International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s, 2025
https://theaspd.com/index.php

Heat And Mass Transfer In Hybrid Nanofluids With MHD And Entropy Effects

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Abstract
The study addresses the need for enhanced thermal and mass transport in fluid systems by exploring the combined effects of hybrid nanoparticles, magnetic field forces, and entropy modulation in complex flow domains. Conventional single-particle nanofluids often face limitations in heat transfer capacity and stability, motivating the development of hybrid nanofluids with synergistic thermal properties. The objectives were to evaluate the influence of varying magnetic parameters and nanoparticle volume fractions on heat and mass transfer rates and to quantify the associated entropy generation in magnetically driven hybrid nanofluid flows. A numerical methodology based on the finite element method was implemented to simulate flow over a range of magnetic parameters ($0 \leq M \leq 4$ *) and total nanoparticle volume fractions up to 0.04. The results reveal that the local Nusselt number increases by approximately* 18.7% *and the Sherwood number by about* 14.3% *As the magnetic parameter rises from 0 to 4, indicating a significant enhancement in both heat and mass transfer. Conversely, entropy generation exhibited a marked rise of nearly.* 21.5% *Under the same conditions, reflecting the trade-off between performance gains and thermodynamic irreversibility. These findings underscore the potential of optimized hybrid nanofluid-magnetic field configurations for applications in thermal energy systems, while highlighting the importance of managing entropy generation to balance efficiency and sustainability.*
Keywords: *hybrid nanofluid, magnetic field, entropy generation, Nusselt number, Sherwood number, heat transfer enhancement*

1. INTRODUCTION

Magnetohydrodynamic (MHD) hybrid nanofluid flows have attracted a lot of research because it has the potential to improve the heat and mass transfer in modern thermal systems. Researchers have extensively studied the interplay between nanoparticle dispersion, magnetic field effects, and entropy generation in complex geometries over the last several years because of its applications in energy systems, cooling of electronics, biomedical, and microfluidics. As reported by Hussain et al. (2024), MHD convection in hybrid nanofluids embedded in wavy enclosures has been investigated, and it is observed that the thermal conductivity is not only augmented by loading nanoparticles, but the profile of entropy generation also varies, especially when thermal radiation is included. Likewise, Nawaz and Arif (2022) considered the thermal and mass transfer in MHD Maxwell fluids with hybrid nanoparticles, demonstrating that subtle manipulation of the dispersion of particles can be used to substantially enhance the transport properties as well as to control the levels of entropy. Along with such numerical investigations, a comprehensive review of nanofluid heat transfer in microcooling systems performed by Elsherbiny et al. (2024) led to the conclusion that hybrid nanoparticle suspensions provide a potentially viable route to eliminating thermal bottlenecks in compact heat exchangers. All these studies tend to highlight the increasing significance of hybrid nanofluid-MHD interactions in the next-generation heat transfer technologies. The basic physics that controls the dynamics of MHD nanofluid is highly interrelated to flow and temperature field changes caused by the presence of magnetic fields. Hussain et al. (2021) explored the synergetic effect of magnetic fields and entropy generation in the case of double-diffusive convection of Casson fluids, by inference that the convective instabilities can be suppressed with the help of magnetic control, and the thermal irreversibility can be refined. In the same vein, Mebarek-Oudina et al. (2024) studied the magneto-convective flows of hybrid nanofluids in porous media and established that the interaction between the concentration of nanoparticles, permeability of the porous matrix, and the strength of the magnetic field has a major impact on the thermal transport and entropy generation. Regarding materials science, Demirkır and Ertürk (2020) explored rheological and thermal characteristics of graphene-water nanofluids and concluded that there was hysteresis in the viscosity-temperature behavior that directly reflects on the stability of the flow of the hybrid nanofluid under MHD flow conditions. These results confirm that not only can magnetic fields be used to exert directional control on heat transfer, but that magnetic fields also interact strongly with the natural rheology of nanoparticle suspensions.

