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Rarefaction and Darcy effects on the hydromagnetic flow of radiating and reacting fluid in a vertical channel

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Abstract: An investigation of the combined influence of rarefaction and Darcy effects on the flow of oscillatory MHD viscous, incompressible, chemically reacting, and electrically conducting fluid in a vertical channel is carried out. The fluid is assumed to be gray and absorbing and emitting radiation but to be a nonscattering medium. The flow is assumed to be laminar and hydrodynamically and thermally fully developed. The Navier–Stokes, energy, and concentration equations, which are accompanied by appropriate velocity-slip and temperature-jump boundary conditions, are analytically solved. It is found that rarefaction effects significantly influence the flow and thermal fields such that mass flow and heat transfer rates are increased as compared to the continuum regime.

Key words: MHD, radiating and reacting fluid, Darcy effect, slip and jump boundary conditions

1. Introduction

Hydromagnetic channel flows under slip and jump boundary conditions have been a subject of experimental and theoretical research for several decades, yet they still present a challenge. Many natural flows can be better understood by exploring the similarities between them and the more easily studied channel flows. Moreover, channel flows are readily controlled in laboratory configurations for a wide range of Reynolds number and permit a rigorous analysis of different aspects of the flow. This has been motivated by their various applications in engineering, medical, and other scientific areas, such as cooling of microelectronic devices; in microreactors, cell reactors, and micro plasma; in polishing artificial heart valves; and in high altitude aircraft and vacuum technology. Extensive research in this discipline has been reported (Chauhan and Jain, 2005; Hayat et al., 2008; Kandasamy et al., 2009). Engineers are continuously attempting to improve the efficiency of the MHD energy system (Aluwalia and Doss, 1980). Recently the hydromagnetic oscillatory flow through a porous channel in the presences of Hall current with variable suction and permeability has been investigated by Chand and Sharma (2012). Rarefaction effects must be considered in fluids in which the molecular mean free path is comparable to the channel's characteristic dimension. The continuum assumption is no longer valid and the fluid exhibits noncontinuum effects such as velocity-slip and temperature-jump at the channel walls. There is strong evidence to support the use of Navier–Stokes and energy equations to model the slip flow problem, while the boundary conditions are modified by including velocity-slip and temperature-jump at the channel walls. The first order velocity slip and the temperature jump boundary conditions (neglecting the thermal creep effects) at a solid surface was studied by Street (1960). Navier (1823) was first to suggest that the fluid flowing past/along the

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surface can slip over it. According to Navier, the difference in the fluid velocity and the velocity at the boundary is proportional to the shear stress at the boundary. The fluid slippage phenomenon at solid boundaries also appears in applications where a thin film of light oils is attached to the moving plates or when the surface is coated with a special coating such as a thick monolayer of hydrophobic octadecyltrichlorosilane or lubrication of mechanical devices where a thin film of lubricant is attached to the surface, slipping over one another, or when the surfaces are coated with a special coating to minimize the friction between them (Derek et al., 2002). The slip flow regime can also occur in a working fluid containing a concentrated suspension (Soltani and Yilmazer, 1998). Moreover, one could impose nonlinear slip boundary conditions (Yu and Ameel, 2002). The effects of slip conditions on Stokes and Couette flows due to an oscillating wall were investigated by Khaled and Vafai (2004). A critical review on convective heat transfer of gas microflows in the slip-flow regime was presented by Colin (2012). A detailed account of the developments on the subject has been compiled by Mehmood and Ali (2007). Combined heat and mass transfer by free convection and boundary layer approximation has been studied by Bejan and Khair (1985) and Kulacki (1991). Cooper et al. (1993) have conducted a detailed study on the fluid mechanics of oscillatory and modulated flows associated with applications in heat and mass transfer. For some industrial applications, such as glass production and furnace design, and in space technological applications such as cosmic flight, aerodynamics, rockets propulsion systems, plasma physics, and spacecraft reentry aerodynamics, which operate at higher temperatures, radiation effects can be significant. In view of this, Hossain and Takhar (1996) have analyzed the effects of radiation on mixed convection along a vertical plate with uniform surface temperature. The effect of radiation on mixed convection flow over a horizontal surface embedded in a porous medium has been analyzed by Bakier and Gorla (1996). On the other hand, the chemical reaction has numerous applications such as manufacturing of ceramics, food processing, and polymer production. The rate of diffusion is affected by the chemical reaction (Muthucumaraswamy, 2010). Many researchers have shown interest in propulsion engines for aircraft technology (Murti et al., 2005). This is due to the significant role of thermal radiation in the surface heat transfer when convection heat transfer is small, particularly in free convection problems involving absorbing–emitting fluids (Mohammed, 2009).

