MHD free convection flow past a vertical porous plate in a slip flow regime with radiation chemical reaction and temperature gradient dependent heat source in presence of Dufour effect

K. Balamurugan¹, M. Selvarasu²* and V. Gopikrishnan³

Abstract
This paper deals with the MHD free convection flow past a vertical porous plate in a slip flow regime taking into account radiation, chemical reaction and temperature gradient dependent heat source in presence of Dufour effect. The magnetic effect is applied normal to the flow. The permeability of the porous medium and the suction velocity at the plate decrease exponentially with time about a constant mean. The expression for velocity, temperature and concentration are obtained using the regular perturbation method. The skin-friction, rate of heat and mass transfer are also derived. A number of graphs are drawn for various flow quantities based on governing parameters and deduce important results.

Keywords
MHD, Free convection, heat and mass transfer, radiation, chemical reaction, and Dufour effect.

1. Introduction
Free convection arises in fluids when temperature changes results in density variation leading to buoyancy forces acting on the fluid elements. This type of flow has applications in many branches of science and engineering. The study of such flow under the influence of magnetic field has attracted the interest of many investigators in view of its application in MHD generators, plasma studies, nuclear reactors etc.

The fluid under consideration there does occur some chemical reaction e.g. air and benzene react chemically, so also water and sulfuric acid. During such chemical reactions, there is always generation of heat. Combining heat and mass transfer problems with a chemical reaction have importance in many processes and have therefore received a considerable amount of attention in recent years. One of the simplest chemical reactions is the first-order reaction in which the rate of the reaction is directly proportional to the species concentration. The chemical reactions can be codified as either heterogeneous or homogenous processes. In most cases of chemical reactions the reaction rate depends on the concentration of the species itself. If the rate of reaction is directly proportional to the concentration then the reaction is said to be a homogeneous reaction or first order reaction.

Radiation effects of MHD oscillatory flow along a porous medium bounded by two vertical porous plates in presence of hall current and Dufour effect with chemical reaction was analyzed by Balamurugan K et al.[5].

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Contents
1 Introduction .............................................. 631
2 Formulation of the problem .......................... 632
3 Method of solution ........................................ 633
3.1 Skin friction ............................................. 634
3.2 Rate of heat transfer ................................... 634
3.3 Rate of mass transfer ................................. 634
4 Results And Discussions .............................. 634
5 Conclusion ............................................... 637
References .................................................. 637
In many practical applications, the particles adjacent to a solid surface no longer takes the velocity of the surface. The particle at the surface has a finite tangential velocity; it “slips” along the surface. The flow regime is called the slip-flow regime and this effect cannot be neglected. Using these assumptions, Sharma and Chaudhary [6], discussed the free convection flow past a vertical plate in slip-flow regime and also discussed the free convection flow past a vertical plate in slip-flow regime and also discussed its various applications for engineering purpose. Also, Coupled non-linear partial differential equations governing free convection flow, heat and mass transfer has been obtained analytically using the perturbation technique. The fluids considered in this investigation are air (Pr = 0.71) and water (Pr = 7) in the presence of Hydrogen (Sc = 0.22). Magneto hydrodynamic convective heat and mass transfer in a boundary layer slip flow past a vertical permeable plate with thermal radiation and chemical reaction were investigated by Pal and Talukda [13], Gupta. M and Sharma. S [7] have studied MHD flow through porous medium bounded by a solid surface no longer takes the velocity of the surface. The Cartesian coordinate system we is adopted ing function of time. It is an extension work of Madhusudhan Rao et.al[17]. by including the dufour effect.

