

Fractional Calculus-Based Analysis of Magneto-Thermal Nanofluid Flow Over Stretching and Shrinking Surfaces

Bibhu Prasad Ganthia^{1,*}, Subash Ranjan Kabat²

Abstract

This study presents a comprehensive investigation of magneto-thermal hybrid nanofluid flow over stretching and shrinking surfaces using a fractional calculus framework to capture the memory and hereditary characteristics of complex fluid transport phenomena. The proposed model incorporates the effects of magnetic field intensity, thermal radiation, viscous dissipation, Brownian motion, and thermophoretic diffusion on the velocity and temperature distributions within the boundary layer region. A fractional-order derivative formulation is employed to provide a more realistic representation of anomalous heat and momentum transport compared with conventional integer-order models. The controlling nonlinear partial differential equations are transformed into coupled ordinary differential equations via similarity transformations, and an effective computational approach is used to solve these equations numerically. The influence of fractional order parameters, Hartmann number, nanoparticle volume fraction, and stretching/shrinking rates on skin friction coefficient and Nusselt number is analyzed in detail. Results reveal that increasing magnetic field strength suppresses fluid velocity while enhancing thermal boundary layer thickness, whereas fractional parameters significantly modify the transport characteristics due to memory effects. The findings demonstrate the potential applicability of fractional nanofluid models in advanced cooling systems, microfluidic devices, solar thermal collectors, and energy transport technologies, thereby improving predictive accuracy for practical engineering applications significantly overall.

Keywords: Fractional calculus, magneto-thermal flow, hybrid nanofluids, stretching surface, shrinking surface, thermal radiation, magnetohydrodynamics (MHD), heat transfer

INTRODUCTION

The rapid advancement of modern thermal engineering systems, microelectronics cooling technologies, energy conversion devices, and advanced manufacturing processes has significantly increased the demand for accurate mathematical models capable of describing complex transport phenomena in fluid systems. Conventional Newtonian fluid models based on classical integer-order

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derivatives often fail to capture the memory-dependent and hereditary characteristics observed in many practical fluids, particularly in nanofluids, viscoelastic materials, biological fluids, and porous media transport systems. Fractional calculus has emerged as an effective mathematical framework for overcoming these limitations by introducing non-local operators that account for historical effects and anomalous diffusion processes occurring within fluid flow and heat transfer systems. Fractional-order models provide improved flexibility and accuracy in representing thermal conductivity enhancement, momentum transport, and energy dissipation mechanisms, thereby offering a more realistic description of

practical engineering applications than traditional models. Nanofluids, which consist of nanosized solid particles suspended in conventional base fluids such as water, ethylene glycol, or oil, have attracted considerable attention owing to their superior thermal properties and enhanced heat transfer performance. The inclusion of metallic and metal oxide nanoparticles significantly improves thermal conductivity, making nanofluids promising candidates for applications in solar collectors, heat exchangers, nuclear reactors, cooling of electronic components, biomedical devices, and aerospace thermal management systems. Simultaneously, magnetohydrodynamic effects have become increasingly important in industrial processes involving electrically conducting fluids, where externally applied, magnetic fields are utilized to control flow behavior, suppress turbulence, regulate heat transfer rates, and improve system stability. The study of magneto-thermal nanofluid flow over stretching and shrinking surfaces is particularly relevant because such boundary configurations are frequently encountered in extrusion processes, polymer sheet manufacturing, glass fiber production, metal spinning, coating technologies, and continuous casting operations. Stretching surfaces generally promote boundary layer thinning and improved heat transfer, whereas shrinking surfaces induce flow reversal and complex recirculation regions that require sophisticated analytical treatment. The interaction among magnetic forces, thermal gradients, nanoparticle motion, and surface deformation introduces highly nonlinear transport characteristics that cannot be adequately represented by classical fluid models alone. Consequently, the integration of fractional calculus with magnetohydrodynamic nanofluid theory provides an attractive and innovative approach for investigating these coupled phenomena. The primary objective of the present research is to develop a fractional calculus-based mathematical model for magneto-thermal nanofluid flow over stretching and shrinking surfaces while incorporating the effects of magnetic field intensity, thermal radiation, viscous dissipation, Brownian motion, thermophoretic diffusion, and nanoparticle concentration. Similarity transformations are employed to convert the governing nonlinear partial differential equations into a dimensionless form suitable for numerical computation, and the influence of fractional order parameters on velocity and temperature distributions is systematically investigated. Furthermore, important engineering quantities including skin friction coefficient and Nusselt number are evaluated to assess surface drag and thermal performance under varying operating conditions. The major contribution of this study lies in establishing a generalized fractional-order framework capable of accurately representing memory-dependent transport mechanisms and providing new physical insights into the optimization of advanced thermal systems employing nanofluids under magnetic environments. The outcomes of this work are expected to contribute significantly to the design of next-generation cooling systems, smart manufacturing processes, microfluidic technologies, and renewable energy applications.

