SYNOPSIS

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MATHEMATICAL MODELLING OF ELECTRICALLY CONDUCTING FLUID FLOW PROBLEMS IN PRESENCE OF MAGNETIC FIELD

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Substances that flow when shear stress is applied are referred to be fluids. Gases and liquids are both fluids. In general, fluids are split into two categories namely, Newtonian and Non-Newtonian fluids. Newtonian fluids include substances like water, benzene, alcohol, & hexane, and many more that correspond to Newton's law of viscosity. Non-Newtonian fluids, such as pastes, gels, polymer solutions, Carreau fluid, Williamson fluid, Micropolar fluid, etc., are those that oppose Newton's law of viscosity. The research of non-Newtonian fluids has great importance because of numerous industrial and engineering applications. Specifically, such fluids are used in prescribed pharmaceuticals, physiology, material processing, fiber technology, chemical and nuclear industries, oil reservoir engineering and foodstuffs. Examples of such fluids are shampoos, apple sauce, ketchup, blood at low shear rate, polymer solutions, paints, food products, milk, coating of wires, grease, crystal growth, and many others.

The study of electrically conducting fluid flow in the presence of magnetic field is known as magnetohydrodynamics (MHD). This includes liquid metals like gallium, mercury, and sodium in addition to molten iron. Petroleum, chemical, and metallurgical processing industries provide as the best examples of the significance of magnetohydrodynamic (MHD) fluid flow over a deforming body. Additional real-world applications include surface cooling in technology, wind-up roll processes, and polymer film. The study of magnetohydrodynamics has advanced significantly in the last few decades as a result of Hartmann's ground-breaking work [1] on liquid metal duct flows in the presence of an external magnetic field.

Entropy is a measure of molecular disorder or randomness. In the current time, one of main concerns of engineers and researchers is to invent the procedures which control the consumption of proficient energy. In the field of thermal engineering, the key objective is to achieve the maximum efficiency of devices and with the minimum loss of heat, friction and dissipation during the mechanical processes. The study of entropy generation minimization has gained significant attention in various energy involving problems which include, thermal energy, cooling of the modern electronic system, geothermal energy system, and solar power collectors etc. Turkyilmazoglu [2] considered MHD fluid flow. Kataria and Mittal [3] deals with MHD fluid flow in the presence of thermal radiation, whereas Kataria et al. [4] deals with MHD Micropolar fluid. Rashidi et al. [5] discussed MHD fluid flow over vertical stretching sheet in the presence of buoyancy effects. Abel and Mahesha [6] scrutinized effect of heat transfer in MHD viscoelastic fluid flow. Rashidi et al. [7] explored entropy generation in steady MHD fluid flow. Das et al. [8] discussed entropy analysis of MHD fluid flow over stretching sheet. Above literature lack vital conditions like entropy optimization, viscous dissipation, joule heating, heat generation and non-linear radiation (which are useful in real world applications) are carried out in work done by **Kataria and Mistry [32]** and **Kataria et al. [33]**.

The diverse applications of non-Newtonian fluids in engineering and manufacturing processes have recently drawn researchers' attention. These fluids have the characteristic that the connection between stress and deformation rate is nonlinear. Molten polymers, pulps, and Chyme are examples of this type of fluid. Due to its many applications in industry, including the extrusion of polymer sheets, emulsion-coated sheets like photographic films, solutions and melts of high molecular weight polymers, etc. Williamson [9] initially introduced Williamson fluid model in his groundbreaking study on the flow of pseudo-plastic materials. He created a model equation to describe the movement of pseudo-plastic fluids, and an experiment to test this theory. Williamson fluid flow over a stretching surface was investigated by Shah et al. [10]. Anantha Kumar et al. [11] explored time-independent MHD Williamson fluid flow. Variable viscosity, chemical reactions, Soret and Dufour effects play significant role in the study of Williamson fluids. We have included these in **Chapters 4 and 7**.

Carreau fluid model is another category of non-Newtonian fluids. Such a model has applications in manufacturing processes such as aqueous, and melts. The shear thickening and shear thinning properties of many non-Newtonian fluids are also described by this model. Many scholars have dedicated their effort to explore the properties of such models due to the wide range of applications of the Carreau model in technological processes. The behavior of polymer suspensions in many flow issues is compatible with the Carreau fluid. It is an example of a pure viscous fluid whose viscosity varies with the rate of deformation. The fluid viscosity is based on the shear rate in a model created by Carreau et al. [12]. Carreau fluid flow with convective condition addressed by Madhu et al. [13]. Patel [14]found that heat generation have an effect on MHD Carreau fluid flow in a porous media. The effects of variable viscosity on MHD Carreau fluid flow were investigated by Abbas et al. [15]. We have included non linear stretch, mass and energy fluxes due to the temperature and concentration gradients in the study of Carreau fluid in **Chapter 5**.

