International Journal of Mathematics and Physical Sciences Research ISSN 2348-5736 (Online)
Vol. 14, Issue 1, pp: (111-120), Month: April 2026 - September 2026, Available at: www.researchpublish.com

STEADY FINITE – AMPLITUDE CONVECTION IN A DARCY ROTATING POROUS LAYER WITH INTERNAL HEATING AND VERTICAL MAGNETIC FIELD

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DOI: https://doi.org/10.5281/zenodo.21723861

Published Date: 31-July-2026

***Abstract:* The problem of steady finite-amplitude convection in a Dacy rotating porous medium with internal heating and vertical magnetic field has been investigated by using weak nonlinear analysis. This was done to give information on heat and mass transport together with convection amplitude. The truncated Fourier representation for stream functions was assumed to obtain the rate of heat (Nusselt number,), and mass (Sherwood number, Sh) transports in the system. It was observed that internal heating strengthens both the heat and mass transport, that is the (Nusselt number, Nu and Sherwoow number, Sh) respectively. Magnetic field was found to reinforced the rate of mass transport, i.e. the Nusselt number, Nu and the Sherwoow number, Sh, while rotation hindered both the Nusselt number, Nu and the Sherwoow number, Sh.**

***Keywords:* Steady Finite -Amplitude, Weakly Nonlinear, porous Layer, internal heat, and Vertical Magnetic Field.**

1. INTRODUCTION

Motivations in the study of nonlinear analysis problems with temperature-dependent internal heating in the presence of magnetic field, in recent times is due to it wide range of applications in Science, Engineering and Technology. These include the drying of porous solids, thermal insulation, pack-bed catalytic reactors, cooling of nuclear reactors, geophysical fluid dynamics, and underground energy transport.

Many researchers have investigated on finite-amplitude and weakly nonlinear convection and extremely good literature may be found in [1,2,6,18,19]. The problem of weakly nonlinear stability analysis of a thin magnetic during spin coating was considered by [1], while [2] employed the method of normal mode analysis to obtain the marginal stability in onset of magnetoconvection in a rotating Darcy-Brinkman porous layer heated from below with temperature-dependent heat source.

Weakly nonlinear stability analysis of double diffusive convection in a porous medium with magnetic field and concentration-based internal heating was looked into by [6], the result showed both Darcy number and magnetic field increases the heat and mass transfer in the system. Recently, [14] investigated the problem Finite-amplitude convection in a rotating Rivlin-Erickson ferrofluid layer with variable viscosity. [18] examined Weakly nonlinear oscillatory convection in a non-uniform heating porous medium with throughflow, whereas in [19] investigation Nonlinear double diffusive convection in a couple stress fluid with rotational modulation was carried out.

A critical analysis of the study the onset of magnetoconvection in a rotating Darcy- Brinkman porous layer heated from below with temperature-dependent heat source was made by [17]. [15,16,17] in their studies use the linear theory via normal mode analysis to predict the criterion of marginal stability. Information on heat and mass transports together with convection amplitude cannot be provided by this method. For the estimation of these quantities, we resort to the weak nonlinear analysis which is the focus of this research.

2. GOVERNING EQUATIONS

Consider the rotating Darcy model with modified Boussinesq approximation involving solute concentration together with stress free boundaries and temperature dependent internal heating in an infinitely horizontal layer of electrically conducting fluid saturated by Darcy layer of thickness d. This fluid layer is held between $z^* = 0$ and $z^* = d$ stress-free boundaries. The lower and upper plates are maintained at temperature and solute concentration $T_h^*(= T_0 + \Delta T), c^*(= c_0 + \Delta c)$ and T_0, c_0, respectively such that $T_h^* > T_0, c_h^* > c_0$. The fluid layer rotates uniformly in the vertical direction with angular momentum, $\boldsymbol{\omega}^* = \omega \boldsymbol{k}$ and (x^*, y^*, z^*) chosen in such a way that $z^* = 0$ is the origin and the gravitational field acts vertically downwards. A uniform magnetic field of strength $\vec{B} = (0,\ 0,\ B_0)$ act vertically upwards. On account of small magnetic Reynolds number, induced magnetic field is neglected. The physical model and coordinate system is shown in Fig.1.

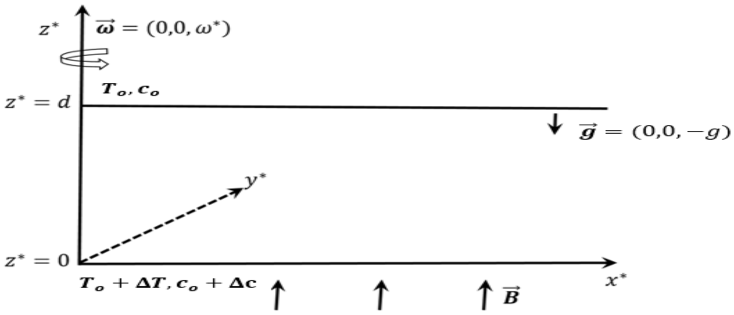

Fig. 1: Schematic diagram of the physical problem.