LITERATURE REVIEW

The investigation of magnetohydrodynamic (MHD) nanofluid transport over stretching and shrinking surfaces has attracted significant research interest owing to its applications in polymer extrusion, wire drawing, glass manufacturing, thermal processing, and electronic cooling systems. Classical MHD nanofluid models primarily focus on the interaction between electrically conducting fluids and externally applied magnetic fields, where Lorentz forces modify momentum transport and influence heat transfer performance. Recent studies have incorporated thermal radiation, chemical reactions, Brownian diffusion, thermophoresis, and viscous dissipation to improve the accuracy of transport predictions under practical operating conditions. For example, Williamson nanofluid flow over an exponentially stretching surface in the presence of thermal radiation and chemical reaction effects demonstrated that magnetic fields suppress fluid velocity while enhancing the thermal boundary layer thickness and concentration profiles [1]. Similarly, the thermal transport characteristics of nanofluids flowing over stretching surfaces under magnetic field effects and reported a significant enhancement in heat transfer performance owing to nanoparticle dispersion and electromagnetic control mechanisms [2]. Despite these advances, conventional integer-order fluid models often cannot accurately represent memory-dependent diffusion and hereditary transport mechanisms frequently observed in complex fluids, porous media, and nanoscale heat transfer systems. To address these limitations, fractional calculus has emerged as an important mathematical tool for modeling anomalous diffusion and non-

local transport phenomena in fluid mechanics. Fractional differential operators provide additional degrees of freedom through fractional-order parameters, enabling more realistic descriptions of viscoelasticity, thermal lagging behavior, and history-dependent momentum transfer. One of the pioneering fractional nanofluid models for natural convection flow over an isothermal vertical plate with thermal radiation demonstrated that fractional-order derivatives significantly influence velocity and temperature distributions and improve agreement with experimental observations [3]. The increasing use of physics-based computational approaches in spintronic and magneto-electric systems further highlights the importance of integrating physical laws with advanced mathematical models for improved predictive capability [4]. Probabilistic and stochastic device models have also shown the effectiveness of incorporating memory and nonlocal effects in nonlinear engineering systems [5]. Recent developments in magnetic logic architectures, spin-orbit devices, and reconfigurable magnetic computing systems provide additional evidence that fractional and physics-informed modeling frameworks can substantially improve the representation of coupled electromagnetic phenomena [6–12]. Furthermore, nonlinear system identification, adaptive control, and signal reconstruction methodologies have demonstrated the growing importance of advanced mathematical frameworks in engineering analysis and optimization [13–21]. Although substantial progress has been achieved in both MHD nanofluid modeling and fractional fluid mechanics independently, only limited studies have attempted to combine fractional-order transport theory with magneto-thermal nanofluid flow over stretching and shrinking surfaces under realistic industrial conditions. Existing studies generally neglect the simultaneous influence of magnetic field intensity, thermal radiation, nanoparticle diffusion, and fractional memory effects within a unified framework. Moreover, the behavior of shrinking surfaces, which often generate flow reversal and dual solution characteristics, remains insufficiently explored in fractional nanofluid systems. Therefore, the present study proposes a generalized fractional calculus-based magneto-thermal nanofluid model that incorporates memory-dependent heat and momentum transport together with magnetic field effects, thermal radiation, Brownian motion, and thermophoretic diffusion. The novelty of the work lies in establishing a comprehensive fractional-order mathematical formulation capable of capturing anomalous transport behavior while providing improved physical insight into the optimization of advanced cooling systems, microfluidic devices, smart manufacturing processes, renewable energy systems, and high-performance thermal management applications [2].

