mass transfer characteristics of Cu-water and Ag-water nanofluid over a rotating disk. It was noted that the temperature profiles elevated with the increasing value of nanoparticle volume fraction parameter.

Kandasamy et al. [21] investigated on Issue of nanoparticle shapes on the squeezed MHD nanofluid flow of water, ethylene glycol and engine oil based Cu, Al$_2$O$_3$ and SWCNTs over a porous sensor surface in the presence of thermal radiation. Researchers observed Organisation of the rate of heat transfer and temperature within the nanofluids with different nanoparticle shapes. Khan et al. [23] investigated on Magneto-hydrodynamic (MHD) mixed convection channel flow of Molybdenum disulphide (MoS$_2$) nanofluid inside vertical porous medium. It was observed that MoS$_2$ nanoparticles with blade and platelet shapes had the highest heat transfer rate compared to cylinder and brick shapes. Porosity and magnetic parameters had opposite effects on velocity, whereas velocity increased with increasing slip. Rehman et al. [28] investigated on the MHD flow of micropolar carbon-water nanofluid in the presence of rotating frame. It is observed that temperature profile decreased with the increase in porosity parameter and nanoparticle volume fraction while enhances for higher values of Biot number.

Sandeep et al. [10] investigated on the momentum, thermal, and concentration boundary layer behaviour of liquid-film flow of water-based non-Newtonian nanofluids dispensed with magnetite nanoparticles. Observed concluded that suspension of magnetite nanoparticles effectively improved the thermal conductivity of the Jeffrey nanofluid. Increasing the values of the Deborah number enhanced the heat transfer rate. Abbas et al. [11] investigated on the effects of EMHD in flow of nanofluid past a porous Riga surface with gyrotactic microorganism and nanoparticles. Researchers observed that velocity almost reduces for larger values of bio-convection Rayleigh number and porosity parameter. Bio-convection Schmidt number and Peclet number resulted a marked resistance in motile microorganism density. Nanoparticle concentration indicated reverse behavior for Nb and Nt. Ramzan et al. [13] investigated on the heat and mass transfer of nanofluid with motile gyrotactic microorganisms. Observers resulted that the motile density of microorganisms showed a decreasing behavior for growing values of bio-convection lewis number and Peclet number. Increment in temperature field was observed for increasing values of Biot number radiation and temperature ratio parameter. The temperature exhibited rise in behavior, while the heat transfer rate reduced for rise in values of viscous dissipation effect. Concentration profile showed reduced tendency for increasing values of Lewis number, mixed convection and constructive chemical reaction parameter. Shagaiya Daniel et al. [14] investigated on the combined effects of thermal radiation, viscous dissipation and Joule heating in steady two-dimensional electrical magnetohydrodynamic boundary layer flow of nanofluids. Researchers concluded that the rate of heat and mass transfer reduced by increasing thermophoresis and thermal stratifications and it increased for larger values of suction. Electric field parameter increased the nanofluid velocity and temperature. The thickness of the thermal boundary layer increases with an increase in thermal radiation parameter Rd, Eckert number Ec, magnetic field M and electric field E.

Hayat et al. [15] investigated on double stratification in magnetohydrodynamic (MHD) flow of nanofluid by a stretching cylinder. Researchers concluded that velocity profile shows a reducing function of magnetic parameter M and velocity slip parameter A. Increase in Nb, showed increase in the rate of heat transfer, while decrease in rate of mass transfer. With the decrease in temperature profile there was an increase in thermal stratification parameter S and thermal slip parameter B. Increase in solutal stratification parameter P and solutal slip parameter B1 showed decrease in
concentration profile. Moshizi et al. [16] investigated on mixed convection of magnetohydrodynamic nanofluids inside microtubes at a constant wall temperature. Observers resulted that with an increase in the magnetic field strength and slippage at the fluid-solid interface, the thermal performance increases. Greater the buoyancy, greater would be the thermal performance, especially for larger nanoparticles. Greater the volume fraction, greater would be the thermal performance for the larger nanoparticles, whereas it would be reduced for the smaller ones. Sheikholeslami et al. [18] investigated on the influence of Lorentz forces on nanofluid free convection inside a porous cavity. Simulations have been done via Lattice Boltzmann Method (LBM). Koo-Kleinstreuer-Li (KKL) model is applied in order to consider Brownian motion impact on nanofluid properties. Observers revealed that the temperature gradient reduced with increase of Ha while it increased with augment of permeability of porous media and buoyancy forces.

Sheikholeslami et al. [19] investigated on the magnetic field impact on nanofluid natural convection inside a porous enclosure with four square heat sources. Brownian motion impact on nanofluid properties was taken into account. Impacts of shapes of nanoparticle, Rayleigh number (Ra), Darcy number (Da), nanofluid volume fraction, Hartmann number (Ha) on heat transfer treatment were demonstrated. Observers resulted that convective heat transfer decreased with increase of Ha but it augmented with increase of Da and Ra. Sandeep et al. [20] investigated on the momentum, thermal, and concentration boundary layer behavior of liquid-film flow of water-based non-Newtonian nanofluids. They found that suspension of magnetite nanoparticles effectively improved the thermal conductivity of the Jeffrey nanofluid. Increasing the values the Deborah number encouraged the heat transfer rate. Nayak et al. [22] investigated on three dimensional magnetohydrodynamic (MHD) flow and heat transfer analysis associated with thermal radiation as well as viscous dissipation of nanofluid. Observers concluded that the presence of magnetic field as well as porous matrix both impeded the fluid motion, associated with an enhancement in the velocity gradient at the wall thereby increasing local skin friction coefficient.