Employing Darcy model, Lorentz force and the Coriolis acceleration together with Boussinesq approximation, the governing equations are [Greenspan,1968; Vadasz, 1998; Nield & Bejan, 2017; Israel-Cookey, *et al.* 2017]

$$\vec{\nabla}^*.\vec{V}^* = 0 \tag{1}$$

$$\frac{\rho_0}{\phi}\frac{\partial \vec{V}^*}{\partial t^*} = -\vec{\nabla}^* P^* - \rho_0[1 - \beta_t(T^* - T_0^*) + \beta_c(c^* - c^*)]g\vec{k} - \frac{\mu}{K}\vec{V}^* - \frac{2\rho_0}{\phi}\vec{\omega} \times \overrightarrow{V}^* - + \mu_e \vec{\nabla}^{*2}\vec{V} + \sigma_c B_0^2(u^*, v^*, 0) \tag{2}$$

$$A\frac{\partial T^*}{\partial t^*} + (\overrightarrow{V}^*.\vec{\nabla}^*)T^* = \alpha_m {\vec{\nabla}^*}^2 T^* + Q(T^* - T_0) \tag{3}$$

$$\phi\frac{\partial c^*}{\partial t^*} + (\overrightarrow{V}^*.\vec{\nabla}^*)c^* = D_c {\vec{\nabla}^*}^2 c^* \tag{4}$$

The variables entering the equations are defined in the nomenclature.

The boundary conditions are

$$\vec{V}^* = 0 \qquad \text{on } z^* = 0, d \tag{5}$$

for the velocity, and

$$T^* = T_0 + \Delta T, c^* = c_0 + \Delta c \qquad \text{on } z^* = 0$$

$$T^* = T_0,\ c^* = c_0 \qquad \text{on } z^* = d \tag{6}$$

The non-dimensional form of Eqs. (1) – (4) and the boundary conditions (5) and (6) can be written as

$$\vec{\nabla}.\overrightarrow{V} = 0 \tag{7}$$

$$\left(\frac{1}{V_a}\frac{\partial}{\partial t} + 1\right)\vec{\mathrm{V}} = -\vec{\nabla}P + RaT\vec{k} - Rs\,c\vec{k} + \wedge D_a\overrightarrow{\nabla^2}\vec{V} - K_D\vec{V} - \sqrt{T_D}\vec{k} \times \vec{V} - Ha^2(U, V, 0) \tag{8}$$

$$\frac{\partial T}{\partial t} + (\vec{\nabla}.\vec{\mathrm{V}})T = \left(\vec{\nabla}^2 + \gamma\right)T \tag{9}$$

$$\varepsilon\frac{\partial c}{\partial t} + (\vec{\nabla}.\vec{\mathrm{V}})c = \frac{1}{L_e}\nabla^2 c \tag{10}$$

with boundary conditions

$W = 0, \quad T = 1, \; c = 1 \qquad$ on $\quad z = 0$

$W = 0, \quad T = 0, \; c = 0 \qquad$ on $\quad z = 1 \qquad (11)$

3. BASIC STATE

The basic state of the system is assumed quiescent and described by

$\vec{V}^* = 0, \quad T = T_b(z), \; c = c_b(z), \; P = P_b(z)$, where the subscript b denotes basic state. Then from equations (7) - (10) and the boundary conditions (11), the governing equations of the basic state are

$$\frac{\partial P_b}{\partial z} = R_a T_b(z) - R_s c_b, \frac{d^2 T_b}{dz^2} + \gamma T_b = 0, \frac{d^2 c_b}{dz^2} = 0 \qquad (12)$$

$$T_b = c_b = 1 \qquad on \qquad z = 0$$
$$T_b = c_b = 0 \qquad on \qquad z = 1 \qquad (13)$$

On solving equation (3.3.12) subject to boundary condition (3.3.13) yield the basic state pressure, temperature and solute concentration profiles as

$$P_b(z) = Ra\frac{\cos[\sqrt{\gamma}(1-z)]}{\sqrt{\gamma}\sin(\sqrt{\gamma})} + R_s\left(\frac{z^2}{2} - z\right), T_b(z) = \frac{\sin[\sqrt{\gamma}(1-z)]}{\sin\sqrt{\gamma}}, c_b(z) = 1 - z \qquad (14)$$

The dimensionless parameters are listed in the nomenclature.

