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MHD Free Convection Heat and Mass Transfer flow in a Porous Medium with Dufour and Chemical reaction Effects

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ABSTRACT
This paper investigates the MHD free convection heat and mass transfer flow in a porous medium with Dufour and chemical reaction effects. Under the Boussinesq approximation and a negligible magnetic Reynolds number the governing equations are formulated. The non-linear coupled governing partial differential equations in dimensionless form are transformed into a system of ordinary differential equations using perturbation technique. The equations are solved analytically and the solutions for the velocity, temperature, concentration field obtained. The effects of various flow parameters on velocity, temperature, and concentration fields are presented graphically. The influence of various physical parameters on the velocity, temperature, concentration as well as skin friction, Nusselt number and Sherwood number are discussed. It is observed that the increase in Dufour parameter or thermal radiation increases the velocity profile while an increase in magnetic field or oscillation parameter decreases the velocity profile. Increase in Schmidt number, Dufour parameter or chemical reaction decreases the temperature profile. Also, increase in chemical reaction decreases the concentration profile.
Keywords: MHD, free convection, heat and mass transfer flow, porous medium, Dufour effect

1. INTRODUCTION

Magnetohydrodynamic free convection flow has attracted many researchers in view of its numerous application in geophysics, astrophysics, aerodynamics, energy generators, accelerators, aerodynamic heating, polymer technology, petroleum industry, purification of crude oil, and in material processing such as metal forming, continuous casting wire and glass fiber drawing. Chaudhary and Jain (2007) studied the combine heat and mass transfer effect on MHD free convection flow past an oscillating plate. Further, convection in porous media has gained significant attention in recent years because of its importance in engineering application such as geothermal system, solid matrix heat exchanges, thermal insulation oil extraction and store of nuclear waste materials. Convection in porous media can also be applied to underground heat gasification, ground water hydrology, iron blast furnaces, wall cooling of nuclear fuel in earth crust. Many studies, with applications, are gathered in a comprehensive review of convective heat transfer mechanism through porous medium in the book by Nield and Bejan (2006). In view of such applications, Sattar (1994) discussed the free convection and mass transfer flow through a porous medium past and infinite vertical porous plate with time dependent temperature and concentration. Rees and pop (1995) investigated the effects of transverse surface waves on the free convective boundary layer induced by a uniform heat flux vertical surface embedded in a porous medium. Acharya *et al* (2000) studied the magnetic effects on the free convection and mass transfer flow through porous medium, whereas Cheng (2000) has presented the phenomenon of natural convection heat and mass transfer near a vertical wavy surface with constant wall temperature and concentration in a porous medium. Mohamed and Aishah (2017) investigated the heat and mass transfer of unsteady hydromagnetic free convection flow through porous medium past a vertical plate with uniform surface heat flux. Gurivireddy *et al.* (2016) studied the thermal diffusion effect on MHD heat and mass transfer flow past a semi-infinite moving vertical porous plate with heat generation and chemical reaction.

Dufour effect is an important phenomenon in areas such as hydrology, petrology, and geosciences. Chamkha and Eli-kabir (2013) presented a theoretical study of Soret and Dufour effects on unsteady heat and mass transfer by mixed convection flow over a vertical core rotating in an ambient fluid in the presence of magnetic field and chemical reaction. Usman and Uwanta (2013) considered the effect of thermal conductivity on MHD heat and mass transfer flow past an infinite vertical plate with Soret and Dufour effects. Anghel *et al.* (2000) analyzed Dufour and Soret effect on free convection boundary layer flow over a vertical surface embedded in a porous medium. Srinvasacharya and Ram (2010) studied the Soret and Dufour effects on steady MHD free convection flow past a semi-infinite moving vertical plate in a porous medium with viscous dissipation. Soret and Dufour effect on steady MHD natural convection flow past a semi-infinite moving vertical plate in a porous medium with viscous dissipation in the presence of chemical reaction was studied by Motsa and Shateyi (2013). Makinde (2012) studied the effect of Soret and Dufour on MHD mixed convection flow past a vertical plate embedded in a porous plate medium, using a numerical approach and observed that the local skin friction coefficient of the flow is significantly enhanced by the Soret and Dufour effects. Similarity, Uwanta *et al.* (2008) analyzed MHD fluid flow over a vertical plate with Dufour and Soret effects.

In another article, Srimivasacharya and Reddy (2011) examined Soret and Dufour effect on mixed convection in a non-Darcy porous medium saturated with micro polar fluid. Sivaraman *et al.* (2012) considered Soret and Dufour effect on MHD free convection heat and mass transfer with thermopheresis and chemical reaction over a porous stretching surface. Srivivasacharya and Upendar (2013) analyzed heat and mass transfer characteristic of the mixed convection on a vertical plate in a micro polar fluid in the presence of Soret and Dufour effects. Boundary layer analysis was presented to study heat and mass transfer in a laminar, viscous and incompressible fluid past a continuously moving plate saturated in a non-Darcy porous medium in the presence of Soret and Dufour effects with temperature dependent viscosity and thermal conductivity by El-kabeir *et al.* (2013). Omowaye *et al.* (2015) studied Dufour and Soret effects on steady MHD convective flow of a fluid in a porous medium with temperature dependent viscosity using homotopy analysis approach. Rajakumar *et al.* (2018) studied radiation; dissipation and Dufour effects on MHD free convection casson fluid flow through a vertical oscillatory porous plate with ion-slip current.

Olanrewaju *et al.* (2013) investigated Dufour and Soret effects on convection heat and mass transfer in an electrically conducting power fluid over a heated porous plate. In view of the above studies, this paper seeks to investigate the MHD free convection heat and mass transfer flow in a porous medium with Dufour and chemical reaction effects.