Additional opportunities to customise thermal and electrical properties exist in the form of carbon-based nanomaterials used in hybrid nanofluids, including graphene and carbon nanotubes. Chattopadhyay and Dhar (2019) observed dielectric relaxation and dissipation of nanocarbon complex fluids, and the results revealed that they possess an accurate control of the electromagnetic fields in MHD thermal systems. In a related area, Heysiattalab et al. (2016) studied the condensation of magnetic nanofluids in variable-directional magnetic fields and found that the direction of the magnetic field can be modified to enhance the velocity of the condensation heat transfer. Alkasmoul et al. (2018) compared the effectiveness of Al_2O_3, TiO_2, and CuO nanofluids in convective cooling and stated that each type of nanoparticle has its unique benefits in thermal conductivity, specific heat, and stability, which further increases when these types are used in hybrid nanofluids. The combination of these works gives the background knowledge required to engineer hybrid nanofluids with desired thermal, electrical, and magnetic properties to suit particular needs in MHD applications.

Irrespective of these developments, hybrid nanofluids remain a challenge in terms of stable dispersion, predictable thermophysical characteristics, and manufacturability of the process. Taha-Tijerina (2018) identified the key issues of thermal transport in nanofluids, pointing out that agglomeration of particles, the interfacial resistance, and their long-term stability are the factors preventing their stable operation. There is a need, therefore, to optimise the base fluid and nanoparticle combinations as well as account for operational factors like temperature gradients, shear rate, and magnetic field intensity when developing application-specific hybrid nanofluids. To overcome such limitations, Alderremy et al. (2025) have shown the promise of hybrid nanofluids in micro-squeezed channel drug delivery systems, where they have used Hall current effects, particle size, and interparticle spacing to optimize heat and mass transfer in biomedical applications. Combining the concepts of MHD with nanofluid engineering, therefore, presents a cross-disciplinary frontier that cuts across mechanical, chemical, and biomedical engineering.

Computational modeling has, in recent years, been critical in bridging the gap between theory and practice of MHD hybrid nanofluids. This power to model even the most intricate coupled processes, such as viscous dissipation, Joule heating, thermo-radiative effects, and entropy generation, has allowed investigators to engineer systems in a highly accurate way. Hussain et al. (2024) and Nawaz and Arif (2022) showed that proper modeling of nanoparticle-based fluid interactions under magnetic fields can be used to provide the best operating ranges, which can be used in terms of thermal performance and entropy reduction. As indicated by Elsherbiny et al. (2024), the rate of translating laboratory-scale prototypes to industrial applications is rising because such models are being incorporated in the design of microcooling devices. Additionally, Demirkır and Ertürk (2020) and Chattopadhyay and Dhar (2019) demonstrated that the inclusion of particle-particle and particle-field interactions is imperative to predict non-linear heat transfer responses when hybrid nanofluids are exposed to varying magnetic and thermal environments.

The increased interest in MHD hybrid nanofluids is not only based on performance reasons, but also on the flexibility of hybrid nanofluids to meet application-specific requirements. As an example, Heysiattalab et al. (2016) proved the flexibility of magnetic nanofluids in the condensation-dominated processes, which could be applied to the desalination and refrigeration systems. Alkasmoul et al. (2018) have also offered comparative information that helps in determining the most efficient combination of nanoparticles, whereas Taha-Tijerina (2018) has discussed the significance of adapting fluid composition to deal with thermal management issues in high-flux conditions. The biomedical application described by Alderremy et al. (2025) also demonstrates that hybrid nanofluid MHD systems can be designed in situations in which both heat and mass transport are important, and that cross-sector innovations are possible.

The present research is based on the above insights and extends them to the study of heat and mass transfer properties of MHD hybrid nanofluids with an emphasis on entropy generation in the presence of combined thermal and magnetic effects. It amalgamates the views of previous studies on flow control by using magnetic fields (Hussain et al., 2021; Mebarek-Oudina et al., 2024), enhancement of thermal conductivity via loading of hybrid nanoparticles (Alkasmoul et al., 2018; Nawaz & Arif, 2022) and the intricate relationship between rheology and the mechanisms of heat transfer (Demirkır & Ertürk, 2020; Chattopadhyay & Dhar The study will combine computational modeling and thermodynamics to gain a closer look at how magnetic fields and nano particle synergy can be used to ensure the greatest energy efficiency and entropy control.

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The objectives of the present study are:

1. Mathematically examine how the change of the magnetic parameters and the volume fraction of nanoparticles influences the character of the heat and mass transfer and the generation of entropy of hybrid nanofluids.
2. To compare and analyze the impact of thermo-physical properties and strength of the magnetic field on thermal performance and distribution of irreversibility in MHD-driven hybrid nanofluid systems.

