

Numerical solutions in a laminar motion of magnetohydrodynamic Maxwell liquid past a permeable shrinking plate

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Received 16 August 2021; revised 01 June 2023

In recent years, there has been a notable rise in interest in the boundary layer theory of non-Newtonian fluids, driven by both academic curiosity and engineering applications. The nonlinearity of the equations can manifest itself in various ways across a broad spectrum of industries, encompassing biotechnology, drilling operations, and the food sector. The term Maxwell fluid describes the characteristics related to relaxation time and falls within the category of rate-type fluids. Researchers are intrigued by the challenges associated with solving nonlinear and higher-order differential equations. In the present problem, the magnetohydrodynamics (MHD) Maxwell liquid over a porous contracting surface is discussed numerically. In the analysis, a consistent transfer of divider concentration is examined. The governing/controlling equations of the fluid flow are changed using similarity transformations. The numerical results were found by using the $R-K-4^{th}$ order-based shooting technique with the assistance of MATLAB software. The graphical representation is displayed through stability analysis. The results indicate that the first solution exhibits greater stability. The magnetic parameter and suction effect enhance the velocity profile, whereas the Deborah number yields opposite results.

[**Keywords:** Maxwell liquid, MHD, Numerical solution, Permeable shrinking plate, Porous contracting surface]

Mathematics subject classification

76Wxx, 76W05, 76N20.

Nomenclature

C	Positive constant/ -	ρ	Fluid density/ $kg\ m^{-3}$
B_0	Applied magnetic field/ $N\ m^{-1}\ A^{-1}$	\mathcal{G}	Kinematic viscosity/ $m^2\ s^{-1}$
f'	Non-dimensional velocity/ -	β	Deborah number/ -
M	Magnetic number/ -	ψ	Stream function/ -
S	Suction parameter/ -	σ	Electrical conductivity/ $simens\ .m^{-1}$
V_w	Suction velocity/ -	η	Similarity variable/ -
x, y	Coordinate axes/ -	<i>Subscripts</i>	
u_w	Surface velocity/ $m\ s^{-1}$	f	Fluid
u, v	Velocity components/ $m\ s^{-1}$	w	At wall
<i>Greek Symbols</i>		x	Differentiation w.r.t x
λ	Maxwell fluid relaxation time/ -	y	Differentiation w.r.t y
μ	Dynamic viscosity/ $kg\ m^{-1}\ s^{-1}$		

Introduction

Boundary layer motions because of extending/shrinking surfaces have stimulated the attention of investigations for their vast applications in numerous engineering processes. Firstly, Crane¹ has examined the viscous motion past a linearly extending sheet. The other extending work considering numerous physical conditions has been the pioneering effort of Crane¹ extended by several researchers working with numerous physical conditions²⁻⁷. In Crane's work which is based on the time-dependent fluid film, Wang⁸ noticed that the fluid flow for the shrinking surface has rare properties. The stable boundary layer extracting flow does not arise due to developed vortices because of the separated boundary layers due to reduction of the boundary layer. The viscous motion because of a shrinking surface through suction has been reported by Miklavčič & Wang⁹. Their results show that the probability of steady motion depends on externally imposed mass suction, which dominates the boundary layer separation. Bachok *et al.*¹⁰ have described the steady 2-D stagnation-point flow of an H₂O-based

nano liquid past an exponentially extending/reducing surface in its particular level.

Further, Fang *et al.*¹¹ inspected viscous motion past a shrinking surface and explained analytically by a newly projected second-order slip conditions. Awais *et al.*¹² surveyed the presence of dual solutions for the MHD flow of Maxwell liquid past a permeable shrinking partition. Additionally, Rauf *et al.*¹³ explored the presence of a chemical reaction of first order on magnetohydrodynamics stagnation point motion of micro-nano liquid over a shrinking surface in the influence of zero mass flux and convective conditions and Kumaran *et al.*¹⁴ analyzed the Brownian motion, thermophoresis effect, irregular heat source/sink, and cross-diffusion on MHD Maxwell and Casson flow past an extending surface. An enhancement in temperature and concentration profile of Maxwell liquid is noticed as compared to the Casson fluid. Iskandar *et al.*¹⁵ have further explored the stagnation point flow over an extending/lessening cylinder in a mixture (copper and aluminium oxide) nanoliquid. They noticed that the heat transmission is higher for the hybrid nanofluid related to the regular nanoliquid as well as the base liquid, and the bifurcation of the solutions arises in the shrinking regions. Also, the non-uniqueness solutions are detected for various physical parameters. Furthermore, skin friction coefficients and the heat transfer rate rise in the influence of nano-sized particles and for greater Reynolds number. Eid *et al.*¹⁶ later conveyed the effect of thermal radiation, suction/injection, magnetic field, and nano-sized particles on the two-segment motion of a comprehensive Carreau liquid past a non-linear permeable extending sheet. Whereas, Balazadeh *et al.*¹⁷ discussed the influences of Joule heating and radiation effect on the mass and heat transfer for time-dependent 2-D magnetohydrodynamics squeezing motion of Eyring-Powell liquid among 2-horizontal infinite sheets.

The Homotopy Analysis Method (HAM) on the MHD second-grade fluid flow past a shrinking surface has been reported by Hayat *et al.*¹⁸⁻¹⁹. They proposed the HAM solution for MHD revolving motion of second-grade liquid past a shrinking surface. The velocity and energy transport past an exponential reduction surface was studied by Bhattacharyya²⁰. Further, the impact of blowing/suction on the steady laminar flow and energy transport past a shrinking surface in the

presence of radiation effect has been analyzed by Bhattacharyya & Layek²¹. Recently, Afsana *et al.*²² have presented the impact of free convection in electrically conducting non-Newtonian ferrofluids within a wavy enclosure. The main attraction of their investigation is the entropy analysis due to the irreversibility of the system. Moreover, Rafiq *et al.*²³ studied the nonlinear thermal radiation on the dusty fluid near a spinning blunt-nosed body. The determination of MHD motion, radiative, and chemical characteristics has attracted the attention of several researchers due to its consequence in the practical problems of improving the performance of various industrial processes, such as manufacturing paper, plastic sheet, and copper wire drawing²⁴⁻²⁶.