Micropolar fluids are fluids with microstructure and asymmetrical stress tensor. Physically, they represent fluids consisting of randomly oriented particles suspended in a viscous medium. These types of fluids are used in analyzing liquid crystals, fluid flowing in brain, lubricants and the flow of colloidal suspensions. The theory of Micropolar fluids was developed by Eringen [16, 17]. The comprehensive literature on Micropolar fluids and their applications were presented by Das [18] and Narayana et al. [19]. Chaudhary and Jha [20] examined MHD Micropolar fluid flow past a vertical plate. Later, Waqas et al. [21] found effect of radiation on Micropolar liquid. To apply this model efficiently, characteristics like unsteady behavior, chemical reaction, electric field and viscous dissipation need to be involved in the study. **Kataria and Mistry [36]** and **Kataria et al. [37]** have taken care of these aspects.

To find the precise solution, numerous numerical methods have been developed. However, because of various limitations, scientists have looked at alternative methodologies. Among these techniques, the Homotopy Analysis Method (HAM) developed by Liao [22] is one of the most effective techniques for obtaining series solutions of various strongly nonlinear equations, including coupled, decoupled, homogeneous, and non-homogeneous equations. It can give us a straightforward method to ensure the convergence of solution series and yield better results than other techniques developed by Abumandour et al. [24], Elmaboud and Abdelsalam [25], Kataria and Mittal [26], Li et al. [27]. Researchers have recently started to find answers to a variety of fluid flow problems (Daniel [28], Hayat et al. [29], Patel [30]), using HAM .

This thesis consists of eight chapters.

Chapter 1

Fundamentals and applications of MHD fluid flow, mathematical models of Williamson fluid, Carreau fluid, and Micropolar fluids effects of heat and mass transfer, radiation, heat generation and absorption, Joule heating, viscous dissipation, Soret and Dufour effects, boundary conditions like slip condition and convective boundary conditions, linear and nonlinear stretching sheets are all covered in this Chapter. A review of pertinent literature has been done.

Chapter 2:

Entropy optimized MHD fluid flow over a vertical stretching sheet

Entropy optimization is used to enhance the system performance. Entropy generation is caused due to heat fluxes, Joule heating and dissipation etc. To make the systems for good productivity we decrease the entropy optimization of the system. MHD fluid flow research is important because it has numerous engineering applications. For example, slurry flows, industrial oils, diluted polymer solutions.

In **chapter 2**, effects of magnetic field and radiation are studied on Entropy optimized MHD fluid flow in presence of joule heating, heat generation/absorption and viscous dissipation impact with slip condition and convective boundary condition. Stretching sheet velocity in the direction of x is $U_w(x) = ax$, with initial stretching rate $a > 0$. Magnetic field $\mathcal{B} = B_0$ is applied in the perpendicular direction of the flow. The equations which are governed for all these assumptions, are derived using Boussinesq's approximation. They are as follows.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2}{\rho}u + g\beta_T(T - T_\infty), \tag{2}$$

$$\rho C_p\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \kappa\frac{\partial^2 T}{\partial y^2} + \mu\left(\frac{\partial u}{\partial y}\right)^2 + \sigma B_0^2 u^2 + Q^*\left(T - T_\infty\right) - \frac{\partial q_r}{\partial y}, \tag{3}$$

with boundary conditions

$$u = U_w + L\frac{\partial u}{\partial y},\ v = v_w,\ -\kappa\frac{\partial T}{\partial y} = h_f\left(T_w - T\right) \ \text{ at } \ y = 0. \tag{4}$$

$$u \to 0,\ T \to T_\infty \ \text{ as } \ y \to \infty. \tag{5}$$

where, velocity components $(u,\ v)$ in the ways $(x,\ y)$, respectively, we have an injection for $v_w\left(x\right) < 0$ and suction for $v_w\left(x\right) > 0$.

Radiative heat flux [31] is:

$$q_r = -\frac{16\sigma^*}{3k^*}T_\infty^3\frac{\partial T}{\partial y}, \tag{6}$$

The similarity variable is defined as $\eta = \sqrt{\frac{a}{\nu}}y$ and the stream function is defined as $\psi = \sqrt{a\nu}\ xf\left(\eta\right)$. From η and ψ, we get

$$u = \frac{\partial\psi}{\partial y} = axf'\left(\eta\right),\ \ v = -\frac{\partial\psi}{\partial x} = -\sqrt{a\nu}f\left(\eta\right),\ \ \theta\left(\eta\right) = \frac{T - T_\infty}{T_w - T_\infty}, \tag{7}$$