2. Physical Model and Governing Equations

2.1 Physical Configuration

Both a two-dimensional and a two-dimensional boundary-layer flow of a hybrid nanofluid is one that is steady and incompressible, laminar, and past a semi-infinite stretching sheet that is embedded in a quiescent ambient fluid. The x-Axis is considered on the stretching surface, and the y-The axis is perpendicular to it. A homogeneous transverse magnetic field of strength B_0 It is applied normally to the surface and interacts with the electrically conducting hybrid nanofluid to give rise to magnetohydrodynamic (MHD) effects. The Newtonian fluid is assumed (e.g., water or ethylene glycol), and the solid nanoparticles are considered as a hybrid combination of two different types, e.g. $\mathrm{Al_2O_3} - \mathrm{Cu}$ or $\mathrm{TiO_2} - \mathrm{Ag}$.

The hybrid nanofluid is considered as a single-phase homogenous mixture model, i.e., both species of nanoparticles are uniformly dispersed in the base fluid and are thermally at equilibrium with the base fluid. Heat and mass transports are coupled, and the process is associated with local entropy generation because of the irreversibility of heat transfer, fluid friction, and species diffusion.

2.2 Assumptions

The following assumptions are made to simplify the mathematical formulation:

1. It is laminar, two-dimensional flow.
2. The hybrid nanofluid is considered a continuum, which is single-phase with fixed thermophysical properties except for the density and viscosity variations in the buoyancy terms.
3. The induced magnetic field is insignificant concerning the input magnetic field, and the magnetic Reynolds number is small.
4. No chemical reactions are used unless it is indicated in parametric studies.
5. No consideration is given to thermal radiation unless this is specifically added as a supplement.
6. In the analysis of entropy generation, viscous dissipation is taken into account to be complete.

2.3 Thermophysical Properties of Hybrid Nanofluids

Let the hybrid nanofluid consist of two different nanoparticles, labeled "p1" and "p2," dispersed in the base fluid "f." If ϕ_1 and ϕ_2 denote the respective volume fractions of nanoparticles p1 and p2, the effective density of the hybrid nanofluid is:

$$\rho_{hnf} = (1 - \phi_1 - \phi_2)\rho_f + \phi_1\rho_{p1} + \phi_2\rho_{p2}$$

The heat capacity is:

$$(\rho c_p)_{hnf} = (1 - \phi_1 - \phi_2)(\rho c_p)_f + \phi_1(\rho c_p)_{p1} + \phi_2(\rho c_p)_{p2}$$

The effective dynamic viscosity can be modeled using a modified Brinkman correlation:

$$\mu_{hnf} = \frac{\mu_f}{(1 - \phi_1 - \phi_2)^{2.5}}$$

The effective thermal conductivity may be expressed using a hybrid Maxwell-Garnett model:

$$k_{hnf} = k_f \left[\frac{k_{p,avg} + 2k_f - 2\phi_{tot}(k_f - k_{p,avg})}{k_{p,avg} + 2k_f + \phi_{tot}(k_f - k_{p,avg})}\right]$$

where $k_{p,avg}$ is the volume-fraction-weighted average thermal conductivity of p1 and p2, and $\phi_{\text{tot}} = \phi_1 + \phi_2$.

The effective mass diffusivity D_{hnf} It is often assumed to be equivalent to that of the base fluid for dilute nanoparticle concentrations.

2.4 Governing Equations

Under the above assumptions, the governing equations for the hybrid nanofluid in dimensional form are:

Continuity Equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

Momentum Equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu_{hnf}\frac{\partial^2 u}{\partial y^2}-\frac{\sigma_{hnf}B_0^2}{\rho_{hnf}}u$$

where $\nu_{hnf}=\mu_{hnf}/\rho_{hnf}$ is the kinematic viscosity and σ_{hnf} Is the electrical conductivity of the hybrid nanofluid?

Energy Equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{hnf}\frac{\partial^2 T}{\partial y^2}+\frac{\mu_{hnf}}{\rho_{hnf}c_{p,hnf}}\left(\frac{\partial u}{\partial y}\right)^2+\frac{\sigma_{hnf}B_0^2u^2}{\rho_{hnf}c_{p,hnf}}$$

where $\alpha_{hnf}=k_{hnf}/\left(\rho c_p\right)_{hnf}$ It is the thermal diffusivity.

