**MHD Maxwell Nanofluid Flow through a Stretching Sheet where Brownian Motion and Thermophoresis Effects are Exhibited**

**ABSTRACT**

This work provides a brief report on MHD unsteady free convection flow of viscous Maxwell nanofluid flow over a stretching sheet in the presence of radiation and the chemical reaction. The analysis explores the implications of varying parameters on the velocity and temperature profiles of the nanofluid. Additionally, the study highlights the impact of thermal radiation and reaction rates on the overall heat transfer characteristics of the system. A few nonlinear systems of partial differential equations (PDEs) that are non-dimensional by the conventional mathematical transformation technique are used to represent the model equations. The equations are then solved using the explicit finite difference method (FDEM), and the numerical results are computed using the computer programming language Compaq Visual Fortran 6.6a. The obtained numerical results demonstrate that the fluid's flow characteristic is significantly influenced by the various dimensionless factors.

**Keywords:** MaxwellNanofluid, EFDM, Stretching Sheet, MHD, Radiation.

**INTRODUCTION**

The study of fluid flow and heat transfer under the influence of magnetic fields has garnered considerable attention due to its broad applications in engineering and industrial processes, such as **cooling of nuclear reactors, crystal growth, polymer processing,** and **electromagnetic casting.** When such flow involves **non-Newtonian fluids** like Maxwell fluids, which exhibit relaxation behavior, the complexity and richness of the physics involved increase significantly. Choi (1195) was the first to conceptualise nanofluids, “which are often designed colloidal suspensions of nanoparticles in a base fluid such as water, ethylene or triethylene glycols, and other coolants. The nanoparticles include oxide ceramic (Al2O3, CuO), metal carbides (SiC), nitride (AlN, SiN), metals (Al, Cu), nonmetals (Graphite, carbon nanotubes), and layered (Al + Al2O3, Cu+C, PCM – S/S) along with oil and other lubricants (biofluids, polymer solutions)”. Likewise, the unsteady MHD free convection flow has been elucidated by Nawaz et al. (2017); Kumaran et al. (2015); Hayat et al. (2018); Will et al. (2017); Xiang Zhe et al. (2018); Kouloulias et al. (2017); Das et al. (2017); and Raju et al. (2017). The supplementary research works, in addition to the previously accomplished studies concerning nanofluids, were directed by Tanveer et al. (2018).

Maxwell fluid having the properties both of elasticity and viscosity, named after James Clerk Maxwell. As may be accurately said, the primary benefit of this type of fluid is its ability to accurately predict stress relaxation. In the past year, a technique that uses the Shooting method in conjunction with the fourth order RK method to focus on MHD and nonlinear thermal radiation in the upper-converted Maxwell nanofluid on the bidirectional stretching sheet was introduced by Billal et al. (2017), Singh et al. (2018), Srikantha et al. (2015), Shin et al. (2017), and Sheikholeslmi et al. (2018). On the other hand, Aman et al. (2018) investigated the heat, “shear stress, and velocity in order to assess the precise solutions of the problem with the direct aid of a Mathcad graphical depiction”.

Al-Odat and Al-Azab (2007) looked at the homogeneous and heterogeneous aspects of the reaction order and how it greatly affects the influence of chemical reactions. Salawu et al. (2016); Pattnaik et al. (2018); Pontes et al. (2019); Mahmood et al. (2017), and Irfan et al. (2017) have capitalised on the effects of thermal conductivity and changing viscosity on the inclined magnetic field with dissipation in a non-Darcy medium. Apart from the aforementioned example, Reddy et al. (2017); Al-Yahia et al. (2017); and Lu et al. (2018) have discussed “the MHD flow and heat transfer properties of Williamson nanofluid”.

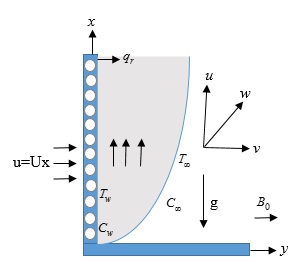
In a moving fluid, where the relationships between the fluxes and the driving potentials are more complex, heat and mass transfer happen simultaneously. In addition to illustrating the effects of various parameters on velocity, temperature, and concentration profiles, Seth et al. (2014), Biswas et al. (2018), Makinde et al. (2011), Mondal et al. (2018), and Liu et al. (2018) initiated “the effects of Hall current, radiation, and rotation on natural convection heat and mass transfer flow”. Furthermore, Asanambigai et al. (2018) have used these kinds of studies.