The flow is entirely due to buoyancy force caused by temperature difference between the porous plate and the fluid. Under the above assumptions, the governing equations are respectively given below

\[
\frac{\partial v}{\partial y'} = 0
\]

\[
\frac{\partial u'}{\partial t} + \nu \frac{\partial u'}{\partial y'} + \frac{\nu}{\rho} \frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_0^2}{\rho} u' + g \beta (T' - T_\infty) + g \beta_e (C' - C_w)
\]

\[
\frac{\partial T'}{\partial t} + \nu \frac{\partial T'}{\partial y'} = \frac{K_s}{\rho C_p} \frac{\partial^2 T'}{\partial y'^2} - \frac{1}{\rho C_p} \frac{\partial q'}{\partial y'} + \frac{Q'}{\rho C_p} \frac{\partial T'}{\partial y'}
\]

\[
\frac{\partial C'}{\partial t} + \nu \frac{\partial C'}{\partial y'} = D \frac{\partial^2 C'}{\partial y'^2} - K'_f (C' - C_w)
\]

The relevant boundary conditions are

\[
u' = \nu' = 0
\]

\[
T' \to T_\infty, C' \to C_w \text{ at } y' \to \infty
\]

Where \(u'\) and \(v'\) are the components of velocity along \(x'\) and \(y'\) directions, \(t\) is the time, \(g\) is the acceleration due to gravity, \(\beta\) and \(\beta_e\) are the coefficients of volume expansion, \(\nu\) the kinematic viscosity of fluid, \(k'(t)\) is the permeability of the porous medium, \(\rho\) is the density of the fluid, \(\sigma\) is the electrical conductivity of the fluid, \(B_0\) the uniform magnetic field, \(T'\) is the temperature, \(K_s\) is the thermal conductivity, \(C_w\) is the specific heat at constant pressure, \(q'\) the radioactive heat flux, \(Q'\) the heat source, \(T'_\infty\) is the temperature of the wall as well as the temperature of the fluid at the plate, \(T'\) is the temperature of the fluid far away from the plate, \(L = \frac{2 - m_1}{m_1}\) is the mean free path where \(m_1\) is the Maxwell’s reflection coefficient, \(C'\) is the concentration, \(D\) the diffusion coefficient, \(D_m\) the thermal diffusion coefficient, \(K'_f\) is the chemical reaction parameter and \(C_w\) is the concentration of the wall as well as the concentration of the fluid at the plate. The equation of continuity (1) relevant that \(v'\) is either a constant or some function of time, hence assume that

\[
v' = -v'_0 \left(1 + e^{-n' t}\right),
\]

where \(v'_0 > 0\) is the suction velocity at the plate and \(n'\) is a positive constant. The negative sign indicates that the suction velocity acts towards the plate.

Consider the fluid which is optically thin with a relatively low density and there by the radioactive heat flux is given by

2. Formulation of the problem

We consider a two-dimensional unsteady free convection flow of an incompressible viscous fluid past an infinite vertical porous plate. The Cartesian coordinate system we is adopted by taking \(x'\)-axis along the plate in the direction of the flow and the \(y'\)-axis normal to it. Further the flow is considered in presence of temperature gradient dependent heat source radiation, chemical reaction and dufour effect.
Ede [7] in the following form

\[
\frac{\partial q_t}{\partial y} = 4 \left( T' - T_{\infty}' \right) I
\]  

(2.7)

Where \( I \) is the absorption coefficient at the plate. The Permeability \( k'(t) \) of the porous medium is considered in the following form

\[
k'(t) = k_0' \left( 1 + e^{-\nu t} \right)
\]  

(2.8)

Introduce the following dimensionless quantities and variable

\[
y = \frac{y'v_0}{v}, \quad t = \frac{t'v_0^2}{v}, \quad u = \frac{u'}{v}, \quad t = \frac{\nu}{v}^2, \quad n = \frac{4v_T}{v^2};
\]

\[
M = \frac{\sigma B_0^2}{v_0^2}, \quad K_c = \frac{k_c'}{v_0^2}, \quad T = T' - T_{\infty}', \quad C = \frac{C' - C_{\infty}}{C'_{w} - C_{\infty}};
\]

\[
Pr = \frac{\nu C_p}{K_T}, \quad Gr = \frac{v g \beta (T_{\infty'} - T_{\infty})}{v_0^2}, \quad Gm = \frac{v g \beta (C_{w}' - C_{\infty}')}{v_0^3};
\]

\[
Du = \frac{D_m K_T}{v C_p (T_{\infty'} - T_{\infty})}, \quad K_0 = \frac{k_0 v_0^2}{v^2};
\]

\[
R = \frac{4v_T}{\rho C_p v_0^2}, \quad \varepsilon = \frac{v}{D}, \quad H = \frac{Q_T}{\rho C_p v_0^2 (T'_{\infty} - T_{\infty})}.
\]  