Similarly, Jena *et al.*²⁷ inspected the heat transmission phenomenon of nanofluid in the presence of magnetic effect and irregular heat source. Pattnaik *et al.*²⁸ conducted a study to examine the velocity slip condition on the Micropolar fluid flow through an enlarging sheet. Likewise, Parida *et al.*²⁹ used a computational approach to analyze the behavior of dust particles in an H₂O- kerosene oil-based mixture. In an another study by Pattnaik *et al.*³⁰ presented the impact of MHD on metallic water-based nanoparticles (Cu, Al₂O₃ and SWCNT's) through a permeable surface. Whereas, Mathur *et al.*³¹ reported the influence of velocity slip on micropolar nanofluid in the presence of Darcy-Forchheimer drag coefficients. Pattnaik *et al.*³² have explored the free convection of a nanofluid flow consisting of gold particles with water and Hamilton-Crosser thermal conductivity model is used. The investigation focused on the flow through a channel with porous walls is considered. Additionally, Pattanaik *et al.*³³ have analyzed the effects of radiative and dissipation effect on the flow of Williamson nanoparticles mixed fluid in a corresponding channel induced by the buoyancy effect. Further, Mohanty *et al.*³⁴ conducted an entropy analysis for the peristaltic flow of a micropolar nanofluid. The study involved simulations obtained through an approximate analytical technique.

In addition to the above studies, Mishra *et al.*³⁵ have analyzed the heat transmission on the MHD micropolar fluid flow through a permeable medium, considering the irregular heat source and radiation effect and Baag *et al.*³⁶ described the MHD boundary layer flow past an exponentially enlarging surface passed through the porous media in the presence of a heat source. Nayak *et al.*³⁷ examined the influence of

chemical reactions on the axisymmetric flow over a radially expandable sheet. Makinde *et al.*³⁸ analyzed the mixed convection Blasius flow in MHD chemically reacting with flexible viscosity surrounded by a porous media, whereas, Nisar *et al.*³⁹ investigated free convection of a Jeffrey fluid flow in the presence of chemical reaction and heat source effect. Mishra *et al.*⁴⁰ further investigated the optical, electrical, dielectric, and structural characteristics of Li/Fe-modified barium tungstate double perovskite for use in microelectronic appliances.

Mishra *et al.*⁴¹ have considered the cross-diffusion and nonlinear radiation effect on micropolar nanoliquid past an enhancing surface with an exponential heat source. On the other hand, a stability analysis on a hybrid nanofluid over a stretchable/shrinkable vertical surface with a nonlinear heat sink/source was conducted by Khan *et al.*⁴². Madhukesh *et al.*⁴³ studied the Cattaneo-Christov theory and slip effects to investigate the flow on a permeable disk for micropolar-Casson nanofluid. Kumar *et al.*⁴⁴ have analyzed the flow of non-Newtonian nanofluid, considering the influence of magnetic dipole, and explored the behavior of nanoparticles in the system. Few more studies like Yun-Xiang Li *et al.*⁴⁵ explored dual solutions for the nonlinear radiative flow of the Maxwell fluid and studied the mass and heat transfer effect on a wedge surface; Madhukesh *et al.*⁴⁶ examined the Casson Marangoni-type nanofluid flow through a void-spaced medium, considering the influence of chemical activation energy; Sowmya *et al.*⁴⁷ have explained the stimulus of the Newtonian heating effect on dusty nano liquid over a Riga surface within void-spaced media; Madhukesh *et al.*⁴⁸ studied the thermal transport characteristics of MHD Casson and Maxwell nano liquid flow between two void-spaced disks; and Alzahrani *et al.*⁴⁹ investigated the impact of a slip boundary condition. The study by Alzahrani *et al.*⁴⁹ focused on examining how radiation affects heat transmission in a wall jet flow of non-Newtonian nanoliquid.

Kumar *et al.*⁵⁰ employed the exponential heat source and optimized the response surface of the electro-hydrodynamic flow of Cu-polyvinyl alcohol/water Jeffrey nanoliquid. Meanwhile, Sharma *et al.*⁵¹ investigated the control of Arrhenius activation energy on MHD nanoliquid flow in the presence of an exponential heat source through an extendable sheet with a modified

Buongiorno model. Further, Sharma *et al.*⁵² explored an ANN model, which is a machine-learning technique used to study the Darcy-Forchheimer flow of a hybrid nano liquid through a spinning Riga disk while taking chemical reactions into account. Mishra *et al.*⁵³ in their later study, added an induced magnetic field to a cilia-regulated MHD ternary Jeffrey nanofluid to study the entropy generation.

The primary objective of the current study is to find the numerical solution of an MHD Maxwell liquid through a porous contracting surface. As per the Author's knowledge, there is literature available on the above-mentioned issues. This problem has direct applications in the manufacturing of paper, solar collectors, plastic melting, and engine cooling. A detailed analysis is done on the stimulus of the various parameters on the energy and velocity distribution, along with graphical representations. It is widely used in geophysical processes and engineering, including gas turbines, rotor systems, food processing, and disk cleaners. Numerical solutions were produced by using the R-K-based shooting technique; while the graphs are used to illustrate the results.