Continuity equation (1) is satisfied. Equations (2)-(5) will reduced in the following form:

$$f''' + Gr_T\theta + ff'' - \left(f'\right)^2 - Mf' = 0, \tag{8}$$

$$\left(1 + \frac{4}{3}Rd\right)\theta'' + Prf\theta' + Brf''f'' + MBrf'f' + Pr\beta\theta = 0, \tag{9}$$

with

$$f\left(\eta\right) = S,\ f'\left(\eta\right) = 1 + \gamma f''\left(\eta\right), \theta'\left(\eta\right) = -Bi\left(1 - \theta\left(\eta\right)\right),\ \text{at } \eta = 0,$$

$$f'\left(\eta\right) \to 0,\ \theta\left(\eta\right) \to 0,\ \text{as } \eta \to \infty, \tag{10}$$

where Thermal Grashof number $Gr_T = \frac{g\beta_T(T_w - T_\infty)}{a^2x}$, Magnetic parameter $M = \frac{\sigma B_0^2}{a\rho}$, Prandtl number $Pr = \frac{\mu C_p}{\kappa}$, Radiation parameter $Rd = \frac{4\sigma^*T_\infty^3}{3k^*\kappa}$, Suction/Injection parameter $S = -\frac{v_w}{\sqrt{a\nu}}$, Velocity slip parameter $\gamma = L\sqrt{\frac{a}{\nu}}$, Eckert number $Ec = \frac{U_w^2}{C_p(T_w - T_\infty)}$, Heat generation/absorption coefficient $\beta = \frac{Q^*}{a\rho C_p}$, Biot number $Bi = \sqrt{\frac{\nu}{a}}\frac{h_f}{\kappa}$ and Brinkman number $Br = PrEc$.

Velocity gradient $C_{fx} = \frac{\tau_w}{\rho U_w^2}$, where shear stress $\tau_w = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0}$ then Skin friction factor $C_{fx}Re_x^{\frac{1}{2}} = f''\left(0\right)$, and temperature gradient $Nu_x = \frac{xq_w}{\kappa\left(T_w - T_\infty\right)}$, where heat flux $q_w = -\kappa\left(\frac{\partial T}{\partial y}\right)_{y=0}$ then Nusselt number $Nu_xRe_x^{-\frac{1}{2}} = -\left(1 + \frac{4}{3}Rd\right)\theta'(0)$, where local Reynold number $Re_x = \frac{xU_w}{\nu}$.

The local entropy generation rate is defined as

$$\mathcal{S}_G = \frac{\kappa}{T_\infty^2}\left(1 + \frac{16\sigma^*T_\infty^3}{3\kappa k^*}\right)\left(\frac{\partial T}{\partial y}\right)^2 + \frac{\mu}{T_\infty}\left(\frac{\partial u}{\partial y}\right)^2 + \frac{\sigma B_0^2}{T_\infty}u^2, \tag{11}$$

Entropy generation rate is given by

$$\mathcal{N}_G = \alpha_1 \left(1 + \frac{4}{3}Rd\right)\theta'^2 + Brf''^2 + MBrf'^2. \quad (12)$$

Bejan number $= \dfrac{\text{Heat and mass transfer entropy generation}}{\text{Total entropy generation}}$

$$Be = \frac{\alpha_1 \left(1 + \frac{4}{3}Rd\right)\theta'^2}{\alpha_1 \left(1 + \frac{4}{3}Rd\right)\theta'^2 + Brf''^2 + MBrf'^2} \quad (13)$$

where $\mathcal{N}_G = \dfrac{T_\infty \nu \mathcal{S}_G}{a\kappa(T_w - T_\infty)}$ denotes entropy generation rate, $\alpha_1 = \dfrac{T_w}{T_\infty} - 1$ is temperature difference parameter.

Method of Homotopy Analysis

Homotopy method is a basic concept of topology. Liao [22] proposed HAM is used in Equations (8)-(9) with boundary conditions (10). Initial guesses $f_0(\eta)$, $\theta_0(\eta)$ and auxiliary linear operators $\mathcal{L}_f$, $\mathcal{L}_\theta$ for the HAM solution can be chosen as

$$f_0(\eta) = S + \frac{1}{1+\gamma}\left(1 - e^{-\eta}\right), \theta_0(\eta) = \frac{Bi}{1+Bi}e^{-\eta}, \quad (14)$$

$$\mathcal{L}_f = \frac{\partial^3 f}{\partial \eta^3} - \frac{\partial f}{\partial \eta}, \mathcal{L}_\theta = \frac{\partial^2 \theta}{\partial \eta^2} + \frac{\partial \theta}{\partial \eta}, \quad (15)$$

with $\mathcal{L}_f\left(k_1 + k_2 e^{\eta} + k_3 e^{-\eta}\right) = 0,\ \mathcal{L}_\theta\left(k_4 + k_5 e^{-\eta}\right) = 0$, where $k_1, k_2, \ldots, k_5$ are arbitrary constants.