(2.9)

The set of equations (2.2)-(2.4) after introducing (2.9), we obtain the non-dimensional form of the governing equations as follows:

\[
\frac{1}{4} \frac{d u}{d t} - \left( 1 + e^{-\nu} \right) \frac{Ou}{d y} = \frac{\partial^2 u}{\partial y^2} = \left[ M + \frac{1}{k_0 (1 + e^{-\nu})} \right] u + GrT + GmC
\]  

(2.10)

\[
\frac{1}{4} \frac{dT}{dt} - \left( 1 + e^{-\nu} \right) \frac{dT}{d y} = \frac{1}{Pr} \frac{\partial T}{\partial y} - RT + H \frac{d^2 T}{d y^2} + Du \frac{\partial^2 C}{\partial y^2}
\]  

(2.11)

\[
\frac{1}{4} \frac{dc}{dt} - \left( 1 + e^{-\nu} \right) \frac{dc}{d y} = \frac{1}{Sc} \frac{\partial C}{\partial y} - K_c C
\]  

(2.12)

and the boundary conditions (2.5) reduce to

\[
u = h \left( \frac{\partial u}{\partial y} \right), \quad T = 1, \quad C = 1, \quad \text{at} \quad y = 0
\]

\[
u \rightarrow 0, \quad T \rightarrow 0, \quad C \rightarrow 0 \quad \text{at} \quad y \rightarrow \infty
\]  

(2.13)

where, \( h = \frac{L_1 v_0^2}{v} \).

### 3. Method of solution

The present flow is governed by the system of partial differential equations (2.10), (2.11) and (2.12), with the boundary conditions (2.13). Assuming \( \varepsilon \) to be so small so that one can express velocity, temperature and concentration as a regular perturbation series in terms of \( \varepsilon \) in the neighborhood of the plate as,

\[
u(y, t) = u_0(y) + \varepsilon u_1(y)e^{-\nu t}
\]

(3.1)

\[
T(y, t) = T_0(y) + \varepsilon T_1(y)e^{-\nu t}
\]

(3.2)

\[
C(y, t) = C_0(y) + \varepsilon C_1(y)e^{-\nu t}
\]

(3.3)

Substituting the above expressions (3.1), (3.2), (3.3) in equations (2.10),(2.11),(2.12) and equating the coefficients of \( \varepsilon^0, \varepsilon^1 \) (neglecting \( \varepsilon^2 \) terms etc.,), we obtain the following set of ordinary differential equations.

\[
u''(y) + u''(y) - M_1 u_0(y) = -GrT_0(y) - GmC_0
\]

(3.4)

\[
u'_1(y) + u'_1(y) = -M_2 F_1(y)
\]

(3.5)

\[
2
\]

(3.6)

\[
C_0'(y) + ScC_0(y) = ScKcC_0(y) = 0
\]

(3.8)

\[
C_1'(y) + ScC_1(y) = -ScKcC_0(y)
\]

(3.9)

Where \( M_1 = M + \frac{1}{k_0} \) and \( M_2 = M + \frac{1}{k_0} - \frac{q}{v} \).

The boundary conditions (2.13) reduce to,

\[
u_0 \rightarrow h u_0, \quad u_1 \rightarrow h u_1, \quad T_0 \rightarrow 0, \quad C_0 \rightarrow 1, \quad C_1 \rightarrow 0 \quad \text{at} \quad y = 0
\]

\[
u_0 \rightarrow 0, \quad u_1 \rightarrow 0, \quad T_1 \rightarrow 0, \quad C_0 \rightarrow 0, \quad C_1 \rightarrow 0 \quad \text{at} \quad y \rightarrow \infty
\]  

(3.10)

The equations from (3.4) to (3.9) are second order ordinary linear differential equations with constant coefficients. The solutions of these paired equations under the corresponding boundary conditions (3.10) are,

\[
C_0(y) = e^{-m_1 y}
\]

(3.11)

\[
C_1(y) = A_1 e^{-m_2 y} + A_2 e^{-m_3 y}
\]

(3.12)

\[
T_0(y) = (1 - A_2) e^{-m_3 y} + A_2 e^{-m_3 x}
\]