Mathematical formulation

Considering a 2-D Maxwell fluid flow past a permeable (Porous media) shrinking plate with wall concentration transport, the plate overlaps with the flat $y = 0$, and the motion occupies the area $y > 0$. The x -axes and y -axes are taken to be along and perpendicular to the plate, correspondingly. The governing equations of flow⁵⁴ are:

$$\partial_x u + \partial_y v = 0 \quad \dots (1)$$

$$u\partial_x u + v\partial_y u + \lambda(u^2\partial_{xx}u + 2uv\partial_{xy}u + v^2\partial_{yy}u) = \mathcal{G}\partial_{yy}u - (\sigma B_0^2/\rho)u \quad \dots (2)$$

Where, $\mathcal{G} = \mu/\rho$

The boundary conditions⁵⁴ are:

$$\begin{aligned} u &= -cx, & v &= -V_w & \text{at} & y = 0 \\ u &\rightarrow 0 & \text{as} & & y &\rightarrow \infty \end{aligned} \quad \dots (3)$$

Where, $c > 0$ is the shrinking rate and $V_w > 0$ is the (velocity) suction effect at the surface.

Here, the stream function $\psi(x, y)$ that proves the continuity equation with $(\psi_y, -\psi_x) = (u, v)$.

Now, Eq. (2) is introduced to the subsequent form

$$\begin{aligned} \partial_{xy}\psi \partial_y \psi - \partial_{yy}\psi \partial_x \psi + \lambda \left((\partial_y \psi)^2 \partial_{xy}\psi + \partial_{yyy}\psi (\partial_x \psi)^2 - 2\partial_{xy}\psi \partial_x \psi \partial_y \psi \right) \\ = \mathcal{G} \partial_{yyy}\psi - \left(\frac{\sigma B_0^2}{\rho} \right) \partial_y \psi \end{aligned} \quad \dots (4)$$

The BCs for the velocity are

$$\left. \begin{aligned} \psi_y = cx, \quad \psi_x = -V_w \quad \text{at } y = 0 \\ \psi_y \rightarrow 0 \quad \text{at } y \rightarrow \infty \end{aligned} \right\} \quad \dots (5)$$

The similarity variables are as follow:

$$\psi = \sqrt{\mathcal{G}cx}f(\eta) \quad \text{and} \quad \eta = y\sqrt{c/\mathcal{G}} \quad \dots (6)$$

Where, η is the similarity variable⁵⁴.

Given the relation (6), the Eq. (1) satisfies automatically, and the Eqs. (4) and (5) reduces to the following equation of motion for Maxwell fluid

$$f''' + ff'' - f'^2 + \beta(2ff'' - f^2 f''') - Mf' = 0 \quad \dots (7)$$

$$\left. \begin{aligned} f(\eta) = S, \quad f'(\eta) = -1, \quad \text{at } \eta = 0 \\ f'(\eta) = 0 \quad \text{as } \eta \rightarrow \infty \end{aligned} \right\} \quad \dots (8)$$

Where, prime represents the d.w.r. to η . The dimensionless parameters are the Deborah number β , the suction parameter S , and the Hartmann number is given by:

$$\beta = \lambda c, \quad S = -V_w / \sqrt{\mathcal{G}c} \quad \text{and} \quad M^2 = \sigma B_0^2 / \rho c$$

Numerical solution

Due to highly nonlinear ordinary differential equations (7) respective to the BCs (8), these are explained numerically using the 4th order *R-K*-shooting method. The set of nonlinear ODEs (7) is transformed into first-order differential equations, which are:

$$f = y_1, \quad \dots (9)$$

$$f' = y_2 \quad \dots (10)$$

$$f'' = y_3, \quad \dots (11)$$

$$f''' = \frac{1}{1+\beta y_1^2} [-y_1 y_3 - y_2^2 - \beta[2y_1 y_2 y_3] + M y_2] \quad \dots (12)$$

and the boundary conditions are:

$$\left. \begin{aligned} y_1 = S, y_2 = -1 \quad \text{at } \eta = 0 \\ y_2 \rightarrow 0, \eta \rightarrow \infty \end{aligned} \right\} \quad \dots (13)$$

To solve the equations (9) to (13), the value of y_3 was taken which is not given at the antecedent conditions. The equations (9) to (13) later approximated by the *R-K* method with the subsequent looping step size 0.001.

Graphical Discussion

The momentum equation (8) along with the BCs (9) are explained numerically with the *R-K* method by taking the step size $\eta = 0.001$ and the relative error of 10^{-6} . The influence of the non-dimensional parameters, M, β , and S on the velocity is analyzed through Figures 1 to 10. The graphical representation examines the numerous dynamical variables of the non-dimensional momentum description for two dissimilar solutions. Figure 1 represents the characteristics of Hartman parameters on the momentum profiles exhibiting the dual solutions. The bold and dotted lines represent the first solution and second solution, respectively. It is noticeable that the improved values of the Hartman parameter augment the velocity profile. Simultaneously, the thickness of the hydrodynamic boundary layer is condensed. The Hartman number exhibits the behavior of the Lorentz forces; a resistive kind of force that can resist the boundary layer thickness for greater magnitude of the magnetic parameters. Also, the fluid velocity distribution is low