2. MATHEMATICAL FORMULATION

We consider an unsteady two-dimensional flow of an incompressible, radiating, electrically conducting, heat absorbing fluid with mass transfer past a semi-infinite vertical porous plate. The plate is along the x-axis with the y-axis perpendicular to it and with velocity components u and v respectively. The plate is at temperature T_w and concentration C_w (at the wall) and far from the plate we have temperature at T_∞ and concentration at C_∞ (free stream). The induced magnetic field is assumed weak so that the magnetic Reynolds number and the induced magnetic field is negligible hence we apply a magnetic field of strength B_0 perpendicular to the x-axis. The semi-infinite nature of the plates makes the flow variable to be function of y and t only. The

Boussinesq approximation is assumed valid and with the boundary layer approximation the governing equation for continuity, momentum, energy and concentration are;

$$\frac{\partial v'}{\partial y'} = 0 \tag{1}$$

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = -\frac{1}{\rho}\frac{\partial P'}{\partial x'} + \upsilon\frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_0^2 u'}{\rho} + g\beta_T(T' - T_\infty) + g\beta_c(C' - C_\infty) - \frac{1}{K'}u' \tag{2}$$

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{k}{\rho c_p}\frac{\partial^2 T'}{\partial y'^2} - \frac{k}{\rho c_p}\frac{\partial q'}{\partial y'} + \frac{Q_0(T' - T_\infty)}{\rho c_p} + \frac{Q_1 k}{\rho c_p}\frac{\partial^2 C'}{\partial y'^2} \tag{3}$$

$$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2} - R(C' - C_\infty) \tag{4}$$

The boundary conditions are

u'=0, $T' = T_w + \varepsilon(T_w - T_\infty)e^{nt}$, $C' = C_w + \varepsilon(C_w - C_\infty)e^{nt'}$, at $y = 0$ (5)

$u' = U'_\infty$, $T' \to T_\infty$, $C' \to C_\infty$ as $y \to \infty$ (6)

where K' is the permeability of the porous medium, q'_r is the radiation heat flux, Q_0 is the heat generation coefficient, B_0 is the magnetic induction, υ is kinetic viscosity, c_p is the specific heat at constant pressure, ρ is the density, σ is the fluid electrical conductivity, β_T and β_c are coefficient of volume expansion due to temperature and concentration respectively, t' is time, k is thermal diffusion ration, g is acceleration due to gravity, D is molecular diffusivity, R is the chemical reaction.

The suction velocity of the plate is a function of time and takes the form

$$v' = -v_0\left(1 + \varepsilon A e^{n't'}\right) \tag{7}$$

where A is a positive constant such that $\varepsilon A << 1$ and v_0 is the suction velocity.

In the free stream, the momentum equation (2) takes the form

$$-\frac{1}{\rho}\frac{\partial p'}{\partial x'} = \frac{\partial u'_\infty}{\partial t'} + \frac{\sigma}{\rho}B_0^2 u'_\infty + \frac{1}{K'}u'_\infty \tag{8}$$

The radiative flux is present in the form of a non-directional flux in the y- direction. Following the Rosseland approximation for an optically thin fluid, it takes the form

$$q'_r = -\frac{4}{3}\frac{\sigma^*}{k^*}\frac{\partial T'^4}{\partial y'} \tag{9}$$

where σ^* is Stefan-Boltzmann constant and k^* is the mean absorption coefficient. If the temperature difference within the flow is sufficiently small, then T'^4 in equation (9) can be expressed as a linear function about the free stream temperature T'_∞ using Taylor series which on neglecting higher order terms gives

$$T'^4 \cong 4T'^3_\infty - 3T'^4_\infty \tag{10}$$

Consequently, following equation (9) and (10) equation (3) becomes

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{k}{\rho c_p}\frac{\partial^2 T'}{\partial y'^2} + \frac{16\sigma^* k T'^3_\infty}{3\rho c_p k^*}\frac{\partial^2 T'}{\partial y'^2} + \frac{Q_0(T' - T_\infty)}{\rho c_p} + \frac{Q_1 k}{\rho c_p}\frac{\partial^2 C'}{\partial y'^2} \tag{11}$$

The non-dimensional parameters for the problem are

$$u = \frac{u'}{V_0}, v = \frac{v'}{V_0}, y = \frac{V_0 y'}{\upsilon}, \emptyset = \frac{C' - C_\infty}{C_w - C_\infty}, \theta = \frac{T' - T_\infty}{T_w - T_\infty}, U_\infty = \frac{U'_\infty}{V_0}, n = \frac{n'\upsilon}{V_0^{\,2}}, t = \frac{t' V_0^{\,2}}{\upsilon} \tag{12}$$

Introducing the non-dimensional variables in equations (12) into equations (2), (4) and (11), including the boundary conditions (5) and (6), the governing equation becomes

$$\frac{\partial u}{\partial t}-(1-\varepsilon A e^{nt})\frac{\partial u}{\partial y}=\frac{\partial U_\infty}{\partial t}+\frac{\partial^2 u}{\partial y^2}+M(U_\infty-u)+\frac{1}{K}(U_\infty-u)+Gr\theta+Gm\emptyset \quad (13)$$

$$\frac{\partial \theta}{\partial t}-(1-\varepsilon A e^{nt})\frac{\partial \theta}{\partial y}=\frac{1}{Pr}\frac{\partial^2 \theta}{\partial y^2}+\frac{Du}{Pr}\frac{\partial^2 \emptyset}{\partial y^2}+\phi\theta+\frac{Ra}{Pr}\frac{\partial^2 \theta}{\partial y^2} \quad (14)$$

$$\frac{\partial \emptyset}{\partial t}-(1-\varepsilon A e^{nt})\frac{\partial \emptyset}{\partial y}=\frac{1}{Sc}\frac{\partial^2 \emptyset}{\partial y^2}-\gamma\emptyset \quad (15)$$

The dimensionless boundary conditions are

$$u=0,\ \theta=1+\varepsilon e^{nt},\ \emptyset=1+\varepsilon e^{nt} \qquad \text{at} \quad y=0 \quad (16)$$

$$u\to 0,\ \theta\to 0,\ \emptyset\to 0 \qquad \text{as} \quad y\to\infty \quad (17)$$

The following are identified in the problem

$$Gr=\frac{\rho g\beta_T\upsilon(T_w-T_\infty)}{U_0V_0^2},\ Gm=\frac{\rho g\beta_c\upsilon(C_w-C_\infty)}{U_0V_0^2},\ M=\frac{\sigma B_0^2\upsilon}{\rho c_p V_0^2},\ Sc=\frac{\upsilon}{D},\ Pr=\frac{\rho c_p\upsilon}{k},\ K=\frac{V_0^2K'}{\upsilon^2},\ \gamma=\frac{R\upsilon}{V_0^2}$$

$$Du=\frac{Q_1k(C'-C_\infty)}{\rho c_p\upsilon(T_w-T_\infty)},\ Ra=\frac{16\sigma^* T_\infty^3}{3k^*(T_w-T_\infty)},\ \phi=\frac{Q_0\upsilon}{\rho c_p {V_0}^2} \quad (18)$$

The terms in equation (18) respectively stand for the thermal Grashof number, solutal Grashof number, magnetic field, Schmidt number, Prandtl number, permeability parameter, chemical reaction parameter, Dufour parameter, thermal radiation parameter, heat source parameter.