However, the literature lacks studies that take into account the possibility of fluid slippage at walls under vibrating conditions. Hence, the objective of the present paper is to study the radiation effects on an unsteady, MHD, viscous, incompressible, electrically conducting, and chemically reacting fluid flow between 2 infinite vertical parallel permeable plates in slip-flow regimes under vibrating conditions.

2. Mathematical analysis

Consider the flow of an electrically conducting, viscous incompressible, radiating, and reacting fluid through saturated porous medium bounded by 2 insulated infinite vertical porous plates distance 'd' apart. A coordinate system is chosen with the origin at the stationary plate, which is subjected to a constant injection velocity V_0, and the other plate to a constant suction, which is oscillating about mean velocity U_0 as shown in Figure 1. In the present work, the following assumptions are made:

1. A uniform magnetic field is applied normal to the planes of the plates.
2. Boussinesq approximation is applied.
3. A slip-flow regime is considered.

4. The magnetic Reynolds number is assumed to be small enough so that the induced magnetic field is negligible.

5. The effect of viscous and Joule's dissipation is assumed to be negligible in the energy equation as small velocity is usually encountered in free convection flows.

6. It is also assumed that there is no applied voltage, which implies the absence of an electrical field.

7. There exists a first order chemical reaction between the fluid and species concentration.

8. The level of species concentration is very low so that the heat generated during the chemical reaction can be neglected.

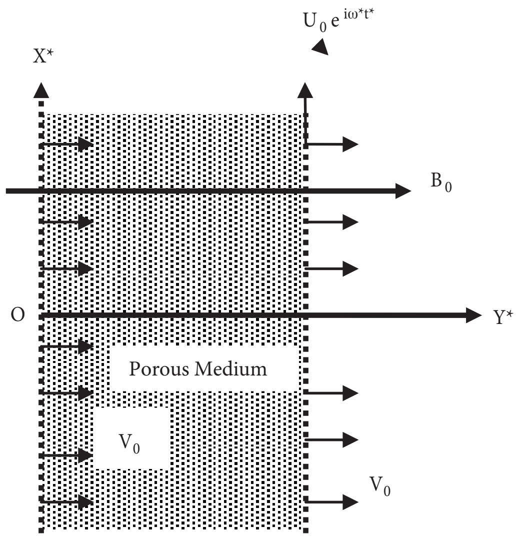

Figure 1. The physical configuration of the problem.

Under these assumptions, the governing boundary layer equations of the problem are given by:

2.1. Conservation of mass

$$\frac{\partial v^*}{\partial t^*} = 0 \Longrightarrow v^* = V_0 \tag{1}$$

2.2. Conservation of linear momentum

$$\frac{\partial u^*}{\partial t^*} + v^* \frac{\partial u^*}{\partial y^*} = -\frac{1 \partial p^*}{\rho \partial x^*} + \upsilon \frac{\partial^2 u^*}{\partial y^{*2}} - \left(\frac{\upsilon^*}{K^*} + \frac{\sigma B_0^2}{\rho} \right) u^* + g \left(\beta T^* + \beta_c C^* \right) \tag{2}$$

2.3. Conservation of energy

$$\frac{\partial T^*}{\partial t^*} + v^* \frac{\partial T^*}{\partial y^*} = \frac{k}{\rho c_p} \frac{\partial^2 T^*}{\partial y^{*2}} - \frac{1}{\rho c_p} \frac{\partial q^*}{\partial y^*} \tag{3}$$

2.4. Conservation of mass diffusion

$$\frac{\partial C^*}{\partial t^*} + v^* \frac{\partial C^*}{\partial y^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} - k_1^* C^* \tag{4}$$