The movement of electrically conducting fluids in electric and magnetic fields is the subject of magnetohydrodynamics (MHD), a branch of magnetofluid dynamics. Biswas et al. (2017, 2018), Ahmmed et al. (2018), Alharbi et al. (2018), Huminic et al. (2018), Uddin et al. (2016), Jena et al. (2018), and Afikuzzaman et al. (2015) have all provided illustrations of the characterisation of chemical reactions to heat transfer. MHD Casson fluid flow, whereas Sharma et al. (2010) have been responsible for the Steady MHD natural convection flow.Likewise, Dufour and Soret effects on steady MHD free Convective flow have been analysed by kabeel et al. (2014) and radiation and mass transfer effects on unsteady MHD convective flow have been elaborated by Yuan et al. (2018). Also, Ramya et al. (2023-2025) have presented this types of work which are very effective in this type of field.

Studying the unsteady MHD heat and mass transfer of Maxwell nanofluid flow across a stretching sheet with thermal conductivity, radiation absorption, and a heat source is the goal of the aforementioned study. These are then made non-dimensional, and a mathematical solution of the flow-controlling model, including transient momentum, energy, and concentration equations, is numerically constructed using the explicit finite difference method (EFDM). We compute our findings for a number of physical attributes and present them in tabular and graphical form.

**MATHEMATICAL ANALYSIS OF THE PROBL**

Here, the behaviour of thermal radiation, thermal diffusion, and heat absorption in the Maxwell nanofluid flow of an electrically conducting viscous incompressible fluid is acknowledged. The y-axis is considered normal to the plate in this evaluation, while the x-axis is extracted on the plate in the diagonally upsloping drift. A uniform magnetic field of strengthis appertained transversely to the y-direction and the velocity of the stretching surface is apprehended with u=Ux. It is speculated that the temperature of the plate is conjectured to be Tw and concentration at the plate is Cw at the initial stage, but at time t >0, the temperature and the concentration level of the plate are escalated exponentially to T∞ and C∞  with time t. The substantial disposition and coordinate system are portrayed in **Figure 1**.



**Fig.1.** Physical model and coordinate system

Beneath these speculations the dimensional continuity, momentum, energy and concentration equations of Maxwell nanofluid boundary layer flow are as follows: [Biswas et al. (2017), Biswas et al. (2018), Ahmmed et al. (2018)]

|  |  |
| --- | --- |
|  | (1) |
|  | (2) |
|  | (3) |
|  | (4) |

The inchoate boundary conditions are:

|  |  |  |
| --- | --- | --- |
|  |  | (5) |

The ensuing dimensionless variables that are accustomed to procure the partial differential equations in terms of dimensionless variables as

|  |  |
| --- | --- |
| ; | (6) |

Now we deputize the values of above derivatives into the equations (1) to (4) and we have accumulated the succeeding nonlinear coupled partial differential equations are:

|  |  |
| --- | --- |
|  | (7) |
|  | (8) |
|  | (9) |
|  | (10) |

Also, the affiliate boundary conditions are:

|  |
| --- |
|  |

The subsequent assertion delineates the physical quantity of Skin friction, Nusselt number and Sherwood number are:

|  |  |
| --- | --- |
|  | (11) |

Stream function ψ(X,Y) appeases the continuity equation and the incidental velocity ingredients as:

|  |  |
| --- | --- |
|  | (12) |

**NUMERICAL TECHNIQUE OF THE PROBLEM**

To retrieve the difference equations, the domain of the flow is segregated into a grid or mesh of lines parallel to X and Y axis where X-axis is endured along the plate in the vertically ascending tenor and the Y-axis is espoused normal to the plate. It has been ascertained that ΔX, ΔY are constant mesh sizes along X and Y directions respectively and **reserved** as follows, ΔX=0.83 (0≤X≤125), ΔY=0.83 (0≤Y≤125) with the smaller time-step, Δτ=0.0005.