3. METHOD OF SOLUTION

Equations (13) to (15) are coupled non-linear partial differential equations and these cannot be solved in closed form. However, these equations can be reduced to a set of ordinary differential equations which can be solved analytically. These can be done by representing the velocity, temperature and concentration as:

$$u(y,t)=u_0(y)+\varepsilon e^{nt}u_1(y)+0(\varepsilon^2)\cdots \quad (19)$$

$$\theta(y,t)=\theta_0(y)+\varepsilon e^{nt}\theta_1(y)+0(\varepsilon^2)\cdots \quad (20)$$

$$\emptyset(y,t)=\emptyset_0(y)+\varepsilon e^{nt}\emptyset_1(y)+0(\varepsilon^2)\cdots \quad (21)$$

Substituting Equations (19) – (21) into equation (13) - (17), equating the harmonic and non-harmonic terms and neglecting the coefficient of $0(\varepsilon^2)$, we get the following pairs of equations for $(u_0,\theta_0,\emptyset_0)$ and $(u_1,\theta_1,\emptyset_1)$.

$$u_0''+u_0'-\left(M+\frac{1}{K}\right)u_0=-\left(M+\frac{1}{K}\right)+Gr\theta_0+Gm\emptyset_0 \quad (22)$$

$$u_1''+u_1'-\left(M+\frac{1}{K}+n\right)u_1=-\left(M+\frac{1}{K}+n\right)-Au_0'-Gr\theta_1-Gm\emptyset_1 \quad (23)$$

$$\theta_0''+\frac{Pr}{1+Ra}\theta_0'+\frac{Pr\phi}{1+Ra}\theta_0=-\frac{Du}{1+Ra}\emptyset_0'' \quad (24)$$

$$\theta_1''+\left(\frac{Pr}{1+Ra}\right)\theta_1'+\left(\frac{Pr}{1+Ra}\right)(\phi-n)\theta_1=-\frac{APr}{1+Ra}\theta_0'-\frac{Du}{1+Ra}\emptyset_1'' \quad (25)$$

$$\emptyset_0''+Sc\,\emptyset_0'-Sc\,\gamma\,\emptyset_0=0$$

(26)

$$\emptyset_1''+Sc\emptyset_1'-Sc(n+\gamma)\emptyset_1=-ASc\,\emptyset_0' \quad (27)$$

where the primes denote differentiation with respect to y. The corresponding boundary conditions can be written as

$$u_0=0,\ u_1=0,\ \theta_0=1,\ \theta_1=1,\ \emptyset_0=1,\ \emptyset=1 \qquad \text{at} \quad y=0 \quad (28)$$

$$u_0\to 0,\ u_1\to 0,\ \theta_0\to 0,\ \theta_1\to 0,\ \emptyset_0\to 0,\ \emptyset_1\to 0 \qquad \text{as} \quad y\to\infty \quad (29)$$

The solutions to equations (22) - (27) which satisfy the boundary condition (28) and (29) are given by

$$u(y,t) = (1 - Q_2 - Q_3)e^{-r_6 y} + Q_2 e^{-r_4 y} + Q_3 e^{-r_2 y} - 1 + \varepsilon e^{nt}\{(1 - Q_7 - Q_8 - Q_9 - Q_{10} - Q_{11})e^{-r_{12} y} + Q_7 e^{-r_6 y} + Q_8 e^{-r_4 y} + Q_9 e^{-r_2 y} + Q_{10} e^{-r_{10} y} + Q_{11} e^{-r_8 y} - 1\} \quad (30)$$

$$\theta(y,t) = (1 + \alpha_3)e^{-r_4 y} - \alpha_3 e^{-r_2 y} + \varepsilon e^{nt}\{(1 - Q_4 - Q_5 - Q_6)e^{-r_{10} y} + Q_4 e^{-r_2 y} + Q_5 e^{-r_4 y} + Q_6 e^{-r_8 y}\} \quad (31)$$

$$\emptyset(y,t) = e^{-r_2 y} + \varepsilon e^{nt}\{(1 - B_2)e^{-r_8 y} + B_2 e^{-r_2 y}\} \quad (32)$$

It is important to calculate the local wall shear stress Cf, the heat transfer rate in terms of the Nusselt number Nu and mass flux in terms of the Sherwood number Sh. They are presented as follows

$$Cf = \frac{\partial u}{\partial y}\bigg|_{y=0} = -r_6(1 - Q_2 - Q_3) - Q_2 r_4 - Q_3 r_2 - \varepsilon e^{nt}\{(1 - Q_7 - Q_8 - Q_9 - Q_{10} - Q_{11})r_{12} + Q_7 r_6 + Q_8 r_4 + Q_9 r_2 + Q_{10} r_{10} + Q_{11} r_8\} \quad (33)$$

$$Nu = \frac{\partial \theta}{\partial y}\bigg|_{y=0} = -r_4(1 + \alpha_3) + \alpha_3 r_2 - \varepsilon e^{nt}\{(1 - Q_4 - Q_5 - Q_6)r_{10} + Q_4 r_2 + Q_5 r_4 + Q_6 r_8\} \quad (34)$$

$$Sh = \frac{d\emptyset}{dy}\bigg|_{y=0} = = -r_2 - \varepsilon e^{nt}\{(1 - B)r_8 + B_2 r_2\} \quad (35)$$

4. DISCUSSION

In this work, we have examined the MHD free convection heat and mass transfer flow in a porous medium with Dufour and chemical reaction effects. The leading governing equation are solved analytically using the perturbation method and obtained to illustrate the influence of Magnetic field parameters M, permeability parameter K, Dufour parameter Du, thermal radiation parameter Ra, thermal Grashof number Gr, solutal Grashof number Gm, chemical reaction parameter γ, heat source ϕ, Schmidt number Sc, oscillation parameter n, suction parameter A, and time t, on the velocity, temperature, and concentration profile as well as skin friction coefficient, Nusselt and Sherwood numbers. The various graphical results shown are discussed below as follows.