4. LINEARIZED EQUATIONS

Let

$$\vec{V} = \vec{v}, \; T = T_b(z) + \theta, P = p_b(z) + p\,, c = c_b(z) + s \qquad (15)$$

in which the perturbed quantities $\vec{v}, \; p, \; \theta$ and s are assumed small compared to the equilibrium quantities. With Eq. (15), the governing Eqs. (7) - (10) and the boundary conditions (11) become

$$\vec{\nabla}.\vec{v} = 0 \qquad (16)$$

$$\left(\frac{1}{V_a}\frac{\partial}{\partial t} + 1\right)\vec{v} + Ha^2(u, v, 0) + \vec{\nabla}P - R_a\theta\vec{k} + R_s s\vec{k} - \sqrt{T_D}\vec{k} \times \vec{v} \qquad (17)$$

$$\frac{\partial \theta}{\partial t} + \vec{v}.\vec{\nabla}\theta + f(z)w = \left(\vec{\nabla}^2 + \gamma\right)\theta \qquad (18)$$

$$Le\varepsilon\frac{\partial s}{\partial t} + \vec{v}.\vec{\nabla}s - Le\,w = \vec{\nabla}^2 s \qquad (19)$$

where $\quad -\frac{dT_b}{dz} = f(z) = \frac{\sqrt{\gamma}}{\sin[\sqrt{\gamma}]}Cos[\sqrt{\gamma}\,(1-z)]$ is the basic state temperature distribution gradient

The boundary conditions are now

$w = \theta = s = 0 \qquad$ on $\; z = 0,1$

5. STEADY FINITE – AMPLITUDE CONVECTION

The linear theory discussed in the model above, Odok & Ebiwareme, Odok et al (2018), (2020) are adequate for predicting only the criterion for marginal stability. Information on heat and mass transfer together with convection amplitude cannot be provided by the marginal stability. For the estimation of these quantities, we re sort to the weak nonlinear analysis.

For now on, all physical quantities are independent of y – axis near the critical condition. Under this assumption, the velocity vector become:

$$\vec{V} = [u(x,z,t), 0, w(x,z,t)] \qquad (20)$$

Using perturbed continuity equation given in (16), the x –and z –components of the velocity are defined in terms of the stream function $\psi(x,z,t)$ as

$$u = \frac{\partial \psi}{\partial z} \quad \text{and } w = -\frac{\partial \psi}{\partial x} \qquad (21)$$

By taking *curl* and *curl curl* of equation (17) together with equations (18) – (19) yields the following equations in stream function

$$\left(\frac{1}{Va}\frac{\partial}{\partial t}+1\right)\vec{\nabla}^{2\psi}+Ha^2\frac{\partial^{2\psi}}{\partial z^2}+Ra\frac{\partial\theta}{\partial x}-Rs\frac{\partial s}{\partial x}-\sqrt{T_D}\frac{\partial V}{\partial z}=0 \qquad (22)$$

$$\left(\frac{1}{Va}\frac{\partial}{\partial t}+1\right)V+\sqrt{T_D}\frac{\partial\psi}{\partial z}=0 \qquad (23)$$

$$\left(\frac{\partial}{\partial t}-\vec{\nabla}^2-\gamma\right)\theta+f\frac{\partial\psi}{\partial x}+\frac{\partial\psi}{\partial z}\frac{\partial\theta}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial z}=0 \qquad (24)$$

$$\left(Le\varepsilon\frac{\partial}{\partial t}-\vec{\nabla}^2\right)s+Le\frac{\partial\psi}{\partial x}+\frac{\partial\psi}{\partial z}\frac{\partial s}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial s}{\partial z}=0 \qquad (25)$$

Where $\vec{\nabla}^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}$ and the basic temperature gradient $f=-\frac{\sqrt{\gamma}}{Sin[\sqrt{\gamma}]}Cos[\sqrt{\gamma}\,(1-z)]$

Next, to obtain the solution of equations (22) – (25), we assume the following truncated Fourier form for $\psi,\theta\ and\ s$ fields (Mamou & Vasseur, 1999)

$$\psi=A_1(t)\mathrm{Sin}(ax)\mathrm{Sin}(\pi z)$$

$$\theta=A_2(t)\,\mathrm{Cos}(ax)\,\mathrm{Sin}(\pi z)+A_3(t)\mathrm{Sin}(2\pi z)$$

$$s=A_4(t)\,\mathrm{Cos}(ax)Sin+A_5(t)\mathrm{Sin}(2\pi z)$$

$$V=A_6(t)\,\mathrm{Sin}(ax)\,\mathrm{Cos}(\pi z)+A_7(t)\mathrm{Sin}(2\pi z) \qquad (26)$$

Where the amplitudes $A_1(t)\,...\,A_7(t)$ are to be determined. Substituting equation (26) into equations (22) – (25), truncating up to $2\pi z$, while neglecting higher order of frequencies yield

$$\frac{dA_1}{dt}=\frac{Va}{\delta}\left[(\delta+\pi^2Ha^2)A_1+aRaA_2-aRsA_4-\pi\sqrt{T_D}A_6\right] \qquad (27)$$

$$\frac{dA_2}{dt}=aF(z)A_1-(\delta-\gamma)A_2+a\pi A_1A_3 \qquad (28)$$

$$\frac{dA_3}{dt}=-(4\pi^2-\gamma)A_3+\frac{\pi}{2}A_1A_2 \qquad (29)$$

$$\frac{dA_4}{dt}=-\frac{1}{Le\varepsilon}(\delta A_4+LeaA_1+a\pi A_1A_5) \qquad (30)$$

$$\frac{dA_5}{dt}=-\frac{1}{Le\varepsilon}\left(a\frac{\pi}{2}A_1A_4-4\pi^2A_5\right) \qquad (31)$$

$$\frac{dA_6}{dt}=-Va\left(MA_6+\pi\sqrt{T_D}A_1\right) \qquad (32)$$

$$\frac{dA_7}{dt}=-VaMA_7 \qquad (33)$$

Where $\delta=\pi^2+a^2,\ M=1+Ha^2$.