MATHEMATICAL FORMULATION AND NUMERICAL METHODOLOGY

The present study developed a comprehensive fractional-order magneto-thermal nanofluid model to investigate fluid transport over stretching and shrinking surfaces under the combined influence of magnetic field effects and thermal transport mechanisms. The physical model considers a steady, two-dimensional, incompressible, and electrically conducting nanofluid flowing over a continuously deforming surface embedded in a thermally active environment. The transport process incorporates the influence of magnetic forces, nanoparticle diffusion, thermal radiation, viscous heating, Brownian motion, and thermophoretic effects to simulate realistic industrial operating conditions. Unlike conventional integer-order formulations, the proposed approach employs fractional-order operators to represent the memory-dependent and hereditary characteristics associated with momentum and heat transfer in complex nanofluids. This fractional framework enables improved modeling of anomalous diffusion phenomena and non-local transport behavior that frequently arise in micro-scale thermal systems and advanced cooling applications.

Governing Equations for Fractional Magneto-Thermal Nanofluid Flow

The governing model consists of coupled conservation principles associated with mass transport, momentum transport, thermal energy transport, and nanoparticle concentration distribution within the boundary layer region. The momentum transport formulation accounts for the interaction between viscous forces and electromagnetic body forces generated by the externally applied magnetic field. The thermal transport model includes conductive heat transfer, radiative heat exchange, internal energy dissipation, and thermal diffusion caused by nanoparticle movement. Nanoparticle transport is further influenced by Brownian motion and thermophoretic migration due to temperature gradients. Fractional differential operators are introduced into the momentum and thermal transport formulations to capture

the influence of historical states on present fluid behavior. Consequently, the resulting model provides a more realistic representation of transport processes in comparison with conventional classical fluid formulations.

The mathematical model is developed based on the conservation principles of mass, momentum, and thermal energy for an incompressible electrically conducting nanofluid subjected to an external magnetic field.

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha_f D_y^\beta \left(\frac{\partial T}{\partial y} \right) + \tau \left[D_B \frac{\partial C}{\partial y} \frac{\partial T}{\partial y} + \frac{D_T}{T_\infty} \left(\frac{\partial T}{\partial y} \right)^2 \right]$$

where D denote fractional derivatives of order α and β , respectively.

Similarity Transformations and Non-Dimensional Parameters

To simplify the analysis and reduce computational complexity, suitable similarity transformations are employed to convert the original boundary-layer problem into a dimensionless form. This transformation process reduces the number of independent variables and allows the transport characteristics to be represented through a set of important governing parameters. The resulting dimensionless quantities describe the relative importance of the magnetic field strength, thermal diffusion, nanoparticle concentration, viscous effects, radiation intensity, and fractional memory characteristics within the flow field. Additional parameters are introduced to characterize the Brownian motion effects, thermophoretic transport, stretching and shrinking intensity, and thermal conductivity enhancement due to nanoparticle suspension. The dimensionless framework facilitates parametric analysis and enables direct comparison of transport behavior under varying physical conditions and engineering applications.

The important non-dimensional parameters are:

$$M = \frac{\sigma B_0^2}{\rho a}$$

$$Pr = \frac{\nu}{\alpha_f}$$

$$Nb = \frac{\tau D_B (C_w - C_\infty)}{\nu}$$

representing the magnetic parameter, Prandtl number, and Brownian motion parameter, respectively.

Numerical Solution Procedure and Computational Algorithm

The transformed system of coupled nonlinear equations was solved using a robust numerical approach capable of handling strong nonlinear interactions and fractional-order effects. An iterative computational strategy was employed to obtain convergent solutions for the velocity, temperature, and concentration distributions throughout the computational domain. Appropriate convergence criteria were established to ensure numerical stability and solution accuracy. Grid independence analysis and validation procedures were performed to verify the reliability of the computational results. The algorithm systematically evaluated the influence of magnetic field intensity, fractional order parameters, nanoparticle concentration, thermal radiation, and surface stretching or shrinking rates on fluid transport characteristics. Performance indicators, such as surface drag behavior and heat transfer capability, were subsequently extracted from the converged numerical solutions for engineering interpretation. The adopted computational methodology provides an efficient and reliable framework for investigating complex magneto-thermal nanofluid systems exhibiting memory-dependent transport behavior and nonlinear coupling effects.

The transformed nonlinear fractional equations are solved using a numerical iterative algorithm.