The response of velocity for variation in thermal radiation is shown in Figure 1. The profiles indicate increase in velocity as the thermal variation increases. Physically this is due to increase in the buoyancy force. The response of velocity for variation in magnetic field is depicted in Figure 2. It is observed that increased magnetic field decreases fluid flow. This is mainly caused by the presence of the Lorentz force which condenses the momentum boundary layer thereby retarding the flow. Figure 3 shows the response of velocity for variation in permeability. The flow increases as a result of increase in permeability. This is expected as more fluid flow in the system due to increased permeability. The effect of the variation in the thermal buoyancy force on the velocity is depicted in Figure 4. The profile indicates that increase in the thermal Grashof number increases the velocity. The buoyancy force increases the boundary layer, hence the flow is enhanced. Figure 5 shows the influence of the solutal Grashof number Gm on the velocity. The flow is enhanced by increase in the solutal Grashof number. Both Gr and Gm enhances the flow due to their increase but is more pronounced in the case of Gm. This effect is similar to that of Gr but is less pronounced. The effect of the variation of the Schmidt number on the velocity is depicted in Figure 6. It reveals that at high Schmidt number, the velocity peaks closer to the plate but moves further away from the plate at low Schmidt number. This is an indication that the Schmidt number enhances the velocity. Figure 7 indicates the influences of the oscillation parameter on velocity. Increase in the oscillations leads to reduction in the velocity. This is true physically as oscillation reduces the pace of flow of the fluid. Figure 8 shows the effect of time variation on the velocity. It is observed that as the time increases, the velocity peaks up close to the boundary layer and thereafter decelerates to attain the free stream velocity. The influence of Dufour on the velocity is depicted in Figure 9. It is shown that as the value of Dufour parameters increases, the velocity also increases. The response of temperature to variation in heat source is shown in Figure 10 the profiles reveal that the temperature decreases due to increase in the heat source. This is primarily because of the fact that heat absorption leads to decrease in the kinetic energy as well as thermal energy of the fluid.

The influence of chemical reaction on the temperature is depicted in Figure 11. It is observed that increase in chemical reaction decreases the temperature. Physically, this is because the thermal boundary layer releases the energy for chemical reaction thereby decreasing the temperature of the system. The effect of variation of the Schmidt number on the temperature is depicted in Figure 12. It is revealed from the profile that increases in Schmidt number decreases the temperature primarily due to decrease in the boundary layer thickness occasioned by the increase in the Schmidt number. Figure 13 shown that increase in Dufour parameters influences the temperature distribution by decreasing its profile. Again, the boundary layer thickness is decreased by the Dufour parameter in more pronounced form. Figure 14 depicts the effect of variation of chemical reaction on the concentration. It is deduced from the profile that increasing the chemical reaction decreases the concentration until it assumes a minimal level i.e. near zero. Figure 15 shows that increase in the Schmidt number decreases the concentration of species in the solutal boundary layer. In effect, increase in Schmidt number decreases the concentration boundary layer thickness which leads to decrease in concentration profiles. Increase in Schmidt number means decrease in molecular diffusion. Figure 16 shows that the concentration increases with time in the solutal boundary layer. Far from the boundary layer as the time increases the concentration becomes zero. Figure 17 shows that increased suction decreases the concentration of species. This is expected as more fluid in the system decreases concentration. The influence of variation in thermal Radiation and magnetic field on the skin of friction is shown in Figure 18. The effect of increase in thermal radiation is to reduce the skin friction with changes in the magnetic field making no difference in the skin friction.

Figure 19 depicts the effects of variation of magnetic field and Grashof number on the skin friction. It is observed that the increased magnetic fluid increases the skin friction. This is due to the drag occasioned by the effect of the Lorentz force on the flow. The increase in the Grashof does not alter the effect of the magnetic field on the skin friction. Figure 20 shows that increasing the heat source decreases the heat transfer rate in the system with the effect of the heat absorption dominating that of magnetic field. Figure 21 shows that increasing the chemical reaction and the thermal buoyancy force increases the heat transfer rate. Similarly it is observed that in Figure 22, that increase in the Schmidt number and thermal Radiation increases the mass transfer. In this case thermal Radiation has little influence.

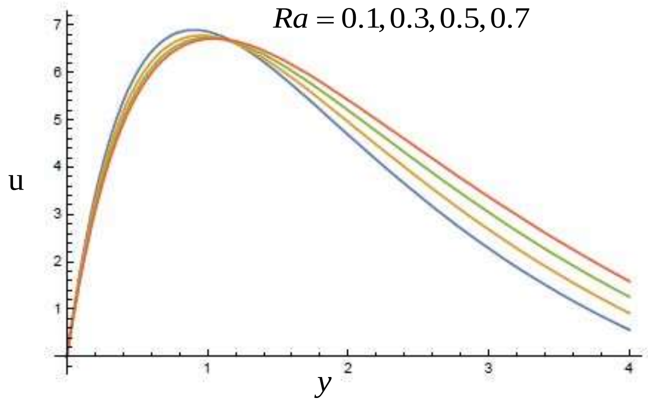

Figure 1: Influence of thermal radiation (Ra) on velocity u for the parameters M=2, k=1, A=0.5, Gr= 5, Pr= 0.71, Du=1, Gm= 5, Sc=0.50, γ=1, n=1, ϕ=0.5, Ɛ=0.1

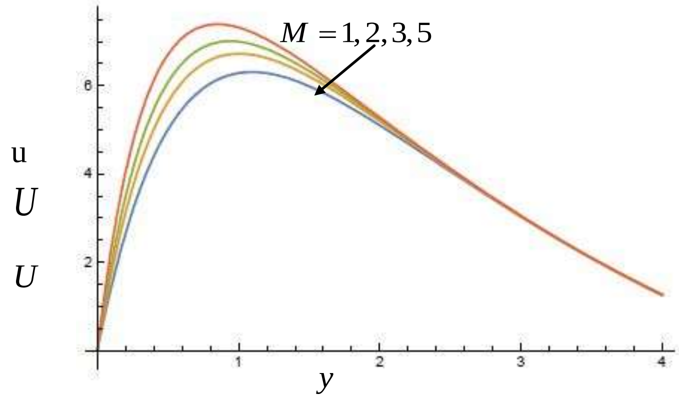

Figure 2: Influence of magnetic field (M) on velocity U for the parameters Ra=0.5, k=1, A=0.5, Gr= 5, Gm= 0.71, Pr=0.71, Du=1, Sc=0.50, γ=1, n=1, ϕ=0.5, Ɛ =0.1