6. WEAKLY NONLINEAR ANALYSIS

In this investigation, the autonomous equations (27) – (33) is intractable, but in the steady state it possesses solution. Setting the time derivatives in equations (27) – (33) to zero, we obtain

$$\left[(\delta+\pi^2Ha^2)A_1+aRaA_2-aRsA_4-\pi\sqrt{T_D}A_6\right]=0 \qquad (34)$$

$$aF(z)A_1-(\delta-\gamma)A_2+a\pi A_1A_3=0 \qquad (35)$$

$$(4\pi^2-\gamma)A_3+\frac{\pi}{2}A_1A_2=0 \qquad (36)$$

$$(\delta A_4+LeaA_1+a\pi A_1A_5)=0 \qquad (37)$$

$$(\delta A_4+LeaA_1+a\pi A_1A_5)=0 \qquad (38)$$

$$(\delta A_4+LeaA_1+a\pi A_1A_5)=0 \qquad (39)$$

$$A_7=0 \qquad (40)$$

The solutions of equations (34) – (40) in terms of the amplitude A_1 are

$$A_2 = \frac{2aA_1F(z)(4\pi^2-\gamma)}{a^2\pi^2A_1^2(4\pi^2-\gamma)(\gamma-\delta)} \tag{41}$$

$$A_3 = \frac{a^2F(z)\pi A_1^2}{a^2\pi^2A_1^2(4\pi^2-\gamma)(\gamma-\delta)} \tag{42}$$

$$A_4 = \frac{RaLeA_1}{a^2A_1^2+8\delta} \tag{43}$$

$$A_5 = -\frac{a^2LeA_1^2}{\pi(a^2A_1^2+8\delta)} \tag{44}$$

$$A_6 = -\frac{\pi\sqrt{T_D}}{M} \tag{45}$$

The substitution of equations (41), (43) and (45) into equation into equation (34) yield the following polynomial in A_1

$$A_1(a_2A_1^4 + a_1A_1^2 + a_0) = 0 \tag{46}$$

where

$$a_2 = \pi^2a^4[\pi^2T_D + M(\pi^2Ha^2 + \delta)]$$

$$a_1 = 2a^2M[4a^2\pi^2LeRs + \gamma\delta(4\pi^2 - \gamma + \delta)] + 2a^2F(z)M(4\pi^2 - \gamma)Ra + 2a^2\pi^2\gamma(4\pi^2 - \gamma + \delta)(T_D + MHa^2)$$

$$a_0 = 16(4\pi^2 - \gamma)[M(\gamma - \delta)\delta^2 + Ma^2(F(z)\delta Ra + Le(\gamma - \delta)Rs) + \pi^2(\gamma - \delta)\delta(T_D + MHa^2)]$$

Equation (46) is a quadratic equation in A_1^2 whose require solution is

$$A_1^2 = -a + \frac{\sqrt{a_1^2-4a_2a_0}}{2a_2} \tag{47}$$

Equating the discriminant of equation (47) to zero, (that is $a_1^2 - 4a_2a_0 = 0$) yields

$$e_2(Ra^F)^2 + e_1(Ra^F) + e_0 = 0 \tag{48}$$

where

$$e_2 = 4a^8F(z)^2M^2(4\pi^2 - \gamma)^2$$

$$e_1 = 4a^8F(z)M(4\pi^2 - \gamma)\{4a^2M\pi^2LeRs + T_D[\pi^2\gamma(\pi^2 - \gamma) - \pi^2\delta(8\pi^2 - \gamma)] + M\pi^2Ha^2[\gamma(4\pi^2 - \gamma) - \delta(8\pi^2 - \gamma)] + M[\gamma\delta(4\pi^2 - \gamma) - \delta^2(8\pi^2 - \gamma)]\}$$

$$e_0 = 4a^4\left[4a^2M\pi^2LeRs - M\gamma\delta(4\pi^2 - \gamma) + M\delta^2(8\pi^2 + \gamma) - [\pi^2\gamma(4\pi^2 - \gamma) - \pi^2\delta(8\pi^2 + \gamma)]M\pi^2Ha^2[\gamma(4\pi^2 - \gamma) - \delta(8\pi^2 - \gamma)]\right]$$

7. RATES OF HEAT AND MASS TRANSPORTS

Next we estimate Nu and Sh at lower boundary for the stationary mode in the horizontal direction. The heat and mass transports are defined respectively as

$$Nu = 1 + \left[\frac{\int^{2\pi/a}\frac{\partial\theta}{\partial z}dx}{\int_0^{2\pi/a}\frac{\partial T_b}{\partial z}dx}\right]_{z=0} \tag{49}$$

$$Sh = 1 + \left[\frac{\int^{2\pi/a}\frac{\partial s}{\partial z}dx}{\int_0^{2\pi/a}\frac{\partial c_b}{\partial z}dx}\right]_{z=0} \tag{50}$$