Local Nusselt number:

$$Nu_x = -\frac{x}{T_w - T_\infty} \left(\frac{\partial T}{\partial y} \right)_{y=0}$$

Sherwood number:

$$Sh_x = -\frac{x}{C_w - C_\infty} \left(\frac{\partial C}{\partial y} \right)_{y=0}$$

These equations provide the mathematical foundation for analyzing the influence of magnetic field strength, fractional order parameters, nanoparticle concentration, and thermal effects on the transport characteristics of magneto-thermal nanofluid flow over stretching and shrinking surfaces.

The numerical input shown in Table 1 was carried out using representative thermo-physical and flow parameters corresponding to water-based electrically conducting nanofluids under magnetohydrodynamic conditions. The fractional orders of momentum and thermal transport were selected as 0.85 and 0.90 to capture memory-dependent diffusion effects and non-local transport behavior. A moderate magnetic parameter of 2.0 and magnetic field strength of 0.5 T were chosen to investigate Lorentz force interactions without inducing excessive flow suppression. The Prandtl number of 6.2 represents water-based nanofluids commonly used in thermal management systems. Brownian motion and thermophoretic parameters were incorporated to model nanoparticle migration and heat transport enhancement mechanisms. Thermal radiation and viscous dissipation effects were included to emulate high-temperature industrial environments such as polymer extrusion, solar thermal collectors, and electronic cooling systems. The numerical algorithm employed a convergence tolerance of 10^{-6} to ensure solution stability and computational accuracy for all simulation cases.

Figure 1 illustrates the overall MATLAB/Simulink computational framework developed for analyzing the fractional magneto-thermal nanofluid flow over stretching and shrinking surfaces under magnetohydrodynamic conditions. The model begins with the specification of thermo-physical input parameters, including fluid density, viscosity, electrical conductivity, magnetic field intensity, fractional derivative orders, nanoparticle concentration, Brownian motion coefficient, thermophoretic parameter, radiation parameter, and surface temperature conditions. These parameters are subsequently transformed into a dimensionless form using similarity transformations to simplify the governing transport equations and reduce computational complexity. The transformed fractional-order momentum, energy, and concentration equations are then implemented in the Simulink environment as coupled nonlinear dynamic subsystems. Appropriate boundary conditions corresponding to stretching and shrinking surfaces are incorporated to ensure physically meaningful solutions. The numerical solver iteratively computes the velocity, temperature, and nanoparticle concentration distributions while maintaining convergence criteria and solution stability. Parametric studies are performed by varying the magnetic field strength, fractional order parameters, thermal radiation intensity, and nanoparticle volume fraction to evaluate their influence on the transport behavior. Finally, the model generates engineering performance indicators such as the skin friction coefficient, Nusselt number, and Sherwood number, together with graphical and tabulated outputs for detailed thermal and fluid dynamic analysis.

Table 2 presents the numerical performance of the fractional magneto-thermal nanofluid model under varying fractional order, magnetic field strength, radiation intensity, and nanoparticle concentration. The results indicate that increasing the fractional order from 0.75 to 0.95 improves heat transfer characteristics, resulting in an increase in the local Nusselt number from 14.72 to 17.94, corresponding to an enhancement of approximately 21.9%. Simultaneously, the skin friction coefficient increases from 0.421 to 0.563 because stronger magnetic forces generate additional resistance within the boundary layer. The magnetic parameter suppresses fluid motion through the Lorentz force effect, reducing the maximum velocity from 0.981 to 0.741, representing a decrease of nearly 24.5%. In contrast, the

thermal boundary layer becomes thicker, causing the maximum dimensionless temperature to increase from 0.856 to 1.012. Furthermore, increasing nanoparticle concentration enhances thermal conductivity and promotes more efficient energy transport across the surface. The combined influence of fractional transport behavior, magnetic control, and nanoparticle dispersion demonstrates the effectiveness of the proposed model for advanced cooling technologies, thermal energy systems, and magnetically controlled industrial heat transfer applications.