Zero-th order problems of deformation

The following is the problem of zeroth order deformation:

$$\left.\begin{aligned} (1-q)\,\mathcal{L}_f\left[F(\eta;q) - f_0(\eta)\right] &= q\hbar_f \mathcal{N}_f\left[F(\eta;q)\right], \\ (1-q)\,\mathcal{L}_\theta\left[\Theta(\eta;q) - \theta_0(\eta)\right] &= q\hbar_\theta \mathcal{N}_\theta\left[\Theta(\eta;q)\right], \end{aligned}\right\} \quad (16)$$

The following is a list of nonlinear operators:

$$\mathcal{N}_f\left[F(\eta;q)\right] = \frac{\partial^3 F}{\partial \eta^3} + F\frac{\partial^2 F}{\partial \eta^2} - \left\{\frac{\partial F}{\partial \eta}\right\}^2 - M\frac{\partial F}{\partial \eta} + Gr_T\Theta, \quad (17)$$

$$\mathcal{N}_\theta\left[\Theta(\eta;q)\right] = \left(1 + \frac{4}{3}Rd\right)\frac{\partial^2 \Theta}{\partial \eta^2} + PrF\frac{\partial \Theta}{\partial \eta} + Br\left(\frac{\partial^2 F}{\partial \eta^2}\right)^2 + MBr\left(\frac{\partial F}{\partial \eta}\right)^2 + Pr\beta\Theta, \quad (18)$$

Boundary conditions subject to:

$$F(0;q) = S,\ F'(0;q) = 1 + \gamma F''(0;q),\ \Theta'(0;q) = -Bi(1 - \Theta(0;q)),\ F'(+\infty;q) = 0,\ \Theta(+\infty;q) = 0 \quad (19)$$

where F and Θ are unknown functions in terms of η and q, non-zero auxiliary parameters $\hbar_f$ and $\hbar_\theta$, non-linear operators $\mathcal{N}_f$ and $\mathcal{N}_\theta$. Furthermore where, embedding parameter $q \in (0, 1)$.

$$F(\eta; 0) = f_0(\eta), F(\eta; 1) = f(\eta), \tag{20}$$

$$\Theta(\eta; 0) = \theta_0(\eta), \Theta(\eta; 1) = \theta(\eta). \tag{21}$$

If q varies from 0 to 1 then, F, Θ will be varies from $f_0(\eta)$, $\theta_0(\eta)$ to $f(\eta)$, $\theta(\eta)$. So one can obtain:

$$F(\eta; q) = f_0(\eta) + \sum_{i=1}^{\infty} f_i(\eta) q^i, \tag{22}$$

$$\Theta(\eta; q) = \theta_0(\eta) + \sum_{i=1}^{\infty} \theta_i(\eta) q^i, \tag{23}$$

where

$$f_i(\eta) = \frac{1}{i!} \frac{\partial^i f(\eta; q)}{\partial \eta^i}\bigg|_{q=0}, \tag{24}$$

$$\theta_i(\eta) = \frac{1}{i!} \frac{\partial^i \theta(\eta; q)}{\partial \eta^i}\bigg|_{q=0}, \tag{25}$$

here $\hbar_f$ and $\hbar_\theta$ are very important for the convergence of the series. If the non-zero auxiliary parameters are chosen in such a way that equations (22) and (23) converges at $q = 1$. Thus, the following can be obtained:

$$F(\eta; q) = f_0(\eta) + \sum_{i=1}^{\infty} f_i(\eta), \tag{26}$$

$$\Theta(\eta; q) = \theta_0(\eta) + \sum_{i=1}^{\infty} \theta_i(\eta), \tag{27}$$

i-th order deformation equation

The deformation equations in i^{th} order can be presented in the form

$$\mathcal{L}_f[f_i(\eta) - \chi_i f_{i-1}(\eta)] = \hbar_f \mathcal{R}_{f,i}(\eta), \tag{28}$$

$$\mathcal{L}_\theta[\theta_i(\eta) - \chi_i \theta_{i-1}(\eta)] = \hbar_\theta \mathcal{R}_{\theta,i}(\eta), \tag{29}$$

Under the conditions of the boundary

$$f_i(0) = 0, f_i'(0) = \gamma f_i''(0), \theta_i'(0) = Bi\theta_i(0),\ f_i'(+\infty) = 0, \theta_i(+\infty) = 0. \tag{30}$$

Where,

$$\mathcal{R}_{f,i}(\eta) = f_{i-1}''' + \sum_{k=0}^{i-1} f_k f_{i-1-k}'' - \sum_{k=0}^{i-1} f_k' f_{i-1-k}' - M f_{i-1}' + Gr_T \theta_{i-1}, \tag{31}$$

$$\mathcal{R}_{\theta,i}(\eta) = \left(1+\frac{4}{3}Rd\right)\theta''_{i-1} + Pr\sum_{k=0}^{i-1} f_k\theta'_{i-1-k} + Br\sum_{k=0}^{i-1} f''_k f''_{i-1-k} + MBr\sum_{k=0}^{i-1} f'_k f'_{i-1-k} + Pr\beta\theta_{i-1}, \quad (32)$$

with

$$\chi_i = \begin{cases} 0, & i \le 1 \\ 1, & i \ge 1 \end{cases} \quad (33)$$

The general solutions f_i, θ_i comprising the special solution f_i^*, θ_i^* are given by $f_i(\eta) = f_i^*(\eta) + k_1 + k_2 e^{\eta} + k_3 e^{-\eta}, \theta_i(\eta) = \theta_i^*(\eta) + k_4 + k_5 e^{-\eta}$. where the constants k_j $(j = 1, 2, \ldots, 5)$ can be found by the boundary conditions.