**Figure 2** The finite difference space grid

Then the explicit finite difference conjecture underneath as:

|  |  |
| --- | --- |
|  | (13) |
|  |  |
|  |  |
|  | (14) |
|  |  |
|  | (15) |
|  |  |
|  | (16) |

In this contingency, the associate boundary conditions for the above equations are:

|  |  |
| --- | --- |
|  | (17) |

**STABILITY AND CONVERGENCE ANALYSIS**

This perusal is a numerical interpretation which model is elucidated by explicit finite difference method (EFDM). So, the aspiration is persisted unmellow without the stability convergence test (SCT). The predominant term of the Fourier expansion for at a despotically time τ=0 are all eiαX eiβY apart form a constant, where. At a time, these denominations become

|  |  |
| --- | --- |
|  | (18) |

After the time step,

|  |  |
| --- | --- |
|  | (19) |

For stability test, and satisfied allowable values are A1= -1, A4= -2 and A5= -1. Therefore, the stability conditions are obtained for the above equations (13) to (16) by solving as follows:

|  |  |
| --- | --- |
|  | (20) |
|  | (21) |
|  | (22) |

Since the initial condition, U=V=0 at τ=0. So, the equations (20) to (22) present Pr≥ 0.54 and Sc≥0.025 respectively.

**RESULTS AND DISCUSSION**

The substantial locus of the contemporary predicament, velocity, temperature, concentration, skin friction coefficient, Nusselt number, Sherwood number, streamlines and isotherms are annexed by exponential values of divergent criterions functioning as M, Kp, Sc, Pr, Gr, Gm, Rd, Nt, Nb, Le, Mx and G, which are evinced in Fig. 3-7. To procure the accuracy of the numerical culminations, the consecutive values of **conventional** parameter are ruminated as: M=1, Pr=0.71, Sc=0.22, Rd=1.0, S=1, Nb=0.1, Nt =0.1, Le=5, G=1, Gm=5, Gr=10, Mx=0.01 and Kp=1with time τ=1.

The stature of multifarious values of Gr, Gm, S, M, Kp, Mx, Nt, Nb, Rd and λ on velocity portraits are unveiled in Fig. 3 and Fig. 4 respectively. It is appraised that velocity depictions are inflating with the intensification of Gr, Gm & S and on the other hand velocity profiles are decreasing by the increasing of M, Kp and Mx which are disposed in Fig. 3(a) and 3(b).

|  |  |
| --- | --- |
| Y  (*a*)  U | (*b*)  U  Y |

**Fig. 3** Illustration of (a) Velocity profiles for different values of Gr, Gm and S and (b) Velocity profiles for different values of M, Kp and Mx

The repercussions of Pr, M, Nb, Nt, Rd and S on temperature rundowns are flaunted in Fig. 4. From Fig. 4(a) it is denominated that temperature outlines are dwindled with the exacerbation of Pr and M, because of which prompted a resistive force in the fluid but temperature is accumulated with the aggravation of Nb, Nt, Rd and S which are disported in the Fig. 4(b). Generally, heat source parameter and radiation parameterpledges more heat into the fluid, which leads to escalation of the thermal boundary layer thickness by accruing the values of radiation parameter*.*

|  |  |
| --- | --- |
| (*a*)    Y | (*b*)    Y |

**Fig. 4** Illustration of (a) Temperature profiles for different values of Pr and M (b) Temperature profiles for different values of Nb, Nt, Rd and S.

The ramifications of Sc, Le and G on concentration contours are divulged in Fig. 5. It is perceived that concentration silhouettes wane to the magnification of Sc, Le and G. Physically, the inducement urging this etiquette is that Schmidt number characterizes the ratio of thermal diffusivity to mass diffusivity.

|  |  |
| --- | --- |
| (*a*)    Y | (*b*)    Y |

**Fig. 5** Illustration of (a) Concentration profiles for different values of Scand Le (b) Concentration profiles for different values of G and Sc.

The ramifications of M, on streamlines and isotherms are paraded in Fig. 6(a) and Fig. 6(b). It is contemplated that momentum boundary layer thickness aggravates attributable to the accrual of magnetic parameter from M=1.0 to M=2.0. It incarnates the velocity direction of fluids correspondingly. The streamlines can be accumulated by depicting lines tangent to the flags. Here, it is procured that thermal boundary layer thickness truncates by the complement of M from M=1.0 to M=2.0. Also, the denouement of Nt on streamlines and isotherms are elucidated in Fig. 7(a) and Fig. 7(b). Here, we implemented that both momentum and thermal boundary layer thickness are exaggerating for the distension of Nt from Nt =0.50 to Nt =1.00.