Substituting the values of $T_D(z), c_b(z), \theta$ and s from equations (14) and (26) into equations (49) and (50), and using the expressions for A_3 and A_5 from equations (42) and (44) we obtain

$$Nu = 1 + \frac{2\pi\gamma Cot[\sqrt{\gamma}]Css[\sqrt{\gamma}(1-z)]}{Sin[\sqrt{\gamma}]}\left[\frac{a^2\pi A_1^2}{a^2\pi A_1^2+2(4\pi^2-\gamma)(\gamma-\delta)}\right] \tag{51}$$

and

$$Sh = 1 + \frac{2a^2LeA_1^2}{a^2A_1^2+8\delta} \tag{52}$$

8. RESULTS AND DISCUSSION

The steady finite- amplitude in a rotating Darcy layer with internal heating and vertical magnetic field is investigated. The effects of the rate of heat and mass transports on a rotating Darcy layer with internal heating and vertical magnetic field with free upper and lower boundaries are analysed. The numerical results computed from these analytical equations using the software "Mathematica" version 11.1 are presented graphically to obtain the rate of heat transfer Nu and mass transport Sh.

The variation of heat transfer Nu with Ra and TD, Ha, γ and fixed Le, a, z are illustrated in figures

(4.1)- (4.3)

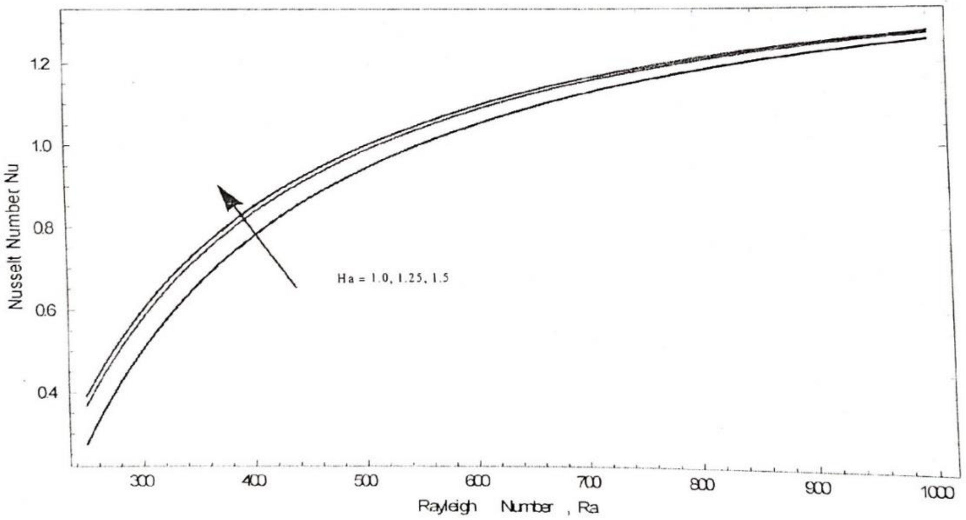

Figure 4.1: Variation of Nu with Ra and fixed $Rs = 100, TD = 10, \gamma = 3, a = 1, Le = 1, z = 0.5$ and various values of Ha.

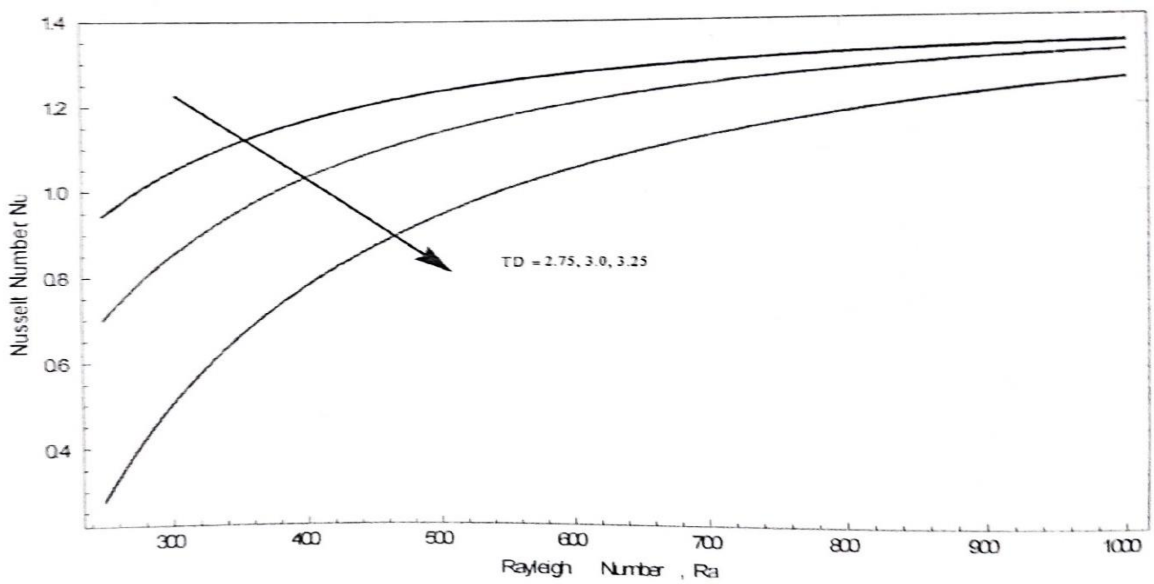

Figure 4.2: Variation of Nu with Ra and fixed $Rs = 100, Ha = 1, \gamma = 3, a = 1, Le = 1, z = 0.5$ and various values of TD.