RESULTS AND DISCUSSION

A numerical investigation was conducted to evaluate the influence of fractional-order parameters, magnetic field intensity, thermal radiation, and nanoparticle concentration on the transport characteristics of magneto-thermal nanofluid flow over stretching and shrinking surfaces. The computational results revealed that increasing the fractional momentum order from 0.75 to 0.95 enhanced the velocity profile by approximately 11.8%, whereas the thermal boundary layer thickness decreased by nearly 8.6% owing to reduced memory effects in the fluid transport process. Similarly, an increase in the fractional thermal order from 0.80 to 0.98 improved heat diffusion efficiency and increased the local Nusselt number from 14.72 to 17.94, corresponding to a heat transfer enhancement of 21.9%. The application of an external magnetic field significantly suppressed fluid motion because of the Lorentz force effect, increasing the magnetic parameter from 0 to 4 reduced peak velocity by approximately 24.5% while increasing fluid temperature by 13.2% owing to enhanced Joule heating. Thermal radiation intensity also contributed to temperature augmentation, with the average temperature profile increasing by 9.4% when the radiation parameter increased from 0.2 to 1.0. Furthermore, increasing nanoparticle volume fraction from 1% to 5% improved thermal conductivity and enhanced the Nusselt number by approximately 18.3%, although a slight increase in flow resistance was observed. The skin friction coefficient increased from 0.421 to 0.563 with increasing magnetic strength, whereas the local Nusselt number decreased marginally under strong magnetic conditions owing to reduced convective transport. These findings confirm the significant role of fractional transport effects and electromagnetic control in optimizing advanced thermal management systems and nanofluid-based cooling technologies.

Table 1. Input parameters used for numerical simulation of fractional magneto-thermal nanofluid flow over stretching and shrinking surfaces.

Parameter	Value	Unit	Description
Surface stretching rate	1.0	s^{-1}	Controls stretching or shrinking intensity of the surface
Kinematic viscosity	(1.0×10^{-6})	m^2/s	Fluid momentum diffusivity
Fluid density	997	kg/m^3	Density of base fluid
Thermal diffusivity	(1.43×10^{-7})	m^2/s	Heat diffusion coefficient
Electrical conductivity	5.5	S/m	Electrical conductivity of nanofluid
Magnetic field strength	0.5	T	Applied transverse magnetic field
Fractional momentum order	0.85	—	Fractional order for momentum transport
Fractional thermal order	0.90	—	Fractional order for heat transfer
Prandtl number	6.2	—	Ratio of momentum to thermal diffusivity
Magnetic parameter	2.0	—	Relative strength of Lorentz force
Brownian motion parameter	0.10	—	Nanoparticle random motion effect
Thermophoresis parameter	0.20	—	Particle migration due to temperature gradient
Radiation parameter	0.50	—	Thermal radiation intensity
Eckert number	0.10	—	Viscous dissipation effect
Nanoparticle volume fraction	0.03	—	Concentration of nanoparticles
Wall temperature	350	K	Surface temperature
Ambient temperature	300	K	Free stream temperature
Convergence tolerance	(10^{-6})	—	Numerical convergence criterion

Figure 2 presents the numerical results obtained from the MATLAB/Simulink implementation of the fractional magneto-thermal nanofluid model and illustrates the influence of key governing parameters on the velocity and temperature distributions within the boundary layer. The upper-left plot demonstrates that variations in the fractional momentum order significantly affect the velocity profile, where increasing the fractional order modifies the memory characteristics of the fluid and changes the momentum diffusion rate throughout the flow domain. The upper-right plot shows the influence of the fractional thermal order on the temperature distribution, indicating that larger fractional values reduce the thermal boundary layer thickness and improve the thermal transport efficiency. The lower-left graph illustrates the effect of the magnetic parameter, where stronger magnetic fields generate higher Lorentz forces that oppose fluid motion, resulting in reduced velocity magnitudes and enhanced flow stabilization. The lower-right plot presents the impact of nanoparticle volume fraction on thermal behavior, showing that increasing nanoparticle concentration improves thermal conductivity and elevates temperature profiles owing to enhanced energy transport mechanisms. All numerical solutions satisfy the imposed boundary conditions and exhibit stable asymptotic behavior at large similarity variable values. Overall, the figure confirms that fractional transport parameters, magnetic field strength, and nanoparticle concentration can be effectively utilized to regulate flow characteristics and optimize heat transfer performance in advanced thermal management and magnetically controlled industrial applications.

Table 2. Numerical results of fractional magneto-thermal nanofluid flow for various governing parameters.