|  |  |
| --- | --- |
| (*a*)  X  Y | (*b*)  X  Y |

**Fig. 6** Illustration of (a) Streamlines for M=1.00 to M=2.00 and (b) Isotherms for M=1.00 to M=2.00.

|  |  |
| --- | --- |
| (*a*)  X  Y | (*b*)  X  Y |

**Fig. 7** Illustration of (a) Streamlines for Nt =0.50 to Nt =1.00 and (b) Isotherms for Nt =0.50 to Nt =1.00.

**Table 1** delineates the numerical values of discrete parameters such as Pr, Rd, Nb, Nt, M, Le and Mx on Nusselt number (Nu) and Sherwood number (Sh). It is explicated that Nusselt number is an elevating function of just for Pr because convective heat transfer amplifies with the waxing of Nusselt number whereas this tendency is quite opposite for permeability of Rd, Nb, Nt, M, Le and Mx. In our handiwork, Nusselt number is elongating with the addendum of Nb but there is no amendment in the works of Macha Madhua et al. (2017). Also it is perceived that the Sherwood number burgeons with the uptrend of Rd, Nb, M, Le and Mx but constricts qualitatively with the snowballing of Pr and Nt. Generally, convective mass transfer is augmented with the extension of Sherwood number but when it is deflated then the antithetical surveillances are supervened.

**Table 1.** Deviation of diverse parameters on Nusselt number and Sherwood number with a analogy of contemporary compositionMacha Madhua et al. (2017).

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | Parameters |  |  |  | Macha Madhua et al. (2017) | Present Value | Macha Madhua et al. (2017) | Present Value |
| Pr | Rd | Nb | Nt | Le | M | Mx | Nu | Nu | Sh | Sh |
| **0.71**  **1.00**  **2.00**  **3.00** | **1** | **0.1** | **0.1** | **5** | **1** | **0.1** | **0.459556**  0.574585  0.899109  1.157085 | **0.379840**  0.568960  0.764983  1.102369 | **-0.42468**  -0.532285  -0.837096  -1.08057 | **-0.403892**  -0.517395  -0.818394  -1.028450 |
|  | **2.00**  **3.00**  **4.00** |  |  |  |  |  | 0.344448  0.285467  0.249527 | 0.289378  0.263909  0.227390 | -0.317242  -0.262289  -0.228835 | -0.317242  -0.262289  -0.228835 |
|  |  | **0.20**  **0.30**  **0.40** |  |  |  |  | 0.459556  0.459556  0.459556 | **0.379200**  **0.402363**  **0.437458** | -0.21234  -0.14156  -0.10617 | -0.203742  -0.182934  -0.120439 |
|  |  |  | **0.20**  **0.30**  **0.40** |  |  |  | 0.456449  0.453426  0.450424 | 0.426484  0.404785  0.390553 | -0.843579  -1.25694  -1.66475 | -0.804633  -1.268594  -1.794034 |
|  |  |  |  | **10.0**  **20.0**  **30.0** |  |  | 0.459161  0.458762  0.458595 | 0.404739  0.387495  0.354902 | -0.404541  -0.37415  -0.350029 | -0.394854  -0.357493  -0.350043 |
|  |  |  |  |  | **0.50**  **1.00**  **1.80** |  | 0.431313  0.397747  0.377644 | 0.384599  0.349603  0.338590 | -0.398711  -0.367638  -0.34887 | -0.346394  -0.335667  -0.304593 |
|  |  |  |  |  |  | **0.5**  **1.0**  **1.5** | 0.456972  0.452147  0.447249 | 0.440593  0.404632  0.384598 | -0.422324  -0.417928  -0.413457 | -0.404634  -0.385476  -0.374683 |

**CONCLUSIONS**

The assessment of MHD unsteady free convection flow of viscous Maxwell nanofluid flow over a stretching sheet is the main focus of this work. The non-Newtonian nanofluid etiquette was singularised by manipulating the Maxwell embodiment. Using explicit finite difference methods, the coupled non-linear ordinary differential equations were explained. Because convective heat transmission increases with the Nusselt number surge, it was discovered that Nusselt number is a prolonged function of only for Pr. Additionally, the Sherwood number decreases qualitatively with the spiral of Pr and Nt but improves with the quadrupling of Rd, Nb, M, Le, and Mx. A resistive force is created in the fluid as a result of the addition of the Brownian motion parameter, thermophoresis parameter, radiation parameter, and heat source parameter. Additionally, the denouement of radiation parameter Rd on streamlines and isotherms is examined, and temperature contours are downscaled with the addition of Prandtl number and magnetic parameter.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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