Street (1960) investigated first order velocity slip and the temperature jump boundary conditions (neglecting the thermal creep effects) at a solid surface such as for the present problem; the flow is subjected to the following appropriate boundary conditions:

$$\left.\begin{array}{llll} u^* = 0, & T^* = T_0, & C^* = C_0 & \text{at} \quad y^* = 0 \\ & \text{and} & & \\ u^* = U_0 e^{i\omega^* t^*} + \frac{2-f_1}{f_1} L \frac{\partial u^*}{\partial y^*}, & T^* = T_0 e^{i\omega^* t^*} + \frac{2-f_2}{f_2} \frac{2\gamma}{\gamma-1} \frac{L}{P_r} \frac{\partial T^*}{\partial y^*}, & C^* = C_0 e^{i\omega^* t^*} & \text{at} \quad y^* = d \end{array}\right\} \tag{5}$$

Following Cogley et al. (1968), it is assumed that the fluid is optically thin with a relatively low density and the radiative heat flux is given by:

$$\frac{\partial q}{\partial y^*} = 4\alpha^2 (T^* - T_0^*) \tag{6}$$

where α is the mean radiation absorption coefficient.

Introducing the following nondimensional parameters

$$x = \frac{x^*}{d}, y = \frac{y^*}{d}, t = \frac{t^* V_0}{d}, u = \frac{u^*}{U_0}, p = \frac{p^*}{\rho V_0 U_0}, \theta = \frac{T^*}{T_0}, C = \frac{C^*}{C_0}$$

The governing equations for the flow problem in nondimensional form become:

$$\frac{\partial u}{\partial t} + \frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \frac{1}{Re}\frac{\partial^2 u}{\partial y^2} + \frac{u}{Da} - \frac{M^2 u}{Re} + Re\left(Gr\theta + GmC\right) \tag{7}$$

$$\frac{\partial \theta}{\partial t} + \frac{\partial \theta}{\partial y} = \frac{1\partial^2 \theta}{Pe \partial y^2} - \frac{N^2}{Re}\theta \tag{8}$$

$$\frac{\partial C}{\partial t} + \frac{\partial C}{\partial y} = \frac{1}{ScRe}\frac{\partial^2 C}{\partial y^2} - \frac{\chi}{Re}C \tag{9}$$

The corresponding boundary conditions reduce to:

$$\left.\begin{array}{llll} u = 0, & \theta = 0, & C = 0, & y = 0 \\ & \text{and} & & \\ u = e^{i\omega t} + h_1 \frac{\partial u}{\partial y}, & \theta = e^{i\omega t} + h_2 \frac{\partial \theta}{\partial y} & C = e^{i\omega t}, & y = 1 \end{array}\right\} \tag{10}$$

3. Solution of the problem

For the present problem, we can assume the solutions of the following forms:

$$-\frac{\partial p}{\partial x} = \lambda e^{i\omega t} \quad u = u_0 e^{i\omega t} \quad \theta = \theta_0 e^{i\omega t} \quad C = C_0 e^{i\omega t} \tag{11}$$

Therefore, using Eq. (11) in Eqs. (7) to (10), the expressions for the velocity, the temperature, and the concentration field are obtained as:

$$u\left(y,t\right) = \left\{ r_7 e^{A_5 y} + r_8 e^{A_6 y} - \left(r_1 e^{A_1 y} + r_3 e^{A_3 y}\right) + \left(r_2 e^{A_2 y} + r_4 e^{A_4 y}\right) + \frac{\lambda Re}{m_3^2} \right\} e^{i\omega t} \tag{12}$$

$$\theta(y,t)=\left\{\frac{e^{A_3 y}-e^{A_4 y}}{(1-h_2A_3)\,e^{A_3}-(1-h_2A_4)\,e^{A_4}}\right\}e^{i\omega t} \tag{13}$$

$$C(y,t)=\left\{\frac{e^{A_1 y}-e^{A_2 y}}{e^{A_1}-e^{A_2}}\right\}e^{i\omega t} \tag{14}$$

From the velocity field, the skin friction coefficient (τ) at the plate in nondimensional form is given by:

$$\tau=\left(\frac{\partial u}{\partial y}\right)_{y=0}=\{r_7A_5+r_8A_6-(r_1A_1+r_3A_3)+(r_2A_2+r_4A_4)\}\,e^{i\omega t} \tag{15}$$

From the temperature, the rate of heat transfer in nondimensional form is given by the Nusselt number:

$$Nu=-\left(\frac{\partial \theta}{\partial y}\right)_{y=0}=-\frac{e^{i\omega t}\,(A_3-A_4)}{(1-h_2A_3)\,e^{A_3}-(1-h_2A_4)\,e^{A_4}} \tag{16}$$

From the concentration field the mass transfer coefficient in nondimensional form is given by the Sherwood number:

$$Sh=\left(\frac{\partial C}{\partial y}\right)_{y=0}=\frac{e^{i\omega t}\,(A_1-A_2)}{(e^{A_1}-e^{A_2})} \tag{17}$$

where all the constants are listed in the appendix.