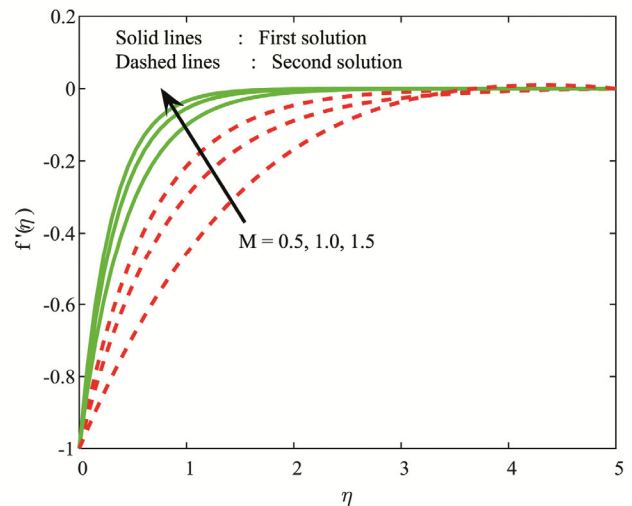


Fig. 1 — Role of M on $f'(\eta)$

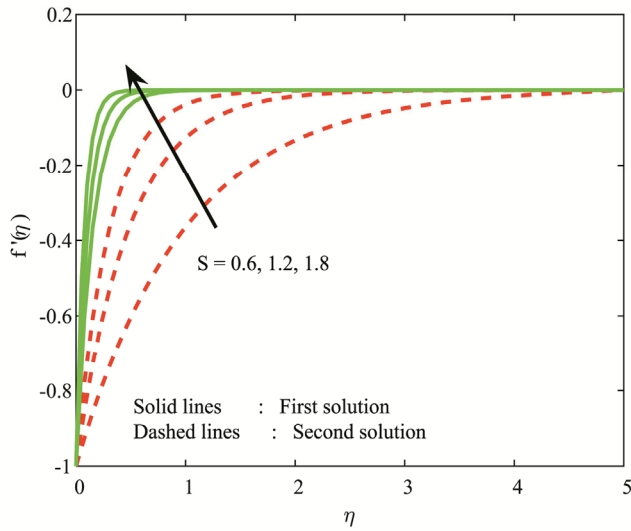


Fig. 2 — Role of S on $f'(\eta)$

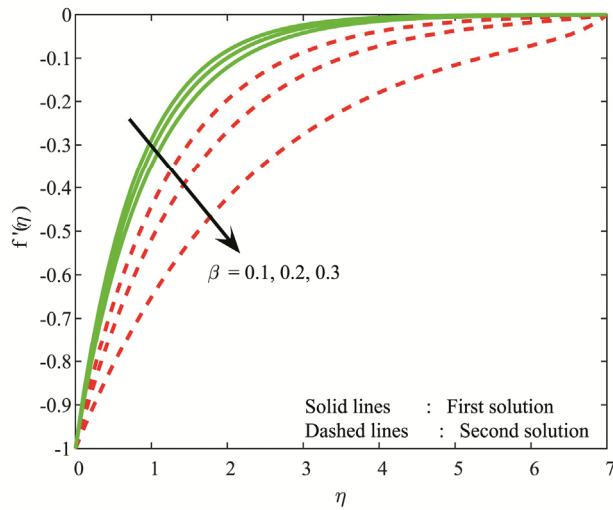


Fig. 3 — Role of β on $f'(\eta)$

for the second solution as associated with the developing values M . Figure 2 shows the description of momentum for a range of suction parameter values. The pressure differential is restricted to the pressure since it results from the expulsion of air from the space. In this instance, the higher-pressure region's pressure will act in opposition to the lower-pressure region. However, for escalating values of S momentum profile rises for both solutions.

Figure 3 illustrates the momentum profile for diverse values of the Maxwell parameter presented in the form of a Deborah number that is proportional to

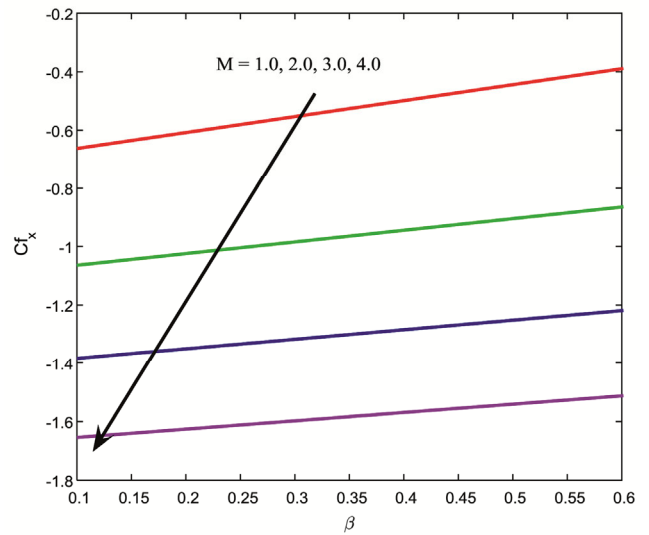


Fig. 4 — Role of β versus M on Cf_x

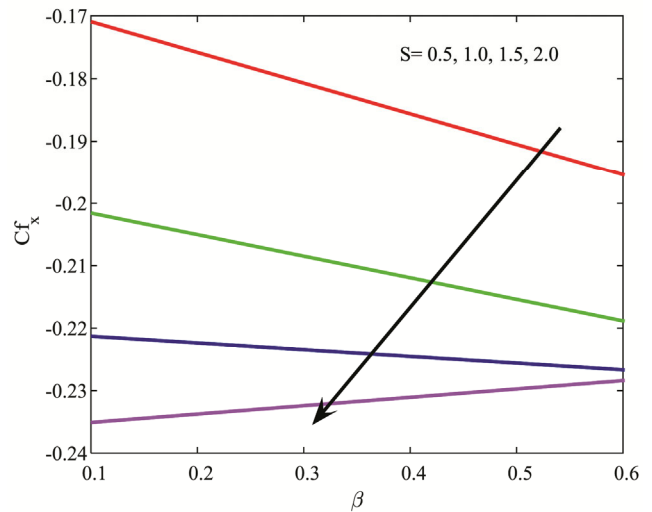


Fig. 5 — Role of β versus S on Cf_x

the relaxation time. The augmented values of β , the velocity distribution decline for both the first and second solutions. The fall in the velocity profile results in a declining amount of heat from the surface of the liquid. Figure 4 illustrates the stimulus of β on the coefficient of skin friction C_f against the M . Augmenting the value of M , C_f diminishes due to a decline in the thickness of the boundary layer. It is also observed that the friction factor declines for larger values of β . Figure 5 illustrates the influence of