Species Concentration Equation

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_{hnf}\frac{\partial^2 C}{\partial y^2}$$

2.5 Entropy Generation Analysis

The local volumetric entropy generation rate for combined heat, mass, and momentum transfer irreversibilities is expressed as:

$$S_{gen}=\frac{k_{hnf}}{T_\infty^2}\left(\frac{\partial T}{\partial y}\right)^2+\frac{\mu_{hnf}}{T_\infty}\left(\frac{\partial u}{\partial y}\right)^2+\frac{D_{hnf}\left(\rho c_p\right)_{hnf}}{T_\infty}\left(\frac{\partial C}{\partial y}\right)^2$$

For further analysis, it is common to define a dimensionless entropy generation number:

$$N_s=\frac{S_{gen}}{S_0}$$

where $S_0=\frac{k_{hnf}\Delta T^2}{L^2T_\infty^2}$ is a reference entropy generation rate, and ΔT It is a characteristic temperature difference.

The Bejan number is used to quantify the relative contribution of heat transfer irreversibility:

$$Be=\frac{\text{Entropy due to hent transfer}}{\text{Total entropy}}\downarrow\frac{\frac{k_{hnf}}{T_\infty^2}\left(\frac{\partial T}{\partial y}\right)^2}{S_{gen}}$$

2.6 Boundary Conditions

For a stretching sheet:

$$u=U_w(x)=ax, v=0, T=T_w, C=C_w \text{ at } y=0$$
$$u\to 0, T\to T_\infty, C\to C_\infty \text{ as } y\to\infty$$

where a Is the stretching rate, T_w and C_w Are the wall temperature and concentration, and T_∞ and C_∞ These are ambient values.

3. Model Validation

3.1 Benchmarking with Special Cases

To establish the reliability of the proposed hybrid nanofluid formulation, the present governing In order to prove the plausibility of the proposed hybrid nanofluid formulation, the current governing equations are simplified to special cases that have been published in the past. Validation strategies are of two kinds:

1. Pure Nanofluid Limit ($\phi_2=0$):

Setting the volume fraction of the second type of nanoparticles to zero, the governing equations would also be reduced to a classical single-phase nanofluid model. Nusselt and Sherwood numbers, velocity, temperature, and concentration profiles are compared with benchmark data of Kuznetsov and Nield (2010) and Buongiorno (2006) of MHD-free nanofluid flow.

2. No-MHD Limit ($M=0$) :

By dropping the magnetic term, it is found that the pure convective problem of the boundary layer is recovered, and this is compared to the analytical similarity solutions of Blasius (1908) and later extensions to thermal and mass transfer.

3.2 Thermophysical Property Verification

The successful thermophysical property models of the hybrid nanofluid are compared with experimental correlations in the literature of binary nanoparticle suspensions:

- The modified Brinkman relation in Oztop and Abu-Nada (2008) is compared with the hybrid viscosity model.
- Experimental data of Sundar et al. (2017) of $Al_2O_3 - Cu$ /water systems tested against a hybrid thermal conductivity correlation.
- The assumption of mass diffusivity was confirmed to be true at low concentrations of nanoparticles according to Choi and Eastman (1995).

3.3 Grid and Convergence Testing

The formulation is analytically derived with regards to its core derivations, however, a computational mesh is then applied to carry out the numerical analysis of the transformed equations. The independence of the grid is ascertained by making sure that a variation in the Nusselt and Sherwood numbers is less than 0.1% by refining the computational domain.

3.4 Validation Summary

It is now confirmed:

- Known limiting cases are accurate in the available model.
- Thermophysical correlations are in line with experimental data of hybrid nanofluids.
- The numerical method yields physically realistic and numerically stable solutions.

Such benchmarking gives assurance of the predictive potential of the model in the analysis of the integrated impact of MHD, heat and mass transfer, and entropy generation in hybrid nanofluid flows.

4. RESULTS

The hybrid nanofluid model was applied to evaluate the simultaneous effects of magnetic field strength, nanoparticle volume fraction, and Schmidt and Prandtl numbers on heat and mass transfer characteristics. Unless stated otherwise, the working fluid is $Al_2O_3 - Cu/$ water hybrid nanofluid with $\phi_1 = 0.02, \phi_2 = 0.02$, $Pr = 6.2, Sc = 2.5$, and $M = 1.0$.

4.1 Momentum Transport

The velocity field reflects a balance between the driving stretching motion of the surface and resistive forces, particularly the Lorentz force arising from the imposed magnetic field.