4. Results and discussion

The following discussion involves the effects of the pertinent parameters such as radiation parameter (N), permeability parameter (Da) magnetic field parameter(M), chemical reaction parameter (χ), frequency of oscillation parameter (ω), amplitude of the pressure gradient parameter (λ), velocity slip parameter (h_1), and the temperature jump parameter (h_2). The values of the Reynolds number (Re), the Grashoff number (Gr), the modified Grashoff number (Gm), the Schmidt number (Sc), and the Peclet number (Pe) are taken as 0.5, 5, 5, 0.22, and 1, respectively, for evaluation of velocity and skin friction fields. Our results agree with those reported by Singh and Garg (2010) in the absence of concentration, oscillation of the plate, slip velocity, and temperature jump.

Figures 2 and 3 show the variation in velocity field with some parameters relevant to the problem. Figure 2 reveals that the velocity field is accelerated near the moving plate of the channel with enhancement in the velocity slip parameter (h_1), curve (I, V). The radiation parameter (N) decelerates the velocity, curve (I, II). The increasing value of radiation parameter (N) implies less interaction of radiation with the momentum boundary layer; hence, the flow becomes decelerated. The velocity profile is first retarded and then accelerated with the increasing frequency of oscillation (ω) and the amplitude of the pressure gradient (λ), curve (I, III) and curve (I, IV), respectively.

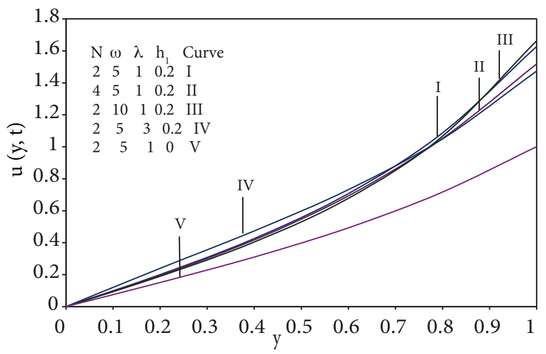

Figure 2. Variation of the velocity field for $Da=0.5$, $M=2$, $\chi=0.2$, $h_2=0.2$, and $t=0$.

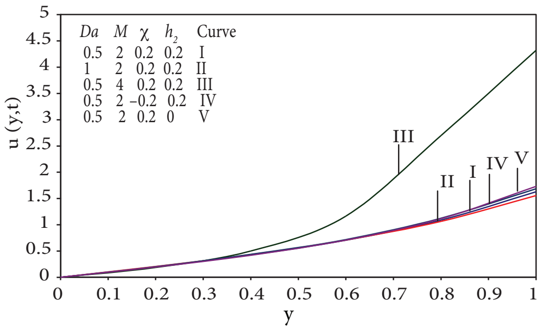

Figure 3. Variation in the velocity field for $N=2$, $\omega=5$, $\lambda=1$, $h_1=0.2$, and $t=0$.

From Figure 3, it is observed that, under the influence of increasing magnetic field parameter (M), the velocity increases, curve (I, III). Physically, it means that the magnetic field parameter, i.e. the Hartmann number, is the ratio of magnetic force to viscous force, and so if it is increased it implies that the viscosity of the fluid is reduced, resulting in velocity increases, whereas it is slightly diminished with the increasing chemical reaction parameter (χ) curve (I, IV). With increasing Darcy number (Da) and the temperature jump parameter (h_2), the velocity is decelerated, curve (I, II) and curve (I, III), respectively. It can be interpreted physically that the porous material offers resistance to the fluid flow.

Figure 4 presents the variation in nondimensional skin friction parameter (τ) at the stationary plate of the channel. It is interesting to note that the radiation parameter (N) and the magnetic field parameter (M) increases the skin friction (τ) curve (I, II) and curve (I, IV), whereas the increasing Darcy number (K), chemical reaction parameter (χ), the slip parameter (h_1), and the temperature jump parameter (h_2) enhances the skin friction (τ) curve (I, III), curve (I, V), curve (I, VI) and curve (I, VII), respectively.