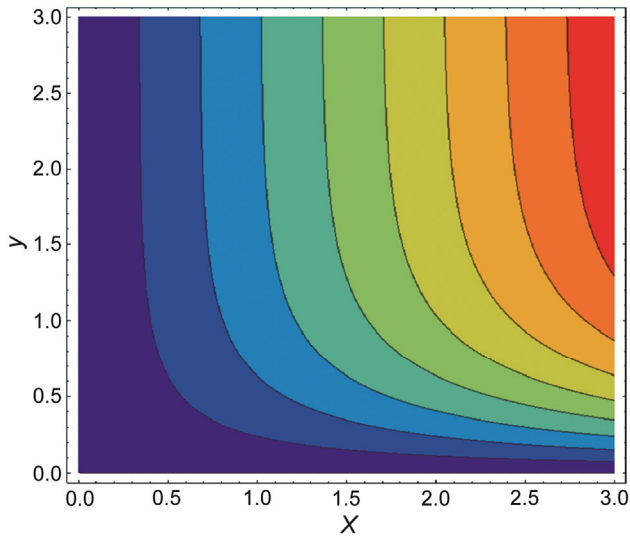


Fig. 6 — Streamlines for $M = 0.5$

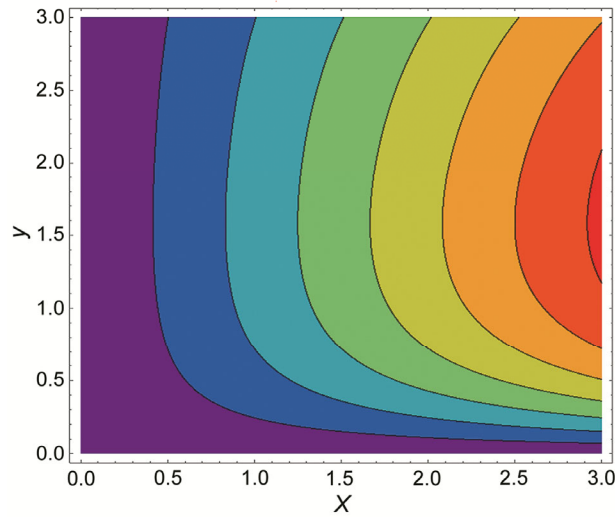


Fig. 7 — Streamlines for $M = 1.5$

β on the C_f against the suction parameter S . As the S rises, the plot of friction factor declines due to decreasing of the boundary layer thickness. Further, a decline in the skin friction factor is noticed for the enhancement of β . Figures 6 – 10 displays the results of the magnetic parameter and Deborah number on streamline flow for fixed values. Thus, for the fixed value of M , the β shows the traces of the fluid particles in a certain manner on the curve along the x -direction. It is observed that when M, β have positive values, their impact is high compared to when they have negative values.

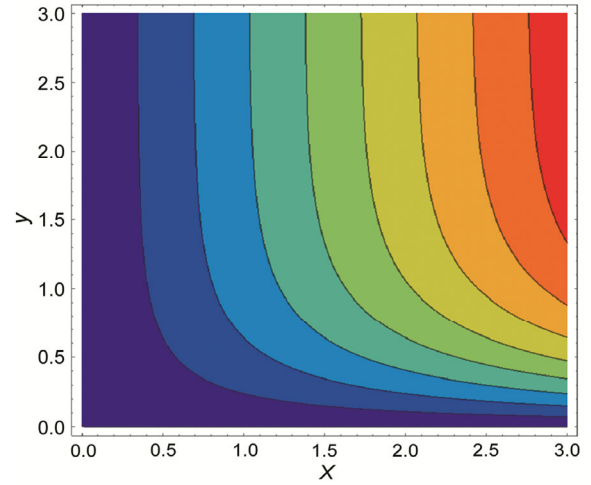


Fig. 8 — Streamlines for $\beta = 0.1$

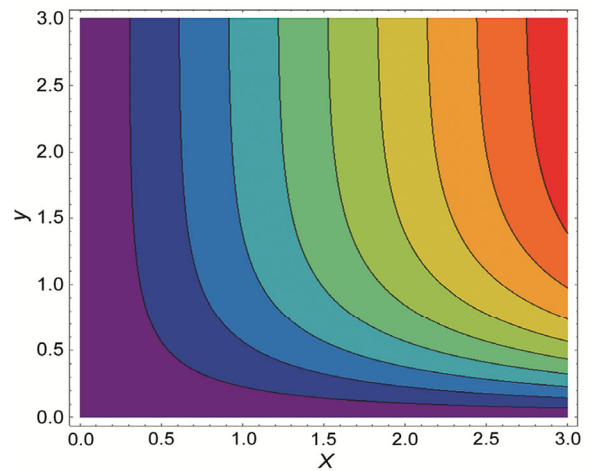


Fig. 9 — Streamlines for $\beta = 1.2$

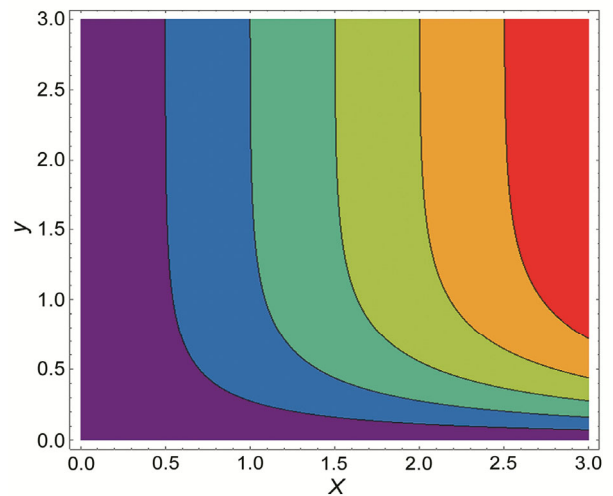


Fig. 10 — Streamlines for $\beta = 2.5$

Conclusion

This work presented the laminar flow of MHD Maxwell liquid over a porous shrinking plate with wall concentration transfer considered. The converted non-dimensional equations are explained numerically by applying the R-K 4th order with the shooting method. The main findings are: i) The velocity profile is enhanced more in the first solution as the magnetic parameter improves. However, the Lorentz force is present in a fluid flow system; ii) Augmenting the values of M and S , the skin friction factor diminishes; iii) The graphical results look more stable for the first solution; and iv) For the larger values of β , the friction factor declines.