(3.13)

\[
T_1(y) = - (A_3 + A_2 + A_3) e^{-m_1 y} + A_3 e^{-m_2 y}
\]

(3.14)

\[
u_0(y) = A_10 e^{-m_3 y} + A_2 e^{-m_3 y} + A_7 e^{-m_3 y} + A_8 e^{-m_3 y}
\]

(3.15)

\[
u_1(y) = A_{27} e^{-m_3 y} + A_{11} e^{-m_3 y} + A_{12} e^{-m_3 y} + A_{13} e^{-m_3 y}
\]

(3.16)

\[
+ A_{14} e^{-m_3 y} + A_{15} e^{-m_3 y} + A_{16} e^{-m_3 y} + A_{17} e^{-m_3 y}
\]

\[
+ A_{18} e^{-m_3 y} + A_{19} e^{-m_3 y} + A_{20} e^{-m_3 y} + A_{21} e^{-m_3 y}
\]

\[
+ A_{22} e^{-m_3 y} + A_{23} e^{-m_3 y} + A_{24} e^{-m_3 y} + A_{25} e^{-m_3 y}
\]

\[
+ A_{26} e^{-m_3 y}
\]  

The values of the constants \( A_1, A_2 \) etc. are given in the Appendix. The profiles of velocity, temperature and the con-
The expression for the rate of heat transfer at the plate in terms of various parameters like Heat source parameter $H$, Dufour number $Du$, Temperature and Concentration distribution are studied in figures 1-12, while keeping the other parameters as constants. The variation in Skin friction, Heat flux and Mass flux have been analysed numerically and discussed with the help of graphical representation.

Figure 1 display the behavior of the velocity distribution by varying the Heat source parameters $H$, this shows that the velocity decreases with an increase in $H$. In figure 2 the effect of Dufour number $Du$ on velocity is shown. From this figure it is noticed velocity increases as an increase in $Du$. In figure 3 the velocity decreases as Radiation parameter $R$ increases. From figure 4 it is observed that the velocity increases as Permeability of porous medium $K_0$ increases. In figure 5 the velocity increases as Grashof number $Gr$ increases. In figure 6 the velocity decreases as Modified Grashof number $Gm$ increases.

In figure 7 the temperature distribution increases as Dufour number $Du$ increases. From figure 8 it is observed that the temperature distribution decreases as Heat source parameters $H$ increases. In figures 9,10 the temperature distribution decreases as the Prandtl number $Pr$ and Radiation parameter $R$ increase respectively.

$$u(y,t) = A_{10}e^{-m_{3}y} + A_{5}e^{-m_{2}y} + A_{7}e^{-m_{2}y} + A_{8}e^{-m_{1}y} + A_{9}e^{-m_{1}y} + \varepsilon(A_{27}e^{-m_{2}y} + A_{11}e^{-m_{1}y} + A_{12}e^{-m_{1}y} + A_{13}e^{-m_{1}y} + A_{14}e^{-m_{1}y} + A_{15}e^{-m_{1}y} + A_{16}e^{-m_{1}y} + A_{17}e^{-m_{1}y} + A_{18}e^{-m_{1}y} + A_{19}e^{-m_{1}y} + A_{20}e^{-m_{1}y} + A_{21}e^{-m_{1}y} + A_{22}e^{-m_{1}y} + A_{23}e^{-m_{1}y} + A_{24}e^{-m_{1}y} + A_{25}e^{-m_{1}y} + A_{26}e^{-m_{1}y})e^{-nt} \quad (3.17)$$

$$T(y,t) = (1 - A_{2})e^{-m_{3}y} + A_{2}e^{-m_{1}y} + \varepsilon(-A_{3} + A_{4} + A_{5})e^{-m_{1}y} + A_{3}e^{-m_{3}y} + A_{4}e^{-m_{1}y} + A_{5}e^{-m_{1}y}e^{-nt} \quad (3.18)$$

$$C(y,t) = e^{-m_{1}y} + \varepsilon(A_{1}(e^{-m_{1}y} - e^{-m_{2}y})e^{-nt} \quad (3.19)$$