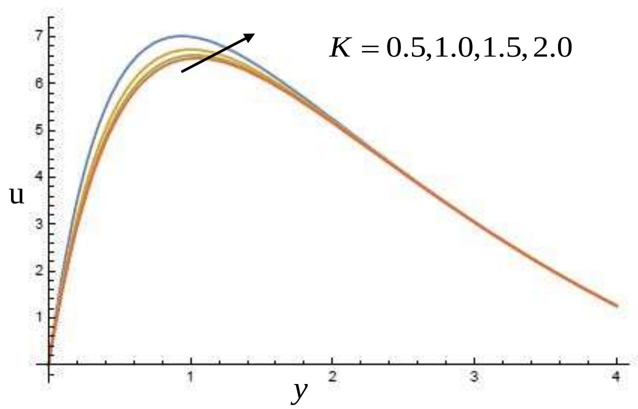

Figure 3: Influence of permeability K on the velocity U for the parameters Ra=0.5, M=2, A=0.5, Gr= 5, Gm=5, Pr= 0.71, Du=1, Gm= 5, Sc=0.50, γ=1, n=1, ϕ=0.5, Ɛ=0.1

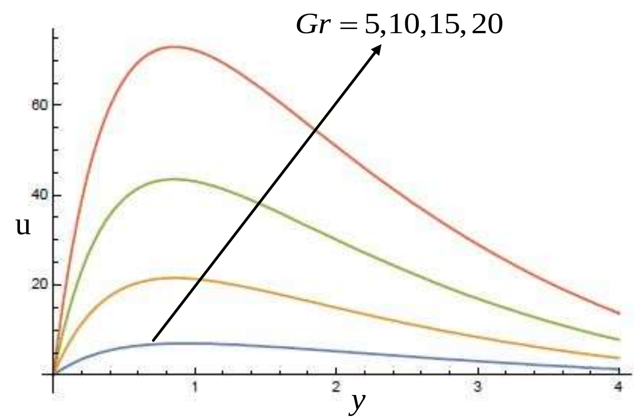

Figure 4: Influence of Grashof number Gr on velocity u for parameters M=2, k=1, A=0.5, Ra=0.5, Pr= 0.71, Du=1, Gm= 5, Sc=0.50, γ=1, n=1, ϕ=0.5, Ɛ=0.1

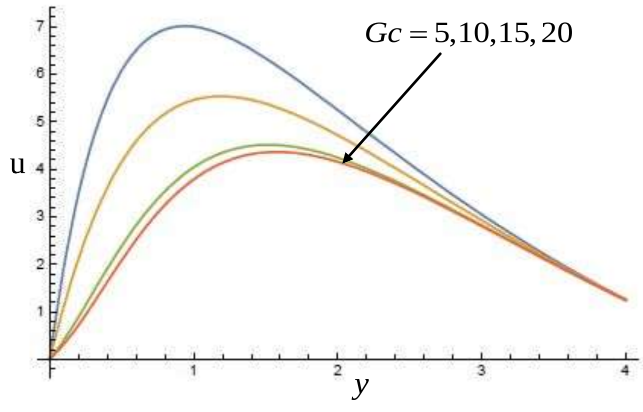

Figure 5: Influence of solutal buoyancy force Gm on velocity U for the parameters M=2, k=1, A=0.5, Gr=5 Ra=0.5, Pr= 0.71, Du=1, Gm= 5, Sc=0.50, γ=1, n=1, ϕ=0.5, Ɛ=0.1

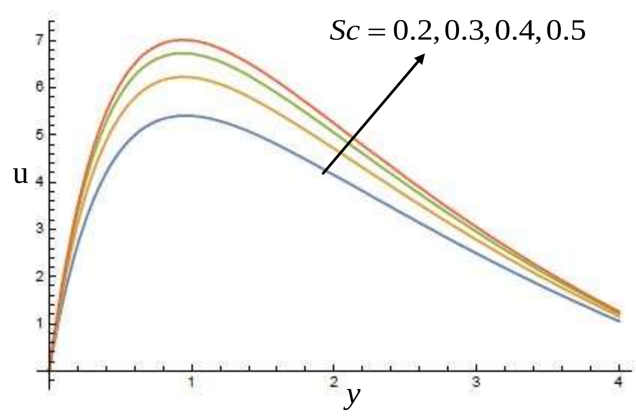

Figure 6: Influence of Schmidt number Sc on velocity U for the parameters Ra=0.5, k=1, A=0.5, Gr=5, Gm= 5, Pr= 0.71, Du=1, γ=1, n=1, ϕ=0.5, Ɛ=0.1

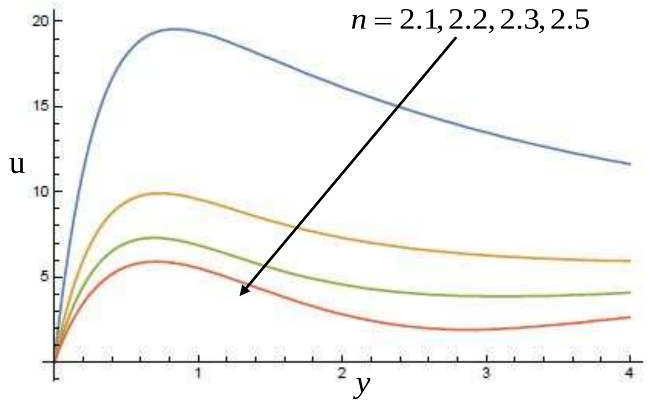

Figure 7: Influence of oscillation parameter N on velocity U for parameter Ra=0.5, k=1, A=0.5, Gr=5, Gm= 5, Pr= 0.71, Du=1, γ=1, n=1, ϕ=0.5, Sc=0.50, Ɛ=0.1

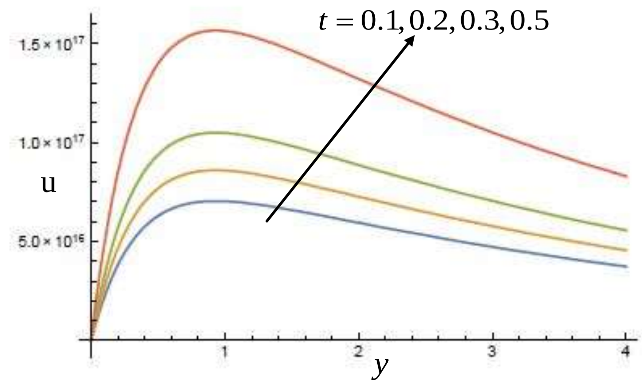

Fig. 8: Influence of time variation t on velocity U for the parameters M=2, k=1, A=0.5, Gr=5, Pr= 0.71, Du=1, Gm=5, Sc=0.50, γ=1, n=1, ϕ=0.5, Ɛ=0.1