These results will be helpful in studying geophysical processes and engineering, including gas turbines, rotor systems, food processing, lubricants, soaps, and disk cleaners. The coating process requires a smooth, glossy surface to satisfy the requirements for strength, transparency, minimal friction, and attractiveness. In the future, the Maxwell fluid can be more effective with nanofluid and hybrid nanofluid for industrial applications using different geometries.

Acknowledgments

Authors are thankful to the Editor in chief and learned reviewers for their qualitative suggestions to improve the quality of our manuscript.

Funding

The author(s) received no financial support for the research, authorship, and publication of this article.

Conflicts of Interest

No potential conflict of interest was reported by the Author(s).

Author Contributions

RPS modelled the problem. MGR and SS solved it using MATLAB software and contributed to the results and discussions. All authors thoroughly checked the mathematical modelling and English corrections and finalized the manuscript after its internal evaluation.

References

- Crane L J, Flow past a stretching plate, *J Appl Math Phys*, 21 (1970) 645–647. <https://doi.org/10.1007/BF01587695>
- Gupta P S & Gupta A S, Heat and mass transfer on a stretching sheet with suction or blowing, *Can J Chem Eng*, 55 (6) (1977) 744-746. <http://dx.doi.org/10.1002/cjce.5450550619>
- Chen C K & Char M I, Heat transfer of a continuous, stretching surface with suction or blowing, *J Math Anal Appl*, 135 (2) (1988) 568-580. [http://dx.doi.org/10.1016/0022-247X\(88\)90172-2](http://dx.doi.org/10.1016/0022-247X(88)90172-2)
- Pavlov K B, Magnetohydrodynamic flow of an incompressible viscous fluid caused by deformation of a plane surface, *Magnetohydrodynamics*, 10 (4) (1974) 507-510.
- Zheng L, Niu J, Zhang X & Ma L, Dual solutions for flow and radiative heat transfer of a micropolar fluid over stretching/shrinking sheet, *Int J Heat Mass Transf*, 55 (25-26) (2012) 7577-7586. <https://doi.org/10.1016/j.ijheatmasstransfer.2012.07.067>
- Zheng L, Wang L, Zhang X & Ma L, Flow and heat transfer of MHD viscous fluid over an unsteady stretching surface with radiation heat flux, *Chem Eng Commun*, 199 (1) (2012) 1-16. <https://doi.org/10.1080/00986445.2010.524503>
- Zheng L, Niu J, Zhang X & Gao Y, MHD flow and heat transfer over a porous shrinking surface with velocity slip and temperature jump, *Math Comput Model*, 56 (5-6) (2012) 133-144. <https://doi.org/10.1016/j.mcm.2011.11.080>
- Wang C Y, Liquid film on an unsteady stretching surface, *Quart Appl Math*, 48 (4) (1990) 601-610. <https://www.jstor.org/stable/43637666>
- Miklavčič M & Wang C Y, Viscous flow due to a shrinking sheet, *Quart Appl Math*, 64 (2) (2006) 283-290. <https://doi:10.1090/S0033-569X-06-01002-5>
- Bachok N, Ishak A & Pop I, Boundary layer stagnation-point flow and heat transfer over an exponentially stretching/shrinking sheet in a nanofluid, *Int J Heat Mass Transf*, 55 (25-26) (2012) 8122-8128. <https://doi:10.1016/j.ijheatmasstransfer.2012.08.051>
- Fang T, Yao S, Zhang J & Aziz A, Viscous flow over a shrinking sheet with a second-order slip flow model, *Commun Nonlinear Sci Numer Simul*, 15 (7) (2010) 1831–1842. <https://doi:10.1016/j.cnsns.2009.07.017>
- Awais M, Hayat T, Irum S & Saleem S, Dual solutions for nonlinear flow using Lie group analysis, *PLOS ONE*, 10 (11) (2015) p. e0142732. <https://doi.org/10.1371/journal.pone.0142732>
- Rauf A, Shehzad S A, Hayat T, Meraj M A & Alsaedi A, MHD stagnation point flow of micro nanofluid towards a shrinking sheet with convective and zero mass flux conditions, *B Pol Acad Sci-Tech*, 65 (2) (2017) 155-162. <https://doi:10.1515/bpasts-2017-0019>
- Kumaran G, Sandeep N & Ali M E, Computational analysis of magnetohydrodynamics Casson and Maxwell flow over a stretching sheet with cross-diffusion, *Results Phys*, 7 (2017) 147–155. <https://doi.org/10.1016/j.rinp.2016.12.011>
- Waini I, Ishak A & Pop I, Hybrid nanofluid flow towards a stagnation point on a stretching/shrinking cylinder, *Sci Rep*, 10 (9296) (2020) 1-13. <https://doi:10.1038/s41598-020-66126-2>
- Eid M R, Mahny K L, Muhammad T & Sheikholeslami M, Numerical treatment for Carreau nanofluid flow over a porous nonlinear stretching surface, *Results Phys*, 8 (2018) 1185-1193. <https://doi.org/10.1016/j.rinp.2018.01.070>
- Balazadeh N, Sheikholeslami M, Ganji D D & Li Z, Semi-analytical analysis for transient Eyring-Powell squeezing