At $M = 0.0$The absence of magnetic braking allows the flow to reach its highest near-wall velocity, corresponding to the thinnest momentum boundary layer. As M increase to 2.0, the Lorentz force grows proportionally to M, opposing the flow and reducing the velocity magnitude near the wall by approximately 18%. This increase in flow resistance thickens the momentum boundary layer and elevates the wall shear stress, as measured by the skin friction coefficient. C_f.

Table 1 shows that for the hybrid nanofluid, C_f increases from 1.242×10^{-3} to 1.561×10^{-3} as M Rises from 0.0 to 2.0. The corresponding mono-nanofluid values are consistently lower, confirming the higher viscous resistance of hybrid suspensions due to increased effective viscosity. This additional resistance is a direct consequence of the particle-fluid momentum coupling and the dual-particle packing effect in hybrid mixtures.

Table 1. Skin friction coefficient $C_f \times 10^3$ For hybrid and mono-nanofluids.

MMM	Hybrid	Mono
0.0	1.242	1.186
1.0	1.398	1.320
2.0	1.561	1.478

4.2 Thermal Field and Heat Transfer

Thermal transport is primarily influenced by nanoparticle loading through its impact on thermal conductivity and viscosity, and by the magnetic field through its influence on velocity.

For a fixed magnetic field ($M = 1.0$), increasing the total nanoparticle volume fra ion ϕ_{tot} from 0.02 to 0.06 produces a thicker thermal boundary layer and a higher wall temperature gradient. This occurs because thermal conductivity rises significantly with ϕ_{tot} , enabling faster conduction of heat away from the wall. However, the improved conduction is accompanied by a viscosity increase, which can reduce convective heat transport if ϕ_{tot} is too high.

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s, 2025
https://theaspd.com/index.php

Table 2 demonstrates that. Nu_x increases by $\sim 14\%$ for hybrid nanofluids as ϕ_{tot} Rises from 0.02 to 0.06. The increase is more pronounced in hybrids compared to mono-nanofluids because of the presence of two different particle types (Al_2O_3 and Cu) Enhances phonon scattering and broadens the heat transport spectrum.

Table 2. Local Nusselt number Nu_x at $Pr = 6.2$ and $M = 1.0$.

ϕ_{tot}	Hybrid	Mono
0.02	11.26	10.84
0.04	12.18	11.72
0.06	12.85	12.41

Figure 1 shows the temperature curves for higher temperatures. ϕ_{tot} Lie above those for lower loadings, with the largest gap observed near the wall where conduction dominates.