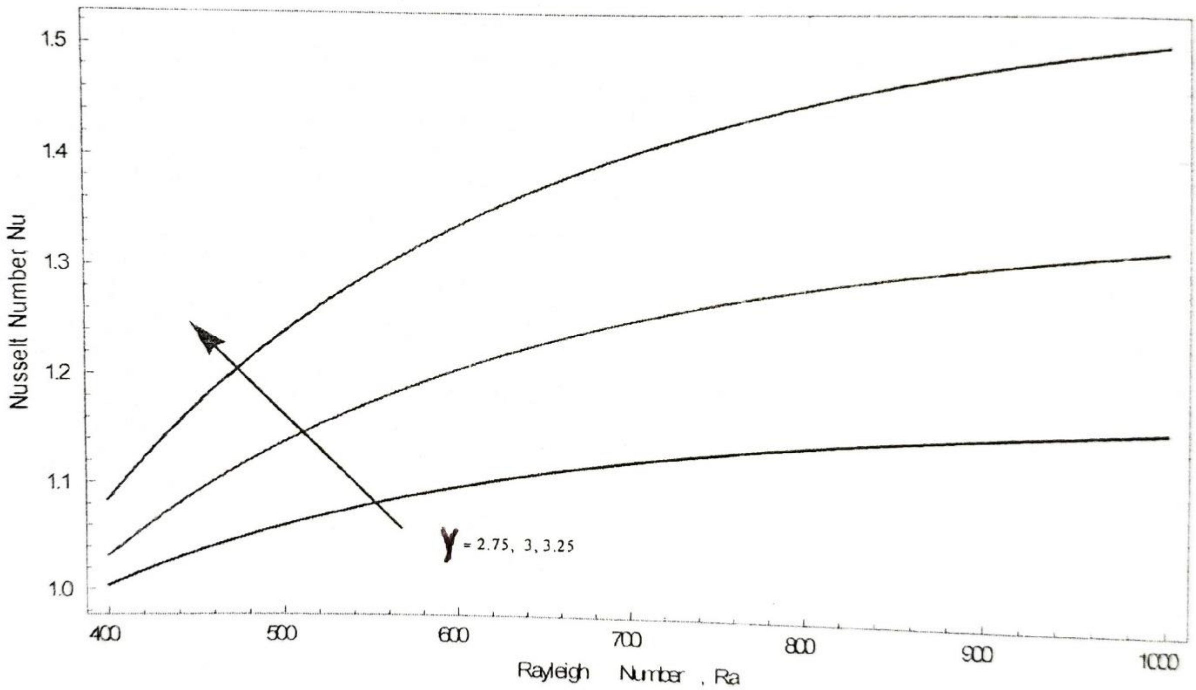

Figure 4.3: Variation of Nu with Ra and fixed $Rs = 100, TD = 10, Ha = 1 a = 1, Le = 1, z = 0.5$ and various values of γ.

The rate of mass transfer or Sherwood number, Sh with Rayleigh number, Ra and TD, Ha, γ and fixed Le, a, z are illustrated in figures 4.4 – 4.5