- flow in a stretching channel due to magnetic field using DTM, *J Mol Liq*, 260 (2018) 30-36. <http://dx.doi.org/10.1016/j.molliq.2018.03.066>
- 18 Hayat T, Abbas Z & Sajid M, On the analytic solution of magnetohydrodynamics flow of a second-grade fluid over a shrinking sheet, *J Appl Mech*, 74 (6) (2007) 1165–1171. <https://doi.org/10.1115/1.2723820>
 - 19 Hayat T, Javed T & Sajid M, Analytic solution for MHD rotating flow of a second-grade fluid over a shrinking surface, *Phys Lett - A*, 372 (18) (2008) 3264-3273. <https://doi.org/10.1016/j.physleta.2008.01.069>
 - 20 Bhattacharyya K, Effects of radiation and heat source/sink on unsteady MHD boundary layer flow and heat transfer over a shrinking sheet with suction/injection, *Front Chem Sci Eng*, 5 (2011) 376–384. <https://doi.org/10.1007/s11705-011-1121-0>
 - 21 Bhattacharyya K & Layek G C, Effects of suction/blowing on steady boundary layer stagnation-point flow and heat transfer towards a shrinking sheet with thermal radiation, *Int J Heat Mass Transf*, 54 (1-3) (2011) 302-307. <https://doi:10.1016/j.ijheatmasstransfer.2010.09.043>
 - 22 Afsana S, Molla M M, Nag P, Saha L K & Siddiqua S, MHD natural convection and entropy generation of non-Newtonian ferrofluid in a wavy enclosure, *Int J Mech Sci*, 198 (2021) p.106350. <https://doi.org/10.1016/j.ijmecsci.2021.106350>
 - 23 Rafiq M, Siddiqua S, Begum N, Mdallal Q, Hossain M, *et al.*, Non-linear radiation effect on dusty fluid flow near a rotating blunt-nosed body, *J Pro Mech Eng*, (2021) <https://doi.org/10.1177/09544089211016207>
 - 24 Jena S, Mishra S R, Pattnaik P K & Sharma R P, The nanofluid flow between parallel plates and heat transfer in the presence of chemical reaction and porous matrix, *Lat Am Appl Res*, 50 (4) (2020) 283-289. <https://doi.org/10.52292/j.laar.2020.476>
 - 25 Barik A K, Mishra S K, Mishra S R & Pattnaik P K, Multiple slip effects on MHD nanofluid flow over an inclined, radiative, and chemically reacting stretching sheet by means of FDM, *Heat transf*, 49 (1) (2020) 477-501. <https://doi:10.1002/htj.21622>
 - 26 Mishra S R, Pattnaik P K & Dash G C, Effect of heat source and double stratification on MHD free convection in a micropolar fluid, *Alex Eng J*, 54 (3) (2015) 681-689. <https://doi.org/10.1016/j.aej.2015.04.010>
 - 27 Jena S, Mishra S R & Pattnaik P K, Development in the Heat Transfer Properties of Nanofluid Due to the Interaction of Inclined Magnetic Field and Non-Uniform Heat Source, *J Nanofluids*, 9 (3) (2020) 143–151. <https://doi.org/10.1166/jon.2020.1749>
 - 28 Pattnaik P K, Mohapatra D K & Mishra S R, Influence of velocity slip on the MHD flow of a Micropolar fluid over a stretching surface, *Recent Trends in Applied Mathematics: Proceedings of AMSE*, (2019) 307-321. https://doi.org/10.1007/978-981-15-9817-3_21
 - 29 Parida S K, Mishra S R, Dash R K, Pattnaik P K, Khan M I, *et al.*, Dynamics of dust particles in a conducting water-based kerosene nanomaterial: a computational approach, *Int J Chem React Eng*, 19 (8) (2021) 1-11. <https://doi.org/10.1515/ijcre-2020-0204>
 - 30 Pattnaik P K, Parida S K, Mishra S R, Ali Abbas M & Bhatti M M, Analysis of Metallic Nanoparticles (*Cu*, *Al₂O₃* and *SWCNT*'s) on Magnetohydrodynamics Water-Based Nanofluid through a Porous Medium, *J Math*, 2022 (2022) 1-12. <https://doi.org/10.1155/2022/3237815>
 - 31 Mathur P, Mishra S R, Pattnaik P K & Dash R K, Characteristics of Darcy-Forchheimer drag coefficients and velocity slip on the flow of micropolar nanofluid, *Heat Transf*, 50 (7) (2021) 6529–6547. <https://doi.org/10.1002/htj.22191>
 - 32 Pattnaik P K, Abbas M A, Mishra S R, Khan S U & Bhatti M M, Free Convective Flow of Hamilton-Crosser Model Gold-water Nanofluid Through a Channel with Permeable Moving Walls, *Comb Chem High Throughput Screen*, 25 (7) (2022) 1103-1114. <https://doi.org/10.2174/1386207324666210813112323>
 - 33 Pattnaik P C, Mishra S R, Jena S & Pattnaik P, Impact of radiative and dissipative heat on the Williamson nanofluid flow within a parallel channel due to thermal buoyancy, *Proc Inst Mech Eng, Part N: J Nanomater Nanoeng Nanosyst*, 236 (1-2) (2022) 3-18. <https://doi.org/10.1177/23977914221080046>
 - 34 Mohanty B, Mohanty S, Mishra S R & Pattnaik P K, Analysis of entropy on the Peristaltic transport of Micropolar nanofluid: a simulation obtained using the approximate analytical technique, *Eur Phys J Plus*, 136 (2021) 1139-1152. <https://doi.org/10.1140/epjp/s13360-021-02150-z>
 - 35 Mishra S R, Hoque M M, Mohanty B & Anika N N, Heat transfer effect on MHD flow of a micropolar fluid through porous medium with uniform heat source and radiation, *Nonlinear Eng*, 8 (2019) 65–73. <https://doi.org/10.1515/nleng-2017-0126>
 - 36 Baag S, Mishra S R, Hoque M M & Nowroz A N, Magnetohydrodynamic boundary layer flow over an exponentially stretching sheet past a porous medium with a uniform heat source, *J Nanofluids*, 7 (3) (2018) 570-576. <https://doi.org/10.1166/jon.2018.1478>
 - 37 Nayak B, Mishra S R & Krishna G G, Chemical reaction effect of an axisymmetric flow over the radially stretched sheet, *Propuls Power Res*, 8 (1) (2019) 79–84. <https://doi.org/10.1016/j.jprr.2019.01.002>
 - 38 Makinde O D & Mishra S R, Chemically reacting MHD mixed convection variable viscosity Blasius flow embedded in a porous medium, *Defect Diffus Forum*, 374 (2017) 83-91. <https://doi.org/10.4028/www.scientific.net/DDF.374.83>
 - 39 Nisar K S, Mohapatra R, Mishra S R & Reddy Gnaneswara M, Semi-analytical solution of MHD free convective Jeffrey fluid flow in the presence of heat source and chemical reaction, *Ain Shams Eng J*, 12 (1) (2021) 837–845. <https://doi.org/10.1016/j.asej.2020.08.015>
 - 40 Mishra S, Choudhary R N P & Parida S K, Structural, dielectric, electrical and optical properties of Li/Fe modified barium tungstate double perovskite for electronic devices, *Ceram Int*, 48 (12) (2022) 17020-17033. <https://doi.org/10.1016/j.ceramint.2022.02.257>
 - 41 Mishra S R, Mahanthesh B, Mackolil J & Pattnaik P K, Nonlinear radiation and cross-diffusion effects on the micropolar nanoliquid flow past a stretching sheet with an exponential heat source, *Heat Transf*, 50 (4) (2021) 3530-3546. <https://doi.org/10.1002/htj.22039>
 - 42 Khan U, Zaib A, Ishak A, Alotaibi A M, Eldin S M, *et al.*, Stability Analysis of Buoyancy Magneto Flow of Hybrid Nanofluid through a Stretchable/Shrinkable Vertical Sheet Induced by a Micropolar Fluid Subject to Nonlinear Heat