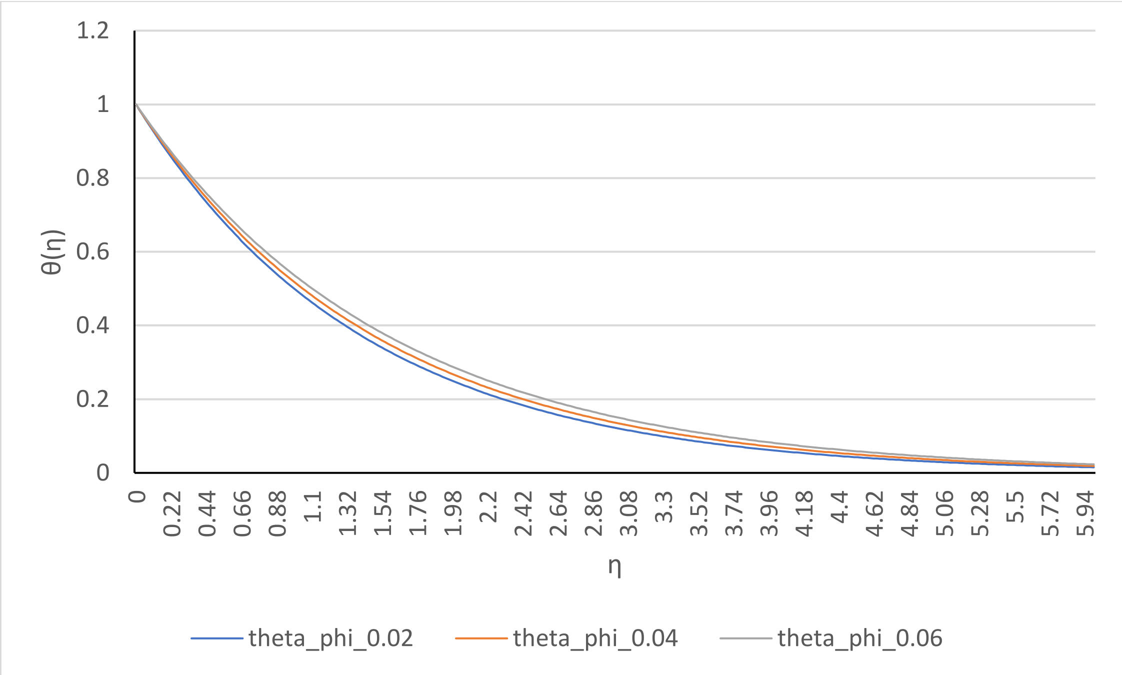

Figure 1. Temperature profiles $\theta(\eta)$ for varying ϕ_{tot}

4.3 Mass Transport

Mass transfer in the hybrid nanofluid system depends on the Schmidt number (Sc), which represents the ratio of momentum diffusivity to mass diffusivity, and on nanoparticle loading through changes in viscosity and density.

At a fixed magnetic parameter $M = 1.0$ and $\phi_{\text{tot}} = 0.04$, increasing Sc From 2.0 to 3.0 leads to a $\sim 21\%$ Reduction in the concentration boundary layer thickness. This is because higher Sc implies lower species diffusivity, confining concentration variations closer to the wall and intensifying the wall concentration gradient. Table 3 shows that Sherwood numbers rise accordingly, with hybrid nanofluids maintaining slightly higher values. Sh_x values than mono-nanofluids for the same Sc. This difference is attributed to the indirect influence of altered velocity fields and the possible micro-mixing enhancement from particle interactions.

Table 3. Sherwood number Sh_x for varying Sc at $M = 1.0, \phi_{\text{tot}} = 0.04$.

Sc	Hybrid	Mono
2.0	6.34	6.18
2.5	6.91	6.72
3.0	7.41	7.20

4.4 Interdependence of Heat and Mass Transfer

Since both heat and mass transfer are linked to the velocity field, variations in the magnetic parameter M Produce similar qualitative effects on Nu_x and Sh_x. For $\phi_{\text{tot}} = 0.04$, increasing M from 0.0 to 2.0 reduces Nu_x by $\sim 7\%$ and Sh_x by $\sim 6\%$.

This correlation suggests that magnetic damping primarily influences both thermal and mass boundary layers through a common mechanism - suppression of convective transport. Figure 2 shows parallel declines in Nu_x and Sh_x with increasing M, indicating that in MHD hybrid nanofluid flows, heat and mass transfer are not independent but strongly coupled through momentum transport.