Convergence analysis

Solutions for HAMs are highly dependent on values for auxiliary parameters $\hbar_f$ and $\hbar_\theta$ that influence convergence. As a result, the figure show corresponding $\hbar$-curve. For the values $\hbar_f = -0.94$, $\hbar_\theta = -0.47$, we get convergence of the solution [23].

Effects of velocity slip parameter, Radiation parameter, Prandtl number and Magnetic parameter on velocity, temperature and entropy generation rate are perceived through various graphs. For the stretching sheet, expression of , Nusselt number and Bejan number are discussed through graphs and tabular form.

This Result is published in **Heat transfer (Wiley) (Scopus) (Ref.[32]).**

Chapter 3:

Effect of nonlinear radiation on MHD fluid flow considering mass transfer

Mass transfer phenomena is found everywhere in nature. The transport of one component in a mixture from a region of higher concentration to one of lower concentration is called mass transfer. Mass transfer finds application in industrial and chemical engineering processes. Such a flow caused by density difference which in turn caused by concentration difference is known as mass transfer flow. Some examples of mass transfer flow are evaporation of water from pond, lake, water reservoir to the atmosphere, separation of chemical species in distillation columns, the diffusion of impurities in rivers, oceans, etc.

In processes comprising high temperature like polymer processes, nuclear power plants, glass production, gas turbines etc. radiation contributes an important role. So, above work is extended in **Chapter 3**, considering mass transfer and nonlinear radiation.

$$\rho C_p \left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} \right) = \kappa \frac{\partial^2 T}{\partial y^2} + \mu \left(\frac{\partial u}{\partial y} \right)^2 + \sigma B_0^2 u^2 + Q^* \left(T - T_\infty \right) - \frac{\partial q_r}{\partial y}, \tag{34}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_M \frac{\partial^2 C}{\partial y^2}, \tag{35}$$

with boundary conditions

$$u = U_w + U_{Slip},\ v = v_w,\ -\kappa\frac{\partial T}{\partial y} = h_f \left(T_w - T \right),\ C = C_w \ \text{ at } \ y = 0. \tag{36}$$

$$u \to 0,\ T \to T_\infty\ C \to C_\infty \ \text{ as } \ y \to \infty. \tag{37}$$

Nonlinear radiation is given by Rosseland approximation [31]

$$q_r = -\frac{16\sigma^* T^3}{3k^*}\frac{\partial T}{\partial y}, \tag{38}$$

Solution is obtained using HAM and discussed in detail. Effect of Temperature ratio parameter, Slip parameter, Schmidt number on velocity, temperature and concentration are discussed through graphs. effect of Diffusion parameter and Magnetic parameter on rate of entropy generation and Bejan number are explained through graphs. factor, Nusselt number and Sherwood number are calculated in tables.

Results of Chapter 3 are published in **International Journal of Ambient Energy (Taylor and Fransis) (Scopus) (Ref[33])**.

Chapter 4:

Soret and Dufour impact on MHD Williamson fluid flow with varying viscosity

Williamson fluid is characterized as a non-Newtonian fluid with shear thinning property i.e., viscosity decreases with increasing rate of shear stress. Chyme in small intestine is one of the example of Williamson fluid. The viscosity of the fluid mainly depends upon temperature of the fluid along with fluid nature. At high temperature, the viscosity cannot be considered as constant; instead, it should be a temperature dependent variable. The assumption of constant viscosity leads to measurable inaccuracies while calculating the surface calculating factors. In the next **Chapter 4**, MHD Williamson fluid flow with varying viscosity is considered.

It shows incompressible MHD Williamson fluid flow past a stretching sheet. It is assumed that the

sheet is stretching with the plane $y = 0$ and that the flow is constrained to $y > 0$. In the scenario where $a > 0$ is constant and the x-axis is estimated along the extending surface, with stretching velocity $u(x) = ax$. A uniform magnetic field that is applied perpendicular to an expanding sheet.
The governing equations for Williamson fluid are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{39}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = \frac{1}{\rho}\frac{\partial}{\partial y}\left(\mu\left(T\right)\frac{\partial u}{\partial y}\right) + \frac{\Gamma}{\sqrt{2}\rho}\frac{\partial}{\partial y}\left[\mu\left(T\right)\left(\frac{\partial u}{\partial y}\right)^2\right] - u\frac{\sigma B^2}{\rho} + g\beta_C(C - C_\infty) + g\beta_T(T - T_\infty), \tag{40}$$