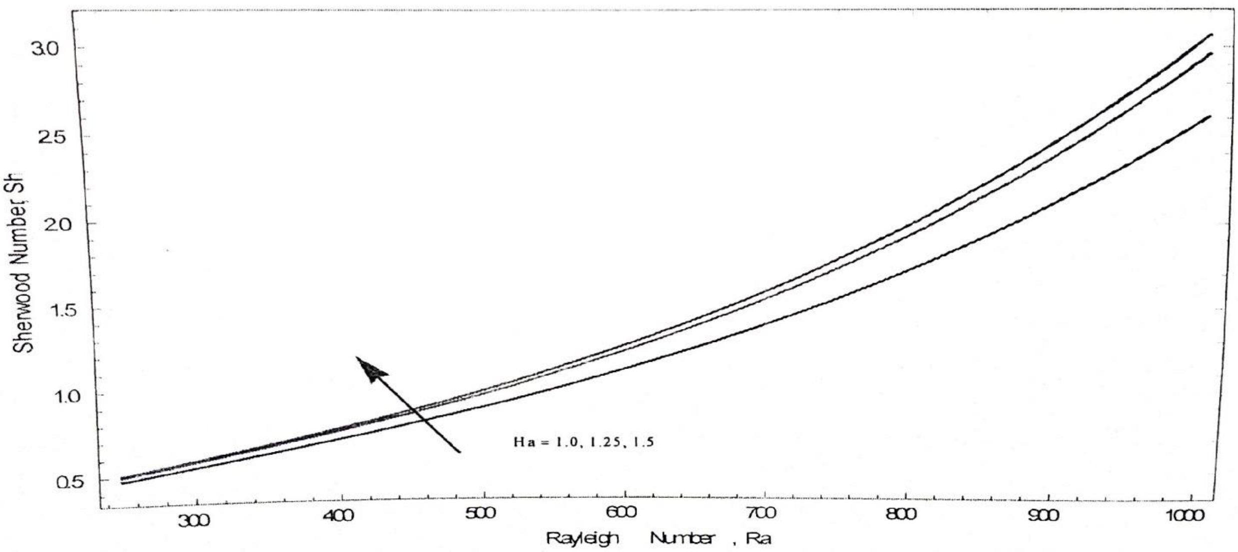

Figure 4.4: Variation of Sherwood number, Sh with Ra and fixed $Rs = 100$, $TD = 10, \gamma = 3, a = 1, Le = 1, z = 0.5$ and various values of Ha.

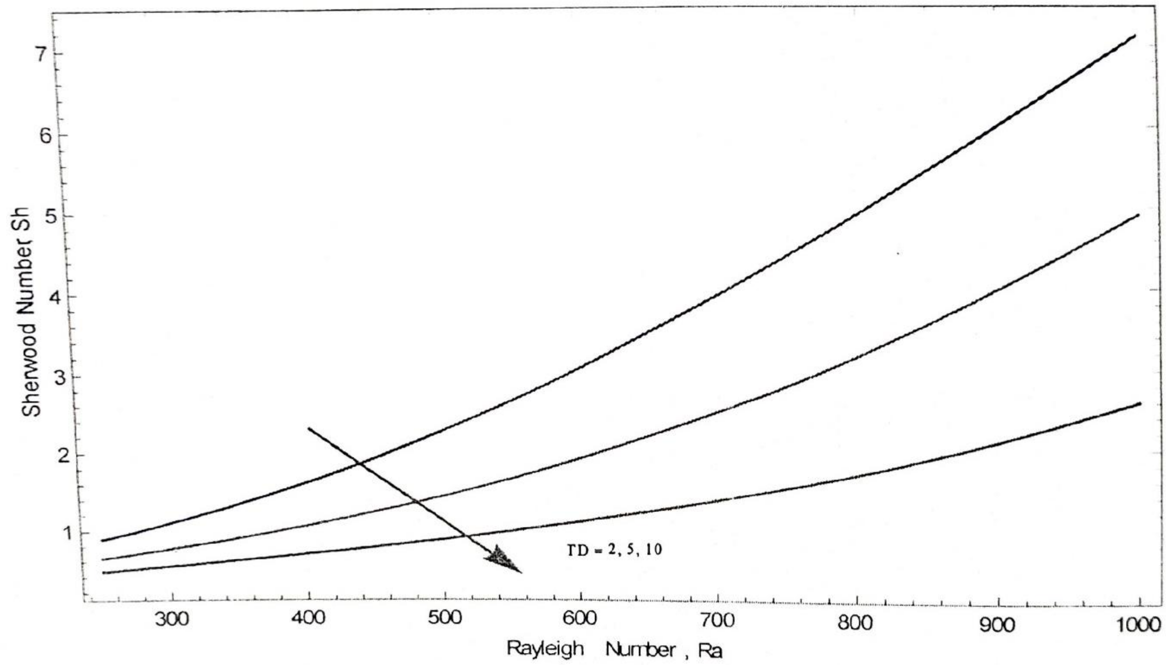

Figure 4.5: Variation of Sherwood number, Sh with Ra and fixed $Rs = 100$, $Ha = 1, \gamma = 3, a = 1, Le = 1, z = 0.5$ and various values of TD.