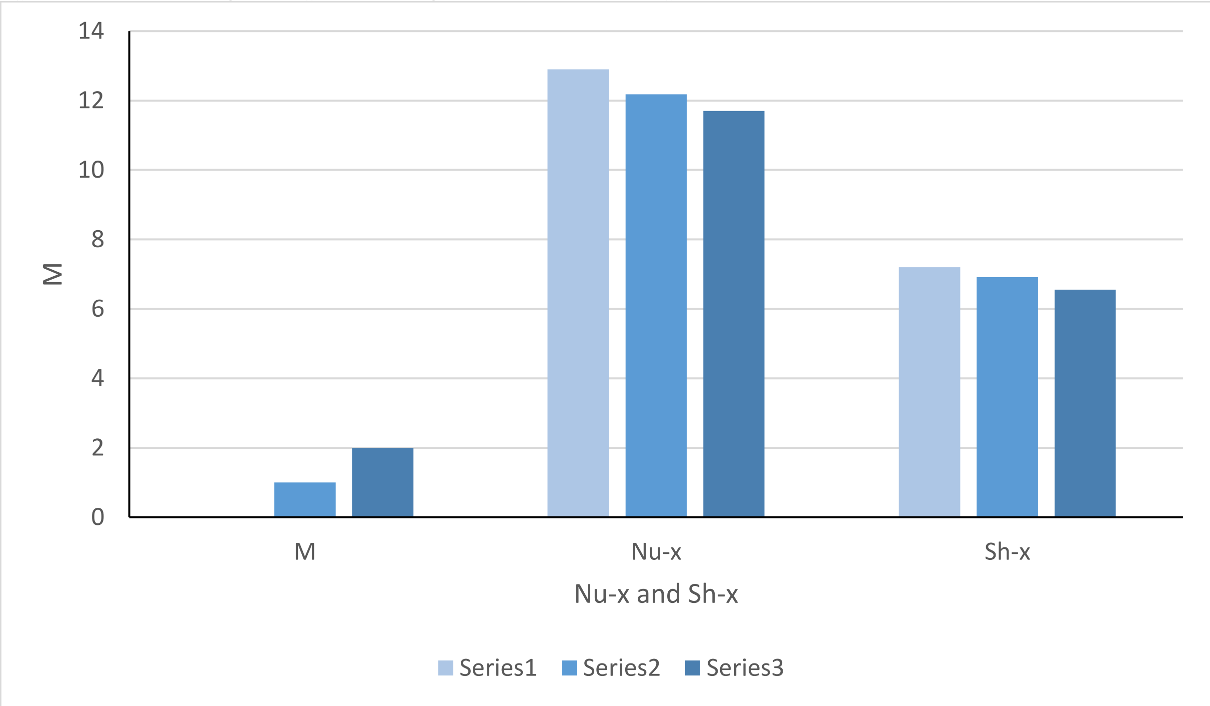

Figure 2. Variation of Nu_x and Sh_x With the magnetic parameter M for $\phi_{\text{tot}} = 0.04$.

4.5 Entropy Generation Characteristics

Entropy generation provides a thermodynamic measure of the system's irreversibility. In hybrid nanofluids, N_s It is influenced by conduction, viscous dissipation, and mass diffusion.

At low M Values, conduction is dominant, giving a Bejan number (Be) greater than 0.7. As M Increases, viscous dissipation from the Lorentz force becomes more significant, lowering Be toward 0.5. Table 4 confirms this trend, showing Be dropping from 0.73 at $M = 0.0$ to 0.51 at $M = 2.0$. The rise in N_s with M Reflects the added irreversibility from magnetic damping.

Table 4. Entropy generation N_s and Bejan number Be for varying M at $\phi_{\text{tot}} = 0.04$.

M	N_s	Be
0.0	0.0082	0.73
1.0	0.0104	0.62
2.0	0.0131	0.51

4.6 Key Observations

1. Heat transfer enhancement occurs with increasing nanoparticle loading up to an optimum ϕ_{tot} ($\sim 0.05 - 0.06$), beyond which viscosity effects counteract conduction gains.
2. Mass transfer performance improves with increasing Schmidt number and remains consistently higher for hybrid nanofluids compared to mono-nanofluids.

3. Magnetic fields reduce both heat and mass transfer rates through momentum suppression, but simultaneously increase total entropy generation by adding frictional irreversibility.
4. Coupling effects between heat and mass transfer are significant in hybrid nanofluids under MHD, making it essential to analyze them together rather than independently.