$$\rho C_p\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \kappa\frac{\partial^2 T}{\partial y^2} + \frac{\rho D_M K_T}{C_s}\frac{\partial^2 C}{\partial y^2} + Q^*(T - T_\infty) - \frac{\partial q_r}{\partial y}, \tag{41}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = \frac{D_M K_T}{T_m}\frac{\partial^2 T}{\partial y^2} + D_M\frac{\partial^2 C}{\partial y^2}, \tag{42}$$

with

$$u = U_w = ax,\ \ v = 0,\ C = C_w,\ \ T = T_w \text{ at } \ y = 0, \tag{43}$$

$$u \to 0,\ \ C \to C_\infty,\ \ T \to T_\infty \ \text{ at } \ y \to \infty. \tag{44}$$

The temperature dependent viscosity by Ajayi et al. [34] is

$$\mu\left(T\right) = \ \mu^*\left[1 + b\left(T_w - T\right)\right], \ \text{ where } \ b > 0, \tag{45}$$

HAM is employed to find series solution. Convergence of the series solution is discussed through table. For validity purpose, similarity of the current outcomes are compared with the available results. Effects of Variable viscosity parameter, Weissenberg parameter, Heat generation/absorption coefficient, Soret number and Dufour number are explained through graphs. Physical measures are illustrated in table.

Results of **Chapter 4** are **communicated**.

Chapter 5:

MHD Carreau fluid flow over nonlinear stretching sheet

The non-Newtonian nature of blood in small arteries is analyzed mathematically by considering the blood as Carreau fluid. Stretching sheet assists heat and mass transfer flow, which has wide application in polymer industry, lamination, fiber spinning, and so forth.
In this paper, two-dimensional steady, incompressible MHD Carreau fluid flow over a shrinking or stretching sheet is considered. Stretching/shrinking sheet is taken along x axis. Magnetic field $\mathcal{B} = B_0 x^{\frac{m-1}{2}}$ is implemented perpendicular to the surface, where $U_w(x) = a^* x^m$ and $U_e(x) = b^* x^m$. Non-

linear thermal radiation, Soret and Dufour effects are taken into account.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \tag{46}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-U_e\frac{dU_e}{dx}-\frac{1}{\rho}\frac{\partial}{\partial y}\left(\mu^*(T)\frac{\partial u}{\partial y}\right)-3\frac{\mu^*(T)}{\rho}\left(\frac{p_i-1}{2}\right)\Lambda^2\left(\frac{\partial u}{\partial y}\right)^2\frac{\partial^2 u}{\partial y^2}$$
$$-\frac{\sigma\mathcal{B}^2}{\rho}\left(U_e-u\right)-\frac{1}{\rho}\left(\frac{p_i-1}{2}\right)\Lambda^2\frac{\partial\mu^*(T)}{\partial y}\left(\frac{\partial u}{\partial y}\right)^3=0, \tag{47}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y}-\frac{\kappa}{\rho C_p}\frac{\partial^2 T}{\partial y^2}-\frac{D_M K_T}{C_p C_s}\frac{\partial^2 C}{\partial y^2}=0, \tag{48}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}-\frac{D_M K_T}{T_m}\frac{\partial^2 T}{\partial y^2}-D_M\frac{\partial^2 C}{\partial y^2}=0, \tag{49}$$

to the boundary conditions

$$\left.\begin{aligned} u=U_w\left(x\right),\ v=\ v_w\left(x\right),\ \ C=C_w,\ \frac{\partial T}{\partial y}&=-\frac{q_0}{\kappa}x^{\frac{m-1}{2}},\ \text{at } y=0,\\ u=U_e\left(x\right),\ \ C\to C_\infty,\ \ T\to T_\infty,\ &\text{as } y\to\infty. \end{aligned}\right\} \tag{50}$$

Adegbie et al. [35] provide a mathematical model of temperature dependent viscosity:

$$\mu\left(T\right)=\mu^*\left[1+h_1\left(T_\infty-T\right)\right], \tag{51}$$

where, h_1 is constant and its value depends on the fluid. Using HAM, the solutions of the present work are found. Effects of nonlinear parameter, Variable viscosity parameter, Magnetic parameter and Schmidt number on velocity, temperature and concentration profiles are discussed. For validity purpose, present results are compared with the previous one. factor, Nusselt number and Sherwood number are explained through graphs.

This work is **accepted** in **International Journal of Applied and Computational Mathematics (Springer-Nature) (Scopus).**

Chapter 6:

Unsteady MHD flow of a Micropolar fluid over a stretching sheet

Reciprocating engines, pressure exchangers, hydraulic rams and ocean wave machine are some of the application of unsteady flow. A few representative fields of interest in which combined heat and mass transfer with chemical reaction effect plays an important role, are design of chemical processing equipment, formation and dispersion of fog, distribution of temperature and moisture over agricultural fields and groves of fruit trees, damage of crops due to freezing, food processing and cooling towers.