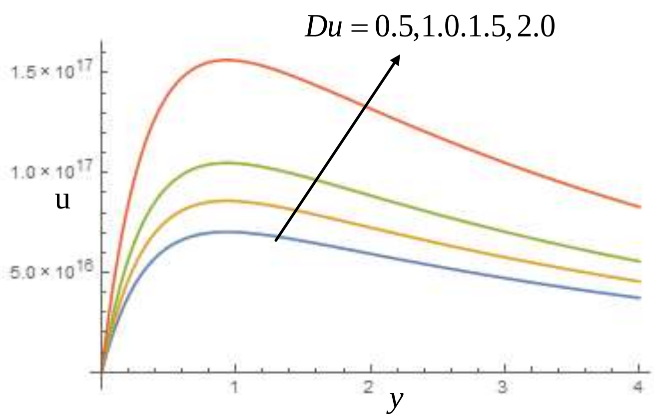

Fig. 9: Influence of Dufour Du on velocity u for the parameters M=2, k=1, A=0.5, Gr=5, Pr= 0.71, Gm=5, Sc=0.50, γ=1, n=1, ϕ=0.5, Ɛ=0.1

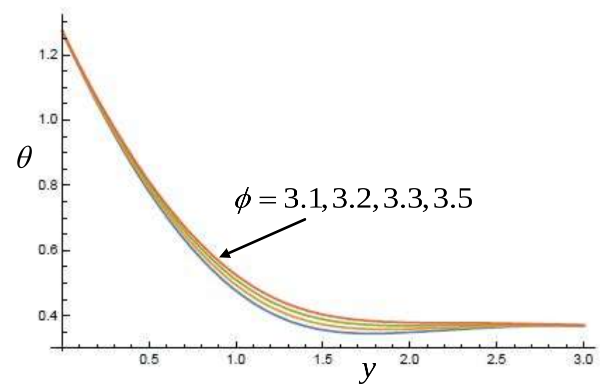

Figure 10: Influence of Heat source ϕ on temperature θ for the parameter Pr= 0.71, Ra=0.5, Du=1, Sc= 0.5, γ=1, n=1, A=0.5, Gr=5, Gm= 5, Ɛ=0.1, m=2,k=1

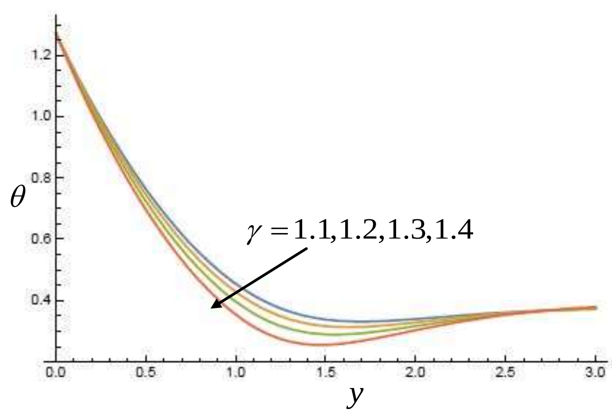

Figure 11: Influence of chemical reaction γ on temperature θ for the parameters M=2, k=1, A=0.5, Gr=5, Pr= 0.71, Du=1, Gm= 5,Ra=0.5, Sc=0.50, n=1, ϕ=0.5, Ɛ=0.1

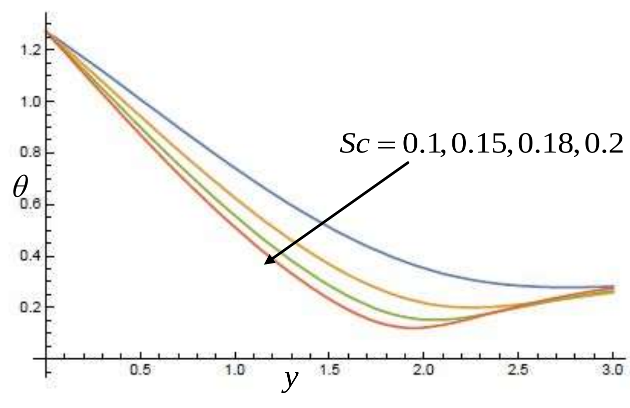

Figure 12: Influence of Schmidt number Sc on temperature θ for the parameters M=2, k=1, A=0.5, Gr=5, Pr= 0.71, Du=1, Gm= 5, γ=1, n=1, Ra=0.5, ϕ=0.5, Ɛ=0.1

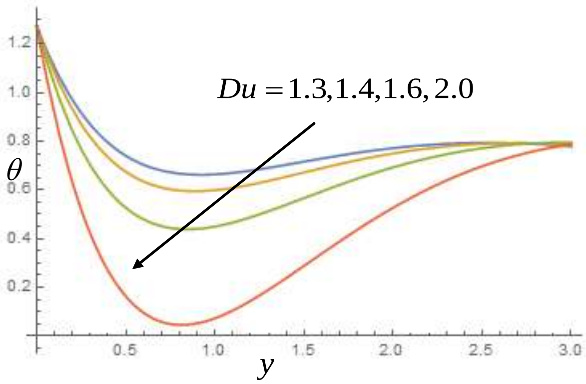

Figure 13: Influence of Dufour Du on temperature θ for the parameters M=2, k=1, A=0.5, Gr=5, Pr= 0.71, Gm= 5, γ=1, n=1, Sc=0.50, Ra=0.5, ϕ=0.5, Ɛ=0.1

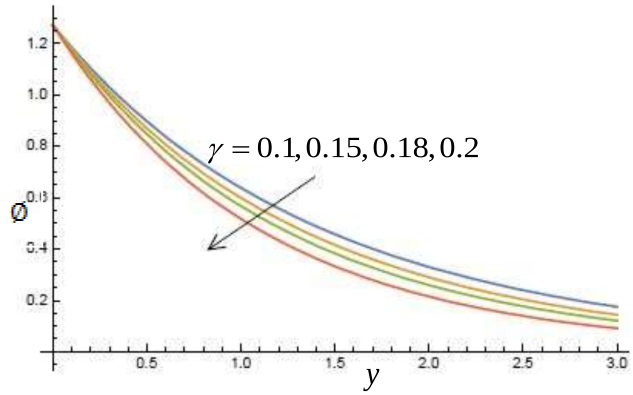

Figure 14: Influence of chemical reaction γ on concentration for the parameters Sc=0.50, Ɛ=0.1, n=1, A=0.5, M=2, k=1, Gr=5, Pr= 0.71, Du=1, Gm=5, Ra=0.5, ϕ=0.5