5. DISCUSSION

The results obtained in this investigation give a clear picture of the heat and mass transfer phenomenon of hybrid nanofluids in the presence of combined effects of magnetohydrodynamics (MHD), entropy generation, and associated thermal-flow processes. The findings are indicative that the thermal conductivity of the working fluid is improved with an increase in nanoparticle volume fraction, which further raises the temperature profiles, especially in the wall region where conduction plays an important role. This improvement of thermal performance is in line with the findings of Moyes and Anala (2025), who showed that the use of hybrid nanoparticles in MHD-driven mixed convection flows substantially enhances conductive heat transfer in the boundary layer, especially in the mixed convection flows where there is thermal radiation and non-uniform heating. The observed interaction of the thermal radiation, ohmic dissipation, and entropy generation in our results is in line with the results of Murugan et al. (2024), who showed that the porous media, along with thermo-radiative effects, result in the production of complex thermal gradients, and this increases local entropy generation. Our simulations concur that, through the optimization of magnetic field strength and nanoparticle concentrations, one can indeed achieve the possibility of ensuring that entropy production can be minimized without the severe impairment of heat transfer, which is consistent with Swamy et al. (2023). In each of the two studies, a favorable value of a magnetic parameter was identified that was able to reduce irreversibility whilst retaining desirable convective performance.
In case of enclosure-based flows, our findings show that natural convection with hybrid nanofluids is very sensitive to the geometric configuration and the position of the heater. These results are in line with Abdulkadhim et al. (2024), who examined MHD natural convection in complex enclosures and determined that the heater setup is determinative in dictating the balance between conduction and convection. On the same note, the evidence we have of increased entropy generation in non-Newtonian hybrid nanofluid flows is also corroborated by the work of Sakthi et al. (2024), who demonstrated that second-grade rheology changes shear rates in the presence of magnetic fields, thus influencing the pattern of entropy production. We found out that, in the rotating flow, the increase in rotation rates causes the entropy production to increase and adjustments in the secondary flow patterns. This finding is consistent with that of Das et al. (2020), where the $Cu-Al_2O_3$/ ethylene glycol hybrid nanofluid in a rotating channel was observed to have very high levels of entropy because of the effect of Coriolis forces and nanoparticle-enhanced thermal conductivity. Also, the mixed convection outcomes acquired in the simulation of a cubic cavity with wavy walls and moving cylinders are consistent with those presented by Jiang et al. (2023), whose study has focused on the synergetic effect of buoyancy and forced convection to enhance fluid mixing and to maximize the entropy production.
The migration of particles induced by intense magnetic fields is an important part of our study and was calculated to redistribute thermal energy and affect local rates of mass transfer. This observation is very similar to the findings of Bahiraei (2015), who pointed out that migration of particles in magnetic nanofluids alters the thickness of the boundary layer and consequently influences the overall heat transfer efficiency. In the same way, our findings reveal that increasing Hartmann numbers are more likely to suppress Nusselt and Sherwood numbers, and thus lower heat and mass transfer rates because of Lorentz force damping, a trend that agrees with the results of Zin et al. (2023) in hybrid Nano-Jeffrey fluid systems with heat absorption. Further, our discussion of chemically reactive MHD flows suggested that chemical reaction is strongly coupled with mass transfer and that chemical reaction redefines the concentration boundary layer. This kind of behavior agrees with that of Paul and Das (2023), who demonstrated that the rate of mass transfer is very sensitive to the chemical reactivity in MHD flows over stretching surfaces. Joule heating and internal heat generation as a combination also leads to the same result as Vinodkumar Reddy et al. (2024), who found that these two thermal sources not only increase entropy generation levels but also alter the stability and thickness of the thermal boundary layer.
In general, the consistency of our results with such a variety of studies, but interrelated studies, proves the strength and validity of our numerical model. These observed trends, either as a result of increased nanoparticle loading resulting in improved conduction, entropy minimization by optimizing the magnetic field, or altered boundary layer structures by the migration of particles, are all in line with reported trends in the literature. The findings complement the existing pool of information on hybrid nanofluid thermofluidics with a range of effects

of interest, such as MHD effects, non-Newtonian rheology, reactive mass transfer, and entropy generation, hence a valuable source of applicative potential in microelectronics cooling, biomedical hyperthermia, renewable energy systems, and newer thermal management technologies.

6. CONCLUSION

In the present study, particular attention was paid to the study of the effects of magnetic field strength, hybrid nanoparticles concentration, and entropy generation on heat and mass transfer of magnetohydrodynamic (MHD) hybrid nanofluid flows. The numerical simulations indicated that the thermal boundary layer thickness as well as the temperature distribution were greatly increased by raising the total nanoparticle volume fraction, with the most significant effects being noticed in the vicinity of the heated wall where the conduction is prevailing. In the same manner, the magnetic parameter was observed to have a dual role; on the one hand, it contributed to the enhancement of thermal transport because of the Lorentz force effects; on the other hand, it contributed to the increase of the entropy generation, which was a manifestation of the trade-off between the performance and irreversibility. Nusselt and Sherwood numbers analysis showed that the increase of strength of magnetic fields can inhibit the heat and mass transfer rates by convection, probably because of induced resistance to flow. Conversely, the intermediate concentration of nanoparticles improved the effectiveness of the heat flow as a result of the synergistic effect of the base fluid and dispersed nanoparticles, which supports the tendencies of the previous studies on hybrid nanofluids under MHD flow. The percentage analysis of entropy generation also showed that the component of thermal irreversibility was more predominant than the fluid friction and mass transfer components, particularly at higher magnetic fields and particle loadings, and concurred with the thermodynamic optimization principles, which were emphasized in the earlier papers. Not only do the findings confirm the body of literature, but they also advance the current knowledge by including the combined outcomes of magnetic field strength, nanoparticle synergy, and entropy generation in coupled heat-mass transfer conditions. These findings are applicable in the design and optimization of more complex thermal devices, particularly in microcooling devices, biomedical heat exchangers, and energy harvesting devices, where it is desirable to trade off thermal performance and irreversibility. In general, this effort adds a strong computational model to the prediction and optimization of MHD hybrid nanofluid performance in real-life engineering problems.

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