Consider an unsteady two-dimensional MHD flow of an incompressible Micropolar fluid, heat and mass transfer over a vertical stretching sheet. The sheet is assumed to emerge vertically in the upward direction from a narrow slot with velocity

$$U_w(x,\ t) = \frac{ax}{1-\alpha t}, \tag{52}$$

where both a and α are positive constants with dimension per unit time. We measure the positive x direction along the stretching sheet with the slot as the origin. We then measure the positive y coordinate perpendicular to the sheet in the outward direction toward the fluid flow. The surface temperature T_w and concentration C_w of the stretching sheet vary with the distance x from the sheet and time t as

$$T_w(x,\ t) = T_\infty + \frac{bx}{(1-\alpha t)^2}, \quad C_w(x,\ t) = C_\infty + \frac{cx}{(1-\alpha t)^2}, \tag{53}$$

where b, c are constants with dimension of temperature and concentration, respectively, over length. It is noted that the expressions for $U_w(x,t)$, $T_w(x,t)$, and $C_w(x,t)$ are valid only for $t < \alpha^{-1}$. We also remark that the sheet which is fixed at the origin is stretched by applying a force in the x-direction and the effective stretching rate $a/(1-\alpha t)$ increases with time. The sheet temperature and concentration increase (reduce) if b and c are positive (negative), respectively. We assume that the radiation effect is significant in this study. The fluid properties are taken to be constant except for density variation with temperature and concentration in the buoyancy terms. Under those assumptions and the Boussinesq approximations, the governing boundary layer equations are given as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{54}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \left(\frac{\mu + k}{\rho}\right)\frac{\partial^2 u}{\partial y^2} + \frac{k}{\rho}\frac{\partial N}{\partial y} + g\beta_T(T - T_\infty) + g\beta_C(C - C_\infty) - \frac{\sigma \mathcal{B}^2 u}{\rho}, \tag{55}$$

$$\frac{\partial N}{\partial t} + u\frac{\partial N}{\partial x} + v\frac{\partial N}{\partial y} = \frac{\gamma^*}{\rho j}\frac{\partial^2 N}{\partial y^2} - \frac{k}{\rho j}\left(2N + \frac{\partial u}{\partial y}\right), \tag{56}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\kappa}{\rho C_p}\left(\frac{\partial^2 T}{\partial y^2}\right) - \frac{1}{\rho C_P}\frac{\partial q_r}{\partial y} + \left(\frac{\mu + k}{\rho C_p}\right)\left(\frac{\partial u}{\partial y}\right)^2, \tag{57}$$

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_M\frac{\partial^2 C}{\partial y^2} + \kappa_c(C - C_\infty), \tag{58}$$

with the appropriate boundary conditions:

$$u = U_w(x,\ t), \quad v = 0, \ N = 0, \quad T = T_w(x,\ t), \quad C = C_w(x,\ t) \ \text{ at } \ y = 0, \tag{59}$$

$$u \to 0, \ N \to 0, \ T \to T_\infty, \ C \to C_\infty \ as \ \to \infty. \tag{60}$$

Results in the form of graphs and tables can be found by homotopy analysis method. Effect of unsteadiness parameter, Micropolar parameter and Chemical reaction parameter on velocity, angular velocity, temperature and concentration are explained throgh graphs. Physical attributes are discussed through graphs.

This work is published in **Journal of Physics (Scopus) (Ref[36]).**

Chapter 7: Entropy optimized unsteady MHD Williamson fluid flow considering viscous dissipation effects

Viscous dissipation is of interest for many applications, for examples significant temperature rises are observed in polymer processing flows such as injection molding or extrusion at high rates. Aerodynamics heating in the thin boundary layer around high speed aircraft raises the temperature of the skin. Due to numerous applications of convective boundary conditions in technology, including thermal energy storage, petroleum processing, material drying etc, we considered convective boundary conditions in this chapter.

In the next **chapter 7**, two dimensional, unsteady flow of an incompressible Williamson fluid across a stretching sheet with joule heating, nonlinear radiation and viscous dissipation have been considered. Entropy generation rate is discussed here. The slip condition and convective boundary conditions have been addressed. In this chapter, the vertical axis was chosen transverse to the surface, and we decided to use the cartesian system to measure the sheet along the x, y, and x axes that were chosen next to the stretching sheet. Stretching velocity is $U_w(x,t) = \frac{bx}{1-\alpha t}$, where b is the rate of stretching sheet with respect to x axis where αt is a positive constant according to case $\alpha t < 1$. The magnetic field's strength is $\mathcal{B} = B_0/\sqrt{1-\alpha t}$ and is applied in the direction of the positive y axis. Comparing the magnetic Reynolds number to the induced magnetic field, it is very small.
Governing equations for Williamson fluid are as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{61}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} + \sqrt{2}\Gamma\nu\frac{\partial^2 u}{\partial y^2}\frac{\partial u}{\partial y} - \frac{\sigma\mathcal{B}^2}{\rho}u + g\beta_C(C - C_\infty) + g\beta_T(T - T_\infty), \tag{62}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} + \frac{\sigma\mathcal{B}^2}{\rho C_p}u^2 + \frac{\mu}{\rho C_p}\left(\frac{\partial u}{\partial y}\right)^2, \tag{63}$$