Figure 5 exhibits the variation in nondimensional rate of the heat transfer parameter (Nu). It has been observed that with increasing Peclet number (Pe) the rate of heat transfer (Nu) is diminished, whereas an increase in the temperature jump parameter (h_2) results in the enhancement in the rate of heat transfer (Nu). It is interesting to note that with increasing radiation parameter (N) the rate of heat transfer (Nu) first increases in the vicinity of the stationary plate and then decreases near the moving plate of the channel.

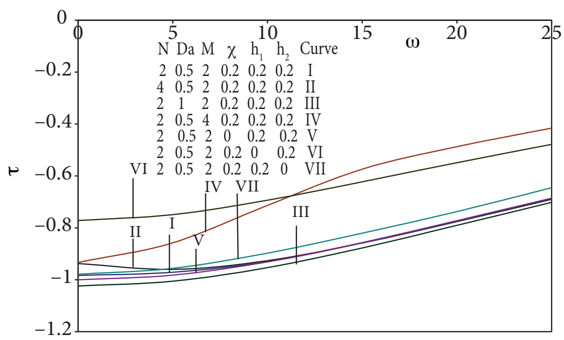

Figure 4. Variation in skin friction at stationary plate of the channel for $\lambda=1$ and $t=0$.

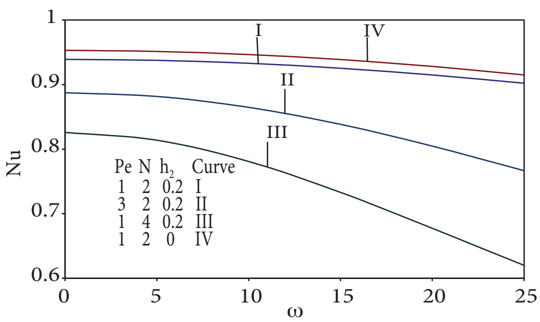

Figure 5. Variation in the Nusselt number for $t=0$.

Another pertinent parameter of the problem is the nondimensional mass transfer coefficient, i.e. the Sherwood number (Sh). Our interest is to note that how the mass transfer coefficient (Sh) is affected due to the suction parameter (Re), the Schmidt number (S_c), and the chemical reaction parameter (χ) Figure 6 depicts that for large value of suction (Re) and chemical reaction parameter (χ), and for the heavier species the rate of mass transfer coefficient (Sh) is adversely affected.

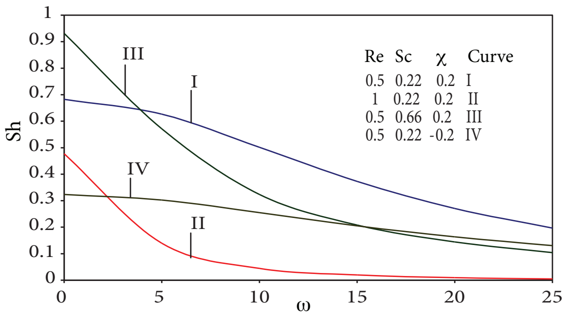

Figure 6. Variation in the Sherwood number for $t = 0$.

5. Conclusion

We made the following conclusions regarding the physical effects of the velocity, the skin friction, the Nusselt number, and the Sherwood number. The velocity slip, the temperature jump parameter, and the magnetic field parameter affect the fluid velocity and rate of heat transfer. The radiation and the magnetic field parameters, and chemical reaction parameter reduce the skin friction coefficient and the rate of mass transfer, respectively. The effects of the radiation and the chemical reaction parameter are opposite to each other.