Chamkha et al. [24] investigated on the effects of the presence of a heat sink and a heat source and their lengths and locations and the entropy generation on MHD mixed convection flow. Observers found that the addition of nanoparticles reduced the convective heat transfer inside the porous cavity at all ranges of the heat sink and source lengths. Bing et al. [25] investigated on the boundary layer magnetohydrodynamics (MHD) flow of Williamson nanofluids over a stretching sheet. Researchers observed that the rate of heat transfer was greater for Williamson nanofluids compared to the classical viscous fluid. Basir et al. [26] investigated on the effect of multiple slip on a chemically reactive magnetohydrodynamic (MHD) non-Newtonian power law fluid flow. Researchers observed that the MHD flow of water-based nanofluid over a stretching sheet with microorganism for non-Newtonian fluid focusing on pseudoplastic fluid was studied. Hamid et al. [27] investigated on the effects of chemically reactive species and thermal radiation on magnetohydrodynamic (MHD) boundary layer flow and heat transfer in a nanofluid. It is found that the second solution existed in the exponentially shrinking flow. Khan et al. [29] investigation is made to examine the influence of chemically reactive species and mixed convection on the MHD Williamson nanofluid. It is found that temperature profile increased for large values of thermophoresis parameter, Brownian motion and Eckert number, but decreased for large values of Lewis number and Brownian motion. Hussain et al. [30] investigated on mathematical model to discuss magnetohydrodynamic Sisko fluid flow over a stretching cylinder. Researchers resulted that conventional heat transfer coefficient progressed positively verses both curvature parameter and Prandtl number Pr while Eckert number , Ec Brownian motion parameter , Nb thermophoresis parameter Nt and magnetic field parameter M had opposite effects. Hayatthe et al. [31] investigated on MHD flow of a nanofluid is examined due to a variable-thickness rotating disk. It was observed that axial and radial velocities increased for larger exponent of the power law fluid. Temperature is a decreasing function of the Prandtl number while it caused an increase in the heat transfer rate. Khan et
al. [32] investigated on locally similar solutions for the unsteady two-dimensional Falkner-Skan flow of MHD Carreau nanofluid past a static/moving wedge in the presence of convective boundary condition. It was noticed that the velocity of the fluid was smaller for static wedge when compared to the stretching wedge. However, qualitatively quite the opposite trend was observed for the temperature and concentration fields. Hayat et al. [33] investigated on the heat and mass transfer effects in a MHD flow of a viscous nanofluid. An exponentially stretching sheet embedded in a porous medium was obtained.

Abbaszadeh et al. [34] investigated on heat transfer entropy generation of forced convection of CuO-water nanofluid in a parallel plate microchannel in the presence of magnetic field. The results showed that when there is an increase in Hartmann or Reynolds numbers, or the volume fraction of nanoparticles, the average Nusselt number and the total entropy generation rate increase. Furthermore, when Knudsen number increased, there was decrease in total entropy generation rate. Mliki et al. [35] investigated on MHD natural convection heat transfer has been analyzed for an inclined C-shaped cavity filled with nanofluid. Researchers revealed that the heat transfer enhances when considering the Brownian motion effect of nanoparticles, whereas presence of magnetic field tries to retard convection. Besthapu et al. [36] Investigated on the influence of both thermal and solutal stratification on MHD nanofluid flow along an exponentially stretching sheet. Researchers observed that temperature and concentration profiles were reduced with an increase in thermally stratified parameter. Giri et al. [37] investigated on the effect of Stefan blowing on the hydro-magnetic bioconvection of a water-based nanofluid flow containing gyrotactic microorganisms through a permeable surface. They found the effects of the traditional Lewis number and suction/blowing parameter on temperature distribution and microorganism concentration are converse to each other. Ahmad et al. [39] investigated on the problem of steady casson nanofluid flow past a wedge. It was found that the surface temperature was slightly higher for the flow over a horizontal plate compared to that over a vertical plate. Hayat et al. [40] investigated on stratified MHD flow of tangent hyperbolic nanofluid past an inclined exponentially stretching the surface. Researchers observed that the temperature and the thermal boundary layer thickness increased noticeably for large values of Brownian motion and thermophoresis effects.

3. Conclusion

This review paper deals with theoretical and experimental review of magnetohydrodynamics flow in nanofluids. The thermal and flow field characteristics of the mixed convection flow in a rectangular lid-driven porous enclosure filled with Cu-water nanofluid subjected to the influence of an inclined uniform magnetic field Heat and mass transfer characteristics are studied using heat and mass convective conditions. It is observed that temperature profile decreases with the increase in porosity parameter and nanoparticle volume fraction while enhances for higher values of Biot number. The governing partial differential equations are transferred to the nonlinear ordinary differential equations. Convergent series solutions are obtained for fluid velocity, temperature and concentrations fields.

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