### 3.1 Skin friction
The expression for the skin-friction ($\tau$) at the plate is,

$$\tau = \left(\frac{du}{dy}\right)_{y=0} = \left(\frac{du_{0}}{dy}\right)_{y=0} + \varepsilon\left(\frac{du_{1}}{dy}\right)_{y=0} e^{-nt}$$

$$\tau = \left(\frac{du}{dy}\right)_{y=0} = A_{28} + \varepsilon A_{29} e^{-nt} \quad (3.20)$$

### 3.2 Rate of heat transfer
The expression for the rate of heat transfer at the plate in terms of Nusselt number ($Nu$) is

$$Nu = \left(\frac{dT}{dy}\right)_{y=0} = \left(\frac{dT_{0}}{dy}\right)_{y=0} + \varepsilon\left(\frac{dT_{1}}{dy}\right)_{y=0} e^{-nt}$$

$$Nu = \left(\frac{dT}{dy}\right)_{y=0} = A_{31} + \varepsilon A_{32} e^{-nt} \quad (3.21)$$

### 3.3 Rate of mass transfer
The expression for the rate of heat transfer at the plate in terms of Sherwood number ($Sh$) is

$$Sh = \left(\frac{dC}{dy}\right)_{y=0} = \left(\frac{dC_{0}}{dy}\right)_{y=0} + \varepsilon\left(\frac{dC_{1}}{dy}\right)_{y=0} e^{-nt}$$

$$Sh = \left(\frac{dC}{dy}\right)_{y=0} = -m_{1} + \varepsilon A_{30} e^{-nt} \quad (3.22)$$

### 4. Results And Discussions
To assess the physical depth of the problem, the effects of various parameters like Heat source parameter $H$, Dufour number $Du$, Radiation parameter $R$, Permeability of porous medium $K_0$, Grashof number $Gr$, Modified Grashof number $Gm$, Prandtl number $Pr$, Schmidt number $Sc$ on Velocity distribution, Temperature and Concentration distribution are studied in figures 1-12, while keeping the other parameters as constants. The variation in Skin friction, Heat flux and Mass flux have been analysed numerically and discussed with the help of graphical representation.

Figure 1 display the behavior of the velocity distribution by varying the Heat source parameters $H$, this shows that the velocity decreases with an increase in $H$. In figure 2 the effect of Dufour number $Du$ on velocity is shown. From this figure it is noticed velocity increases as an increase in $Du$. In figure 3 the velocity decreases as Radiation parameter $R$ increases. From figure 4 it is observed that the velocity increases as Permeability of porous medium $K_0$ increases. In figure 5 the velocity increases as Grashof number $Gr$ increases. In figure 6 the velocity decreases as Modified Grashof number $Gm$ increases.

In figure 7 the temperature distribution increases as Dufour number $Du$ increases. From figure 8 it is observed that the temperature distribution decreases as Heat source parameters $H$ increases. In figures 9,10 the temperature distribution decreases as the Prandtl number $Pr$ and Radiation parameter $R$ increase respectively.
In figure 13 the skin friction increases as Grashof number $Gr$ increases. Figure 14 the Nusselt number $Nu$ increases as Schmidt number $Sc$ increases. In figure 15 the Sherwood number $Sh$ decreases as Radiation parameter $R$ increases.

Figure 3. Velocity Profile For Various Value of $R$  
$(Pr = 0.71, H = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, Kc = 2.25, K0 = 2, Du = 1.0, M = 2.0, Gr = 2, Gm = 4, h = 1.0)$

Figure 4. Velocity Profile For Various Value of $K0$  
$(Pr = 0.71, R = 2, H = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, Kc = 2.25, Du = 1.0, M = 2.0, Gr = 2, Gm = 4, h = 1.0)$

Figure 5. Velocity Profile for various value of $Gr$  
$(Pr = 0.71, H = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, Kc = 2.25, K0 = 2, Du = 1.0, M = 2.0, Gm = 4, h = 1.0)$

Figure 6. Velocity profile for various value of $Gm$  
$(Pr = 0.71, H = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, Kc = 2.25, Du = 1.0, M = 2.0, Gr = 2, h = 1.0)$

Figure 7. Temperature profile for various value of $Du$  
$(Pr = 0.71, R = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, Kc = 2.25, Gr = 2, Gm = 4, h = 1.0)$