- Sink/Source, *Magneto chemistry*, 8 (12) (2022) 188-199. <https://doi.org/10.3390/magnetochemistry8120188>
- 43 Madhukesh J K, Prasannakumara B C, Kumar R S V, Rauf A & Shehzad S A, flow of Hydromagnetic Micropolar-Casson nanofluid over porous disks influenced by Cattaneo-Christov theory and slip effects, *J Porous Media*, 25 (3) (2022) 35-49. <https://doi.org/10.1615/JPorMedia.2021039254>
- 44 Kumar V, Madhukesh J K, Jyothi A M, Prasannakumara B C, Khan M I, *et al.*, Analysis of single and multi-wall carbon nanotubes (SWCNT/MWCNT) in the flow of Maxwell nanofluid with the impact of magnetic dipole, *Comput Theor Chem*, 1200 (2021) p. 113223. <https://doi.org/10.1016/j.comptc.2021.113223>
- 45 Li Yun-Xiang, Hamid A, Khan M I, Elmasry Y, Qayyum Sumaira, *et al.*, Dual branch solutions (multi-solutions) for nonlinear radiative Falkner-Skan flow of Maxwell nanomaterials with heat and mass transfer over a static/moving wedge, *Int J Mod Phys B*, 32 (10) (2021) p. 2150130. <https://doi.org/10.1142/S0129183121501308>
- 46 Madhukesh J K, Ramesh G K, Prasannakumara B C, Shehzad S A & Abbasi F M, Bio-Marangoni convection flow of Casson nano liquid through a porous medium in the presence of chemically reactive activation energy, *Appl Math Mech*, 42 (8) (2021) 1191-1204. <https://doi.org/10.1007/s10483-021-2753-7>
- 47 Sowmya G & Madhukesh J K, Impact of Newtonian heating on dusty nanofluid flow over a Riga plate embedded in a porous medium, *Waves Random Complex Media*, (2022) 1-24. <https://doi.org/10.1080/17455030.2022.2098413>
- 48 Madhukesh J K, Ramesh G K, Shehzad S A, Chapi S & Kushalappa I P, Thermal transport of MHD Casson-Maxwell nanofluid between two porous disks with Cattaneo-Christov theory, *Num Heat Transf, Part-A: Applications*, 138 (2022) 1-16. <https://doi.org/10.1080/10407782.2023.2214322>
- 49 Alzahrani H A H, Alsaiani A, Madhukesh J K, Kumar R N & Prasanna B M, Effect of thermal radiation on heat transfer in plane wall jet flow of Casson nanofluid with suction subject to a slip boundary condition, *Waves Random Complex Media*, (2022) 1-18. <https://doi.org/10.1080/17455030.2022.2030502>
- 50 Kumar A, Sharma B K, Gandhi R, Mishra N K & Bhatti M M, Response surface optimization for the electromagnet hydrodynamic Cu-polyvinyl alcohol/water Jeffrey nanofluid flow with an exponential heat source, 576 (5) (2023) p. 170751. <https://doi.org/10.1016/j.jmmm.2023.170751>
- 51 Sharma P K, Sharma B K, Mishra N K & Rajesh H, Impact of Arrhenius activation energy on MHD nanofluid flow past a stretching sheet with exponential heat source: A modified Buongiorno model approach, *Int J Mod Phys B*, 37 (32) (2023) p. 2350284. <https://doi.org/10.1142/S0217979223502843>
- 52 Sharma B K, Sharma P, Mishra N K & Fernandez-Gamiz U, Darcy-Forchheimer hybrid nanofluid flow over the rotating Riga disk in the presence of chemical reaction: Artificial neural network approach, *Alex Eng J*, 76 (2023) 101-130. <https://doi.org/10.1016/j.aej.2023.06.014>
- 53 Mishra N K, Sharma B K, Sharma P, Muhammad T & Pérez L M, Entropy generation optimization of cilia regulated MHD ternary hybrid Jeffery nanofluid with Arrhenius activation energy and induced magnetic field, *Sci Rep*, 13 (1) (2023) p. 14483. <https://doi.org/10.1038/s41598-023-41299-8>
- 54 Bhattacharyya K, Hayat T & Alsaedi A, Dual solutions in boundary layer flow of Maxwell fluid over a porous shrinking sheet, *Chin Phys B*, 23 (12) (2014) p. 124701. <https://doi.org/10.1088/1674-1056/23/12/124701>