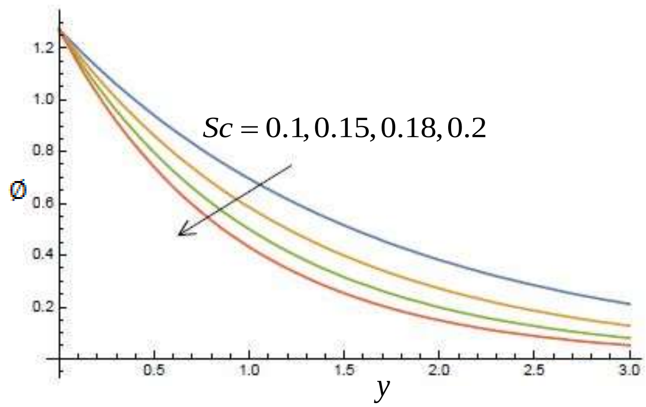

Figure 15: Influence of Schmidt number Sc on concentration for the parameter M=2, k=1, A=0.5, Gr=5, Pr= 0.71, Du=1, Gm= 5, γ=1, n=1, ϕ=0.5, Ɛ=0.1, Ra=0.5

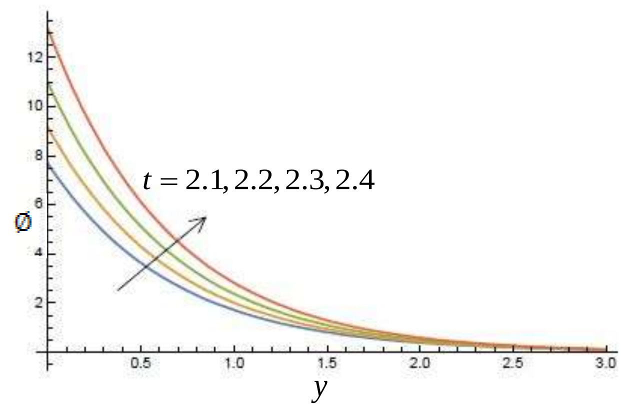

Figure 16: Influence of time on concentration for the parameters M=2, k=1, A=0.5, Gr=5, Pr= 0.71, Du=1, Gm= 5, Sc=0.50, γ=1, Ra=0.5,n=1, ϕ=0.5, Ɛ=0.1

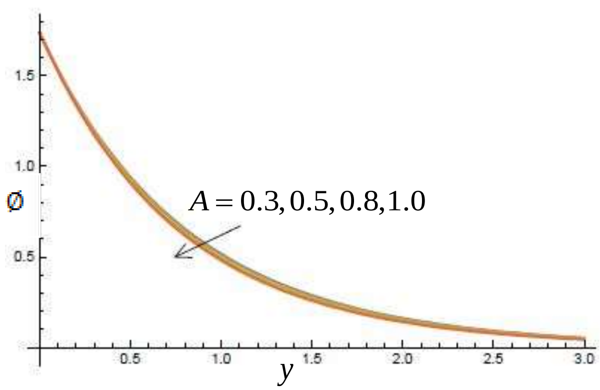

Figure 17: Influence of function parameter A on concentration for the parameters M=2, k=1, Gr=5, Pr= 0.71, Du=1, Gm= 5, Sc=0.50, γ=1, Ra=0.5,n=1, ϕ=0.5, Ɛ=0.1

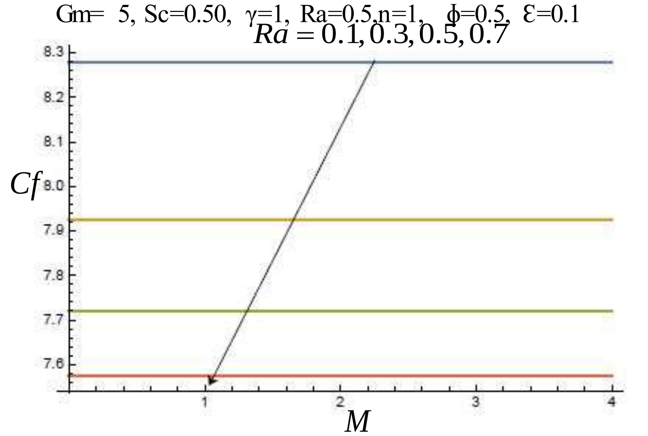

Figure 18: Influence of thermal Rediation (Ra) and magnetic field (M) on skin function (Cf) for the parameters K=1, A=0.5, Gr=5, Pr=0.71, Du=1, Gm=5, Sc=0.50, γ=1,n=1, ϕ=0.5, Ɛ=0.1

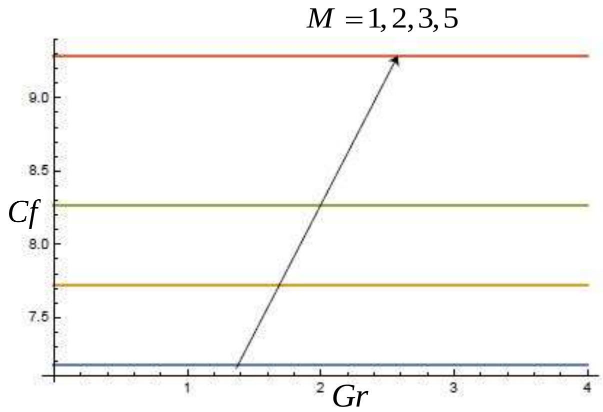

Figure 19: Influence of magnetic field M and Grashof number on skin function for the parameters k=1, A=0.5, Pr= 0.71, Du=1, Gm= 5, Sc=0.50, γ=1, Ra=0.5,n=1, ϕ=0.5, Ɛ=0.1

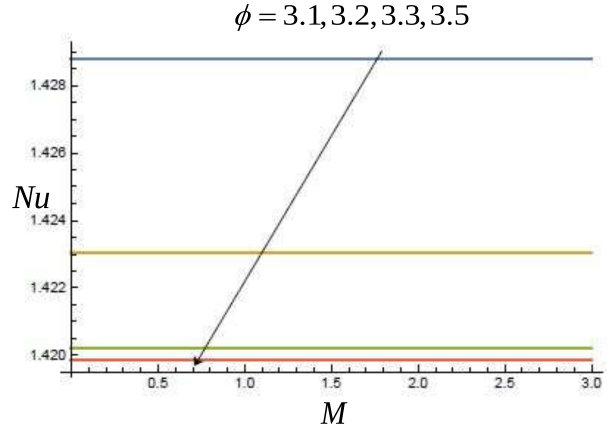

Figure 20: Influence of heat source ϕ and magnetic field M on heat transfer Nu for the parameter k=1, A=0.5, Gr=5, Pr= 0.71, Du=1, Gm= 5, Sc=0.50, γ=1, n=1, ϕ=0.5, Ɛ=0.1, Ra=0.5