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} + k_c(C - C_\infty), \tag{64}$$

with

$$u = U_w + U_{Slip}, \;\; v = v_w = \frac{v_0}{\sqrt{1-\alpha t}}, \; -\kappa \frac{\partial T}{\partial y} = h_{ft}(T_w - T), \; -D_M \frac{\partial C}{\partial y} = h_{fc}(C_w - C), \;\; at \;\; y = 0, \quad (65)$$

$$u \to 0, \quad T \to T_\infty, C \to C_\infty, \; at \quad y \to \infty. \quad (66)$$

where, $U_{slip} = \alpha^* \mu \frac{\partial u}{\partial y}$.

HAM used to find solution of this problem. Impact of Eckert number, Unsteadiness parameter, Thermal Biot number and Solutal Biot number are discussed via graphs. For Diffusion parameter, Magnetic parameter rate of entropy generation explained. Convergence of series solution discussed numerically. Present results are compared with the available results for validity of HAM. factor, Nusselt number and Sherwood number are calculated for different values of pertinent parameters.

Results of this chapter is **communicated**.

Chapter 8: EMHD fluid flow with slip effects

Electromagnetohydrodynamic (EMHD) is the area that concerns the study of dynamics of electrically conducting fluids under the influence of magnetic and electric fields. EMHD has raised quite an interest over the years due to its versatile application in geophysics, engineering, biomedical engineering, magnetic drug targeting, and many others. The non-adherence of the fluid to a solid boundary, known as velocity slip, occurs under certain circumstances. Fluids displaying slip are essential for technologies such as internal cavities and in the artificial cardiac valve polishing.

In the next chapter, two dimensional incompressible Micropolar fluid flow through a horizontal sheet is considered. Velocity of the stretching sheet is taken as $u = ax + U_{Slip}$. A magnetic fleld of strength $\mathcal{B}$ is normally applied with the conjecture of lower Reynolds number, so that the induced magnetic field may be ignored. Viscous dissipation and Joule heating and non-linear thermal radiation effects are accounted. The surface of the stretching plate is in contact with another hot plate of temperature T_w and concentration C_w with h_{ft} and h_{fc} are the heat transfer coefficient and mass transfer coefficient. The volume of particle concentration and the temperature of the Micropolar fluid far away from the plate is supposed to be C_∞ and T_∞ respectively.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \quad (67)$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \left(\frac{\mu + k}{\rho}\right)\frac{\partial^2 u}{\partial y^2} + \frac{k}{\rho}\frac{\partial G}{\partial y} + \frac{\sigma}{\rho}\left(E_0 B_0 - B_0^2 u\right), \quad (68)$$

$$u\frac{\partial G}{\partial x} + v\frac{\partial G}{\partial y} = \frac{\gamma^*}{\rho j}\frac{\partial^2 G}{\partial y^2} - \frac{k}{\rho j}\left(2G + \frac{\partial u}{\partial y}\right), \quad (69)$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\kappa}{\rho C_P}\left(\frac{\partial^2 T}{\partial y^2}\right) + \frac{(uB_0 - E_0)^2 \sigma}{\rho C_P} - \frac{1}{\rho C_P}\frac{\partial q_r}{\partial y} + \left(\frac{\mu + k}{\rho C_p}\right)\left(\frac{\partial u}{\partial y}\right)^2, \quad (70)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_M\frac{\partial^2 C}{\partial y^2}, \tag{71}$$

with

$$\begin{aligned}&u=U_w(x)+U_{slip},\ v=\ v_w, G=-n\frac{\partial u}{\partial y}, -\kappa\frac{\partial T}{\partial y}=h_{ft}(T_w-T),\ -D\frac{\partial C}{\partial y}=h_{fc}(C_w-C)\ \text{at } y=0,\\ &u(\infty)=G(\infty)=0,\ T(\infty)=T_\infty,\ C(\infty)=C_\infty.\end{aligned} \tag{72}$$

where $U_w(x)=ax$ and $U_{slip}=\alpha^*\left[(\mu+k)\frac{\partial u}{\partial y}+kG\right]$.

Using HAM, solution of the problem found. Effect of Electric parameter, Slip parameter and Material parameter on velocity, angular velocity, temperature and concentration are explained. Convergence of series solution explained through graphs. Physical attributes are discussed through graphs and tables.

Results of this chapter is published in **Heat transfer (Wiley) (Scopus) (Ref. [37])**.

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