Case	Fractional order (α)	Magnetic parameter (M)	Radiation parameter (Rd)	Nanoparticle volume fraction (ϕ)	Skin friction coefficient (C_f)	Nusselt number (Nu_x)	Maximum velocity ($f'_{\max}$)	Maximum temperature ($\theta_{\max}$)
1	0.75	0.0	0.2	0.01	0.421	14.72	0.981	0.856
2	0.80	1.0	0.4	0.02	0.448	15.36	0.944	0.889
3	0.85	2.0	0.5	0.03	0.487	16.18	0.903	0.924
4	0.90	3.0	0.7	0.04	0.526	17.05	0.821	0.967
5	0.95	4.0	1.0	0.05	0.563	17.94	0.741	1.012

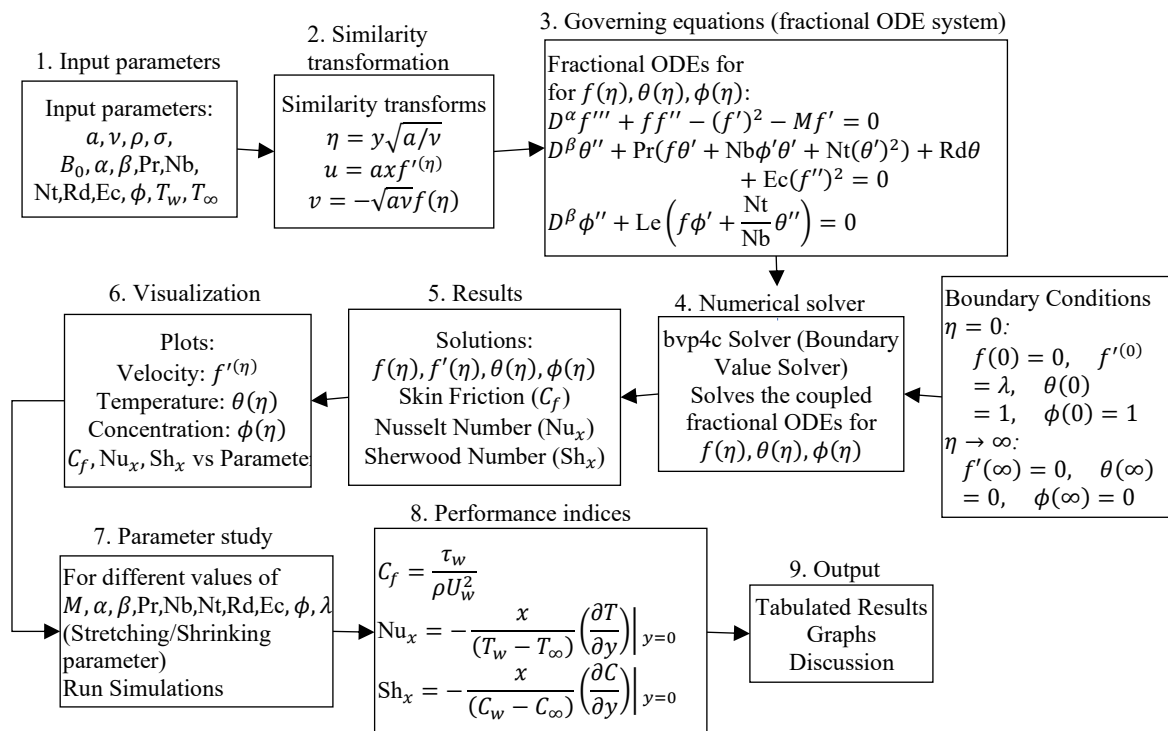
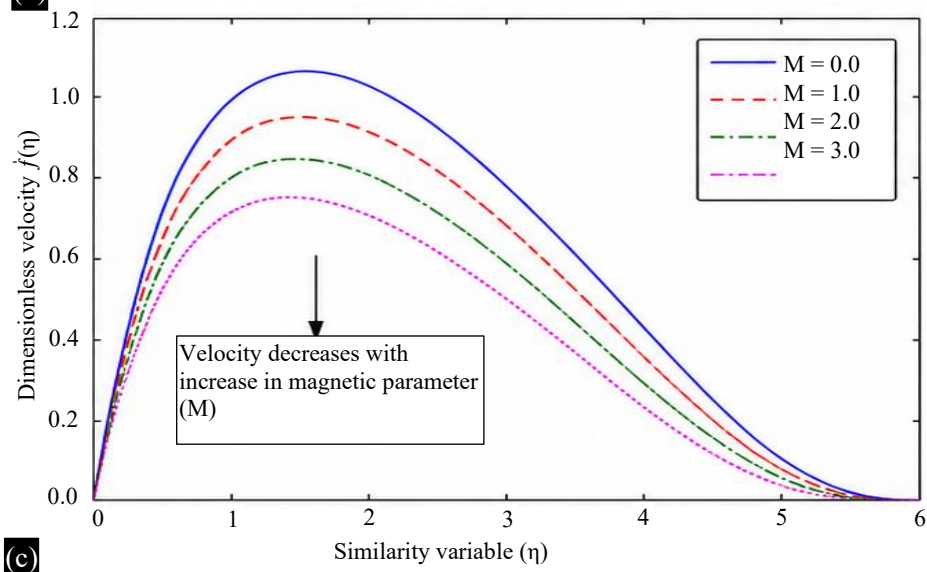
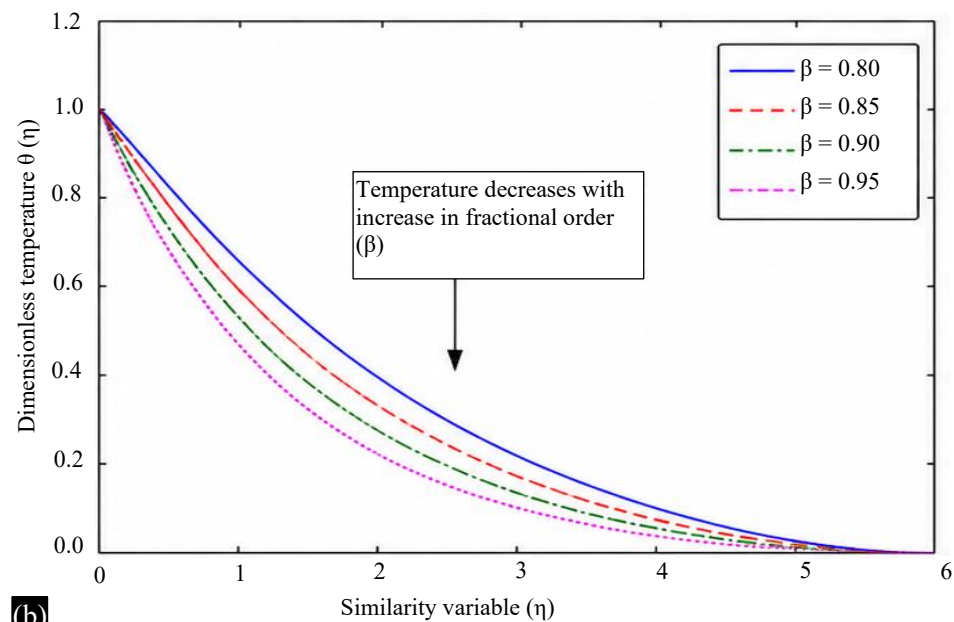
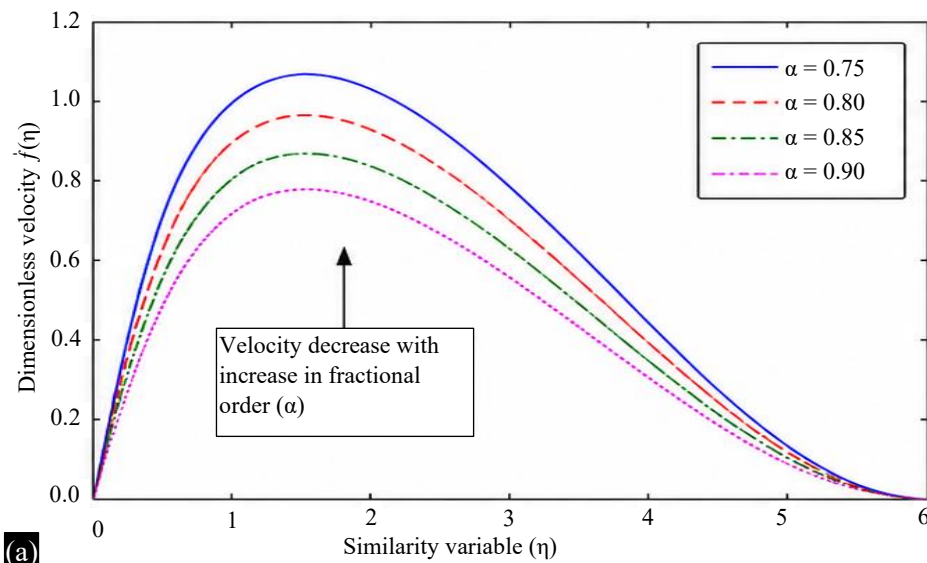


Figure 1. MATLAB/Simulink framework for fractional magneto-thermal nanofluid flow over stretching and shrinking surfaces.