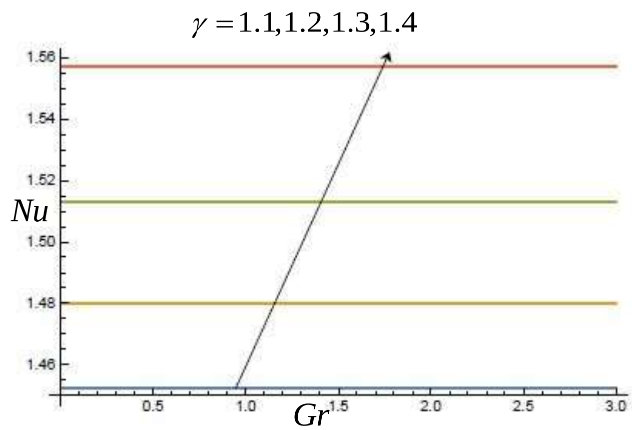

Figure 21: Influence of chemical reaction and Grashof number Gr on skin function for the parameters M=2, k=1, A=0.5, Pr= 0.71, Du=1, Gm= 0.5, Sc=0.50, n=1, ϕ=0.5, Ɛ=0.1, Ra=0.5

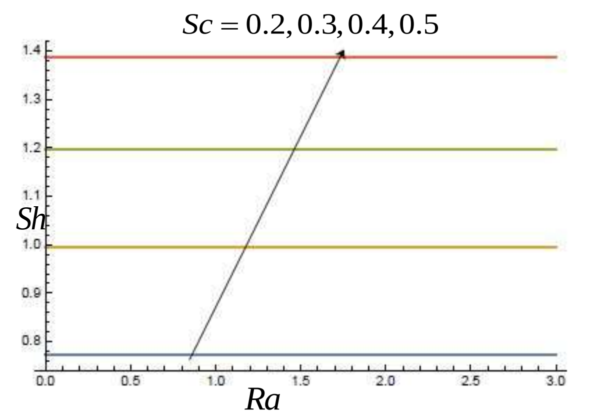

Figure 22: Influence of Schmidt number Sc and thermal radiation Ra on mass transfer Sh for the parameter M=2, k=1, A=0.5, Gr=5, Pr= 0.71, Du=1, Gm= 5, Sc=0.50, γ=1, n=1, ϕ=0.5, Ɛ=0.1

CONCLUSION

We have investigated MHD free convection heat and mass transfer flow in a porous medium with Dufour and chemical reaction effects. The transformed system of non-linear, coupled ordinary different equations governing the problem were solved analytically by perturbation technique. We presented the results to illustrate the flow characteristics for the velocity, temperature and concentration and the effects of the physical parameters of the flow. We therefore conclude follows:

1. An increase in value for thermal radiation Ra, permeability K, thermal Grashof number Gr, Dufour Du, solutal buoyancy force Gm, Schmidt number Sc, and time variation t enhances the velocity while an increase in value for magnetic field M and oscillation n, decreases the velocity.
2. An increase in the values for heat source ϕ, chemical reaction γ and Schmidt number Sc, decreases the temperature profile.

3. An increase in the value for chemical reaction γ, Schmidt number Sc, suction parameter A and Dufour Du decreases the concentration profile while increase in time t enhances the concentration profile but far from the boundary layer the concentration is zero.
4. An increase in the value of thermal radiation Ra decreases the skin friction while the increase in magnetic field M increases the skin friction while that of Grashof number Gr leaves the skin friction unchanged
5. An increase in the value of heat source ϕ, decreases the heat transfer rate while an increase in the chemical reaction γ and thermal buoyancy force Gr, increases the heat transfer rate.
6. An increase in Schmidt number Sc and thermal radiation Ra, increases the mass transfer.

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Appendix

$$r_2 = \frac{Sc}{2} + \sqrt{\frac{Sc^2}{4} + Sc\gamma}, \quad \alpha_1 = \frac{Pr}{1+Ra}, \quad \alpha_2 = \frac{Du}{1+Ra}, \quad r_4 = \frac{\alpha_1}{2} + \sqrt{\frac{\alpha_1^2}{4} - \alpha_1\varphi}, \quad r_3 = \frac{\alpha_2 r_2^2}{r_2^2 - \alpha_1 r_2 + \alpha_1\varphi},$$

$$Q_1 = M + \frac{1}{K}, \quad r_6 = \frac{1}{2} + \sqrt{\frac{1}{4} + Q_1}, \quad Q_2 = \frac{Gr(1+\alpha_3)}{r_4^2 - r_4 - Q_1}, \quad Q_3 = \frac{Gr\alpha_3 - Gm}{r_2^2 - r_2 - Q_1}, \quad B_1 = Sc(n+\gamma),$$

$$r_8 = \frac{Sc}{2} + \sqrt{\frac{Sc^2}{4} + B_1}, \quad B_2 = \frac{AScr_2}{r_2^2 - Scr_2 - B_1}, \quad r_{10} = \frac{\alpha_1}{2} + \sqrt{\frac{\alpha_1^2}{4} - \alpha_1(\varphi - n)}, \quad Q_4 = \frac{A\alpha_3\alpha_1 r_2 - \alpha_2 r_2^2\alpha_3}{r_2^2 - \alpha_1 r_2 - \alpha_1(\varphi - n)}$$

$$Q_5 = \frac{AGr(1+\alpha_3)\alpha_1 r_4}{r_4^2 - \alpha_1 r_4 + \alpha_1(\varphi - n)}, \quad Q_6 = \frac{\alpha_2 r_8^2 Gr(1+\alpha_3)}{r_8^2 - \alpha_1 r_8 + \alpha_1(\varphi - n)}, \quad r_{12} = \frac{1}{2} + \sqrt{\frac{1}{4} + (Q_1 + n)}, \quad Q_7 = \frac{Ar_6 Gr(1+\alpha_3)}{r_6^2 - r_6 - (Q_1 + n)}$$

$$Q_8 = \frac{AQ_4 r_4 - GrQ_5}{r_4^2 - r_4 - (Q_1 + n)}, \quad Q_9 = \frac{AQ_5 r_2 - GrQ_4 - Gm\alpha_3}{r_2^2 - r_2 - (Q_1 + n)}, \quad Q_{10} = \frac{Gr^2(1+\alpha_3)}{r_{10}^2 - r_{10} - (Q_1 + n)}, \quad Q_{11} = \frac{-GrQ_6 - GmGr(1+\alpha_3)}{r_8^2 - r_8 - (Q_1 + n)}$$