Figure 8. Temperature profile for various value of $H$  
$(Pr = 0.71, R = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, Du = 1.0, Kc = 2.25, Gr = 2, Gm = 4, h = 1.0)$
MHD free convection flow past a vertical porous plate in a slip flow regime with radiation chemical reaction and temperature gradient dependent heat source in presence of Dufour effect — 636/638

**Figure 9.** Temperature profile for various value of $Pr$ ($R = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, Du = 1.0, Kc = 2.25, Gr = 2, Gm = 4, h = 1.0$)
5. Conclusion

1. The velocity increases with an increase in Heat source parameter H, Dufour number Du, permeability of porous medium Ko, Grashof number Gr,

2. The temperature decreases with an increase in Heat source parameter H, Prandtl number Pr, Radiation parameter R. Also temperature increases when increase in the Dufour number Du.

3. The concentration decrease with an increase in Radiation parameter R, Schmidt number Sc,

4. The Skin friction increases while increase in the Grashof number. The Nusselt number increases with increase in the Schmidt number. Increase in the radiation parameter decreases the Sherwood number.

APPENDIX

\[ m_1 = \frac{S_c + \sqrt{S_c^2 + 4K_cS_c}}{2}, \quad m_2 = \frac{S_c + \sqrt{S_c^2 + 4(K_c - \frac{3}{4})S_c}}{2}, \]

\[ m_3 = \frac{(1 + H)P_r + \sqrt{(1 + H)^2P_r^2 + 4P_rR}}{2}, \]

\[ m_4 = \frac{(1 + H)P_r + \sqrt{(1 + H)^2P_r^2 + 4P_r(R - \frac{3}{4})}}{2}, \]

\[ m_5 = \frac{1 + \sqrt{1 - 4M_1}}{2}, \quad m_6 = \frac{1 + \sqrt{1 - 4M_2}}{2}. \]

\[ A_1 = \frac{S_mC_1}{m_1^2 - S_mC_1 - (K_c - \frac{9}{4})S_c}, \quad A_2 = \frac{P_r m_2^2 Du}{m_1^2 - (1 + H)P_r m_1 - P_r R}, \]

\[ A_3 = \frac{P_r m_3}{m_1^2 - (1 + H)P_r m_3 - P_r (R - \frac{3}{4})}, \]

\[ A_4 = \frac{1}{m_1^2 - (1 + H)P_r m_3 - P_r (R - \frac{3}{4})}, \]

\[ A_5 = \frac{GrA_2}{m_1^2 - m_3 - M_1}, \quad A_6 = \frac{GrA_2}{m_1^2 - m_3 - M_2}, \quad A_7 = \frac{GmA_2}{m_1^2 - m_3 - M_1}, \quad A_8 = \frac{GmA_2}{m_1^2 - m_3 - M_2}, \]

\[ A_{10} = \frac{1}{(1 + h_m)} \left[ A_6 (1 + h_m) + A_3 (1 + m_m) + A_3 (1 + h_m) \right] \]

\[ A_{11} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{12} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{13} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{14} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{15} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{16} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{17} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{18} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{19} = \frac{1}{m_1^2 - m_3 - M_2}, \]

\[ A_{20} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{21} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{22} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{23} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{24} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{25} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{26} = \frac{1}{m_1^2 - m_3 - M_2}, \quad A_{27} = \frac{1}{(1 + h_m)}, \]

\[ A_{28} = - (m_5 A_{10} + m_3 A_6 + m_3 A_7 + m_1 A_9 + m_1 A_9) \]

\[ A_{29} = - (m_6 A_{27} + m_5 A_{11} + m_3 A_{12} + m_3 A_{13} + m_1 A_{14} + m_1 A_{15} + m_3 A_{16} + m_3 A_{17} + m_3 A_{18} + m_1 A_{19} + m_1 A_{20} + m_4 A_{21} + m_1 A_{22} + m_3 A_{23} + m_3 A_{24} + m_1 A_{25} + m_3 A_{26}) \]

\[ A_{30} = - A_1 m_1 + A_1 m_2 \]

\[ A_{31} = - m_3 + A_2