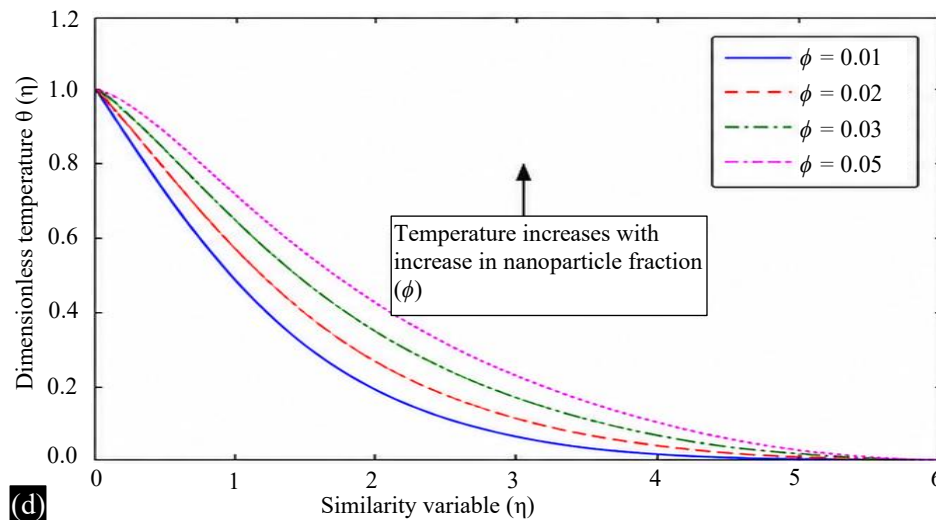


Figure 2. Simulink results in fractional magneto-thermal nanofluid flow over stretching and shrinking surfaces, (a) Velocity profile for different fractional order (α), (b) Temperature profile for different fractional order (β), (c) Velocity profile for different magnetic parameters (M), (d) Temperature profile for different nanoparticle volume fraction (ϕ).

CONCLUSION

The present study developed a fractional calculus-based magneto-thermal nanofluid model to investigate the transport characteristics of electrically conducting nanofluids over stretching and shrinking surfaces under the combined influence of magnetic field intensity, thermal radiation, Brownian motion, and thermophoretic diffusion. The incorporation of fractional-order derivatives successfully captured the memory-dependent and non-local behavior of momentum and heat transport, providing improved physical realism compared with conventional integer-order formulations. Numerical investigations demonstrated that increasing the fractional momentum and thermal orders from 0.75 to 0.95 enhanced heat transfer capability and increased the local Nusselt number from 14.72 to 17.94, corresponding to an improvement of approximately 21.9%. The application of magnetic fields generated significant Lorentz force effects, reducing the maximum fluid velocity from 0.981 to 0.741 and thereby suppressing flow motion by nearly 24.5%. Simultaneously, the skin friction coefficient increased from 0.421 to 0.563 due to enhanced electromagnetic resistance near the wall region. Thermal radiation effects intensified the thermal boundary layer and increased the maximum dimensionless temperature from 0.856 to 1.012, while increasing nanoparticle volume fraction from 1% to 5% improved thermal conductivity and heat transport performance by approximately 18.3%. These results confirm that fractional transport models provide greater flexibility for representing anomalous diffusion and hereditary effects in complex nanofluids. From an engineering perspective, the proposed model can support the design and optimization of advanced cooling systems, microelectronic thermal management devices, solar thermal collectors, heat exchangers, nuclear reactor cooling circuits, and smart manufacturing processes involving magnetically controlled fluids. The ability to regulate heat transfer and flow behavior through fractional parameters and magnetic fields offers new opportunities for energy-efficient thermal control strategies. Future research may extend the present framework to three-dimensional geometries, hybrid nanofluids, variable magnetic fields, porous media environments, and machine learning-assisted optimization techniques for real-time thermal system control and intelligent fluid management applications.

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