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Nomenclature

B = magnetic field,

C^* = concentration,

C_p = specific heat at constant pressure

d = distance between 2 plates,

D = mass diffusivity,

$Da = \frac{K^* V_0}{\upsilon d}$ (Darcy number),

f_1 = Maxwell's reflexion coefficient,

f_2 = thermal accommodation coefficient

g = acceleration due to gravity,

$Gm = \frac{g\beta_c \upsilon C_0}{U_0 V_0^2}$ (mass Grashoff number),

$G_r = \frac{g\beta\nu T_0}{U_0 V_0^2}$ (thermal Grashoff number),

$h_1 = \frac{L_1}{d}$ (rarefaction parameter),

$h_2 = \frac{L_2}{d}$ (temperature jump parameter),

K = permeability coefficient,

K_1^* = reaction rate constant,

$L = \mu \left(\frac{\pi}{2p\rho}\right)^{\frac{1}{2}}$ = mean free path,

$L_1 = \frac{2-f_1}{f_1} L$ = constant,

$L_2 = \frac{2-f_2}{f_2} \frac{2\gamma}{\gamma+1} \frac{L}{P_r}$ = constant,

$M = B_0 d\sqrt{\frac{\sigma}{\mu}}$ (Hartmann number),

$N^2 = \frac{4\alpha^2 d^2}{k}$ (radiation parameter),

p = nondimensional pressure,

$Pe = \frac{\rho C_p V_0 d}{K}$ (Peclet number),

$P_r = \frac{\mu c_p}{k}$ Prandtl number,

q = radiative heat flux,

$Re = \frac{V_0 d}{\upsilon}$ (Reynolds number),

$Sc = \frac{\upsilon}{D}$ (Schmidt number),

T_0 = mean temperature of the plate,

T^* = temperature,

t = nondimensional time coordinates,

t^* = time,

u = nondimensional velocity,

u^* = velocity in x^*-direction,

U_0 = mean velocity of the plate,

V_0 = constant suction/injection,

x, y = nondimensional space coordinates,

θ = nondimensional temperature,

β = coefficient of the volumetric expansion due to temperature,

β_c = coefficient of volumetric expansion due to concentration,

k = the thermal conductivity of fluid,

$\omega = \frac{\omega^* d}{V_0}$ (frequency of oscillations),

$\upsilon = \frac{\mu}{\rho}$ (kinematic viscosity),

σ = electrical conductivity of the fluid,

ρ = density of the fluid,

μ = viscosity of the fluid,

γ = specific heat ratio,

λ = amplitude of the pressure gradient,

$\chi = \frac{K_1^* d^2}{\nu}$ (chemical reaction parameter),

α = mean radiation absorption coefficient,

Superscript $*$ means dimensional quantities

Appendix

$$m_1 = \sqrt{\chi Sc + ReSci\omega}, m_2 = \sqrt{N^2 + i\omega Pe}, m_3 = \sqrt{M^2 + \frac{R_e}{D_a} + i\omega R_e}, A_1 = \frac{ReSc + \sqrt{(ReSc)^2 + 4m_1^2}}{2}$$

$$A_2 = \frac{ReSc - \sqrt{(ReSc)^2 + 4m_1^2}}{2}, A_3 = \frac{Pe + \sqrt{(Pe)^2 + 4m_2^2}}{2}, A_4 = \frac{Pe - \sqrt{(Pe)^2 + 4m_2^2}}{2}$$

$$A_5 = \frac{Re + \sqrt{(Re)^2 + 4m_3^2}}{2}, A_6 = \frac{Re - \sqrt{(Re)^2 + 4m_3^2}}{2}, r_1 = \frac{GmRe^2}{(e^{A_1} - e^{A_2})(A_1^2 - R_e A_1 - m_3^2)},$$

$$r_2 = \frac{GmRe^2}{(e^{A_1} - e^{A_2})(A_2^2 - R_e A_2 - m_3^2)}, r_3 = \frac{GmRe^2}{\{(1 - h_2 A_3) e^{A_3} - (1 - h_2 A_4) e^{A_4}\}(A_3^2 - R_e A_3 - m_3^2)},$$

$$r_4 = \frac{GmRe^2}{\{(1 - h_2 A_3) e^{A_3} - (1 - h_2 A_4) e^{A_4}\}(A_4^2 - R_e A_4 - m_3^2)},$$

$$r_5 = r_1 (1 - h_1 A_1) e^{A_1} - r_2 (1 - h_1 A_2) e^{A_2} + r_3 (1 - h_1 A_3) e^{A_4} - r_4 (1 - h_1 A_4) e^{A_4} - \frac{\lambda R_e}{m_3^2},$$

$$r_6 = 1 + r_5 - (r_1 - r_2 + r_3 - r_4 - \frac{\lambda R_e}{m_3^2}), r_7 = \frac{1 + r_5 - r_8 (1 - h_1 A_6) e^{A_6}}{(1 - h_1 A_5) e^{A_5}}, r_8 = \frac{r_6}{(1 - h_1 A_6) e^{A_6} - (1 - h_1 A_5) e^{A_5}}$$

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