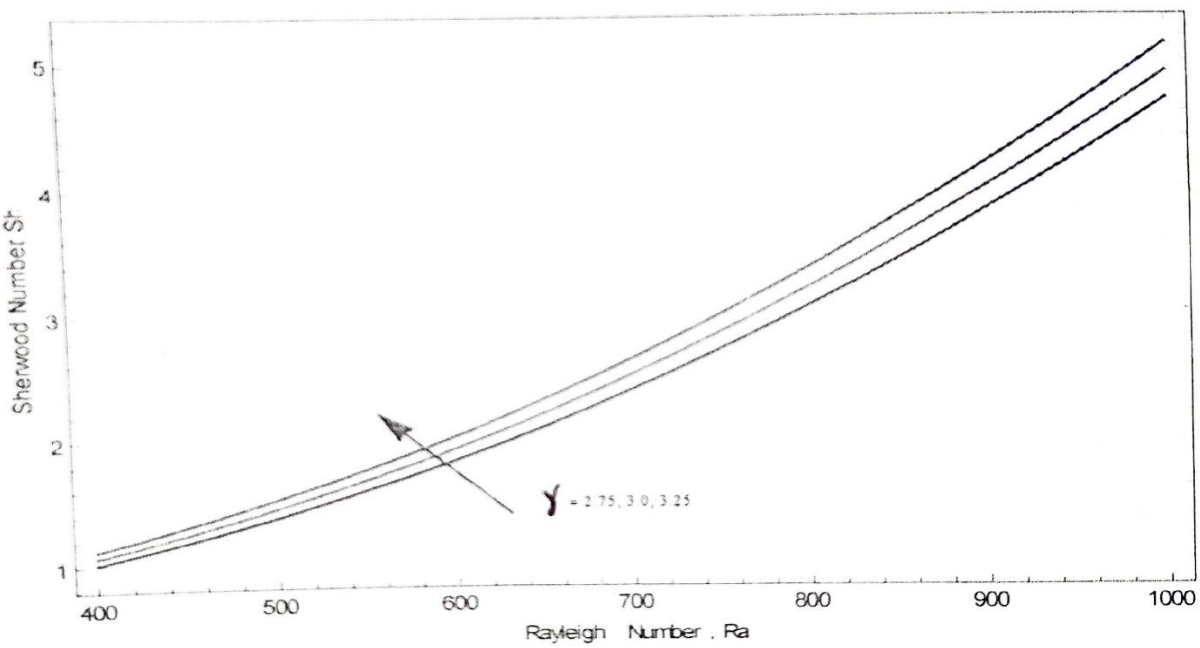

Figure 4.6: Variation of Sherwood number, Sh with Ra and fixed $Rs = 100$, $TD = 10, Ha = 1, a = 1, Le = 1, z = 0.5$ and various values of γ.

The effects of the parameters, $Ha, Rs,\ \gamma,\ Le, TD$ and a at the centre of the channel $(z = 0.5)$ on the rate of heat and mass transfer are illustrate in figures 4.1 – 4.6.

Figure 4.1 shows the rate of heat transfer,Nu against Ra for the parameters $(Rs = 100, TD = 10, \gamma = 3, a = 1, Le\ 1\ and\ z = 0.5)$ with the variation in the Hartman number, Ha. It it observed that increased in the magnetic field parameter, Ha resulted to a rapid increase in Nu. Thus magnetic field, Ha enhanced system heat transport.

Figure 4.2 depicts the rotation parameter, TD $(= 2.75, 3.00, 3.25)$ with fixed values of $(Ha = 1, Rs = 100, \gamma = 3, a = 1, Le = 1 \; and \; z = 0.5)$ on the Nusselt number, Nu with Ra. Obtained result shows that as rotation increases, the heat transfer rate decreased. This is an indication that, rotation through the Taylor-Darcy number, TD inhibits the rate of heat transport in the system. This is in agreement with the result of Zhao et al (2014) without magnetic field, rotation and relaxation time.

The Nusselt number, Nu against Ra and internal heating, γ $(= 2.75, 3.00, 3.25)$ with fixed values of $(Ha = 1, Rs = 100,$ $a = 1, Le = 1 \; and \; z = 0.5)$ are illustrated in figure 4.3. Nusselt number, Nu increased rapidly with increased in internal heating. Thus, as the internal heating grows, Nu is reenforced. Without magnetic field, rotation and viscoelastic properties, this is consistent with the result of Gaikwad and Kouser (2023).

The rate of mass transfer, given as the Sherwood number, Sh with Ra and the parameters ($Rs = 100,\; TD = 10, \gamma = 3, a = 1, Le = 1 \; and \; z = 0.5$) for varying Hartman number, Ha is shown in figure 4.4. It is found that as the magnetic parameter, Ha increase, the Sherwood number, Sh also increases. This is an indication that Ha strengthened the rate of mass transfer, and agreed with Zhao et al (2014) in the absence of magnetic field, rotation and relaxation time.

Figure 4.5 illustrates the relationship of the Sherwood number, Sh and contrl parameter, Ra for rotation, $TD, (Ha = 1, Rs = 100, \gamma = 3,\; a = 1, Le = 1 and \; z = 0.5)$. The result shows a reduction in Sh as TD increased. Which is an indication that rotation impede the rate of mass transfer. This result coincides to those of Zhao et al (2014) without magnetic field, rotation and relaxation time.

The Sherwood number, Sh against Ra and internal heating, γ $(= 2.75, 3.00, 3.25)$ with fixed values of $(Ha = 1, Rs = 100,\; a = 1, Le = 1 \; and \; z = 0.5)$ are illustrated in figure 4.6. As internal heat increases, Sherwood number, Sh is increased. Thus internal heat strengthens the rate of mass transfer and in the absence of magnetic field, rotation and viscoelastic properties. This is consistent with the results of Gaikwad and Kouser (2013).

9. CONCLUSION

In this study, the steady-state finite amplitude has used to determine the conditions leading to both convection, and to give information regarding transport of heat and mass in the fluid layer. From the analyses, we see that internal heating strengthens the rates of heat and mass transports in the system. While rotation hinders both the Nusselt and Sherwood numbers (i.e. heat and mass transports) in the system. Furthermore, magnetic field was found to reinforced transports of heat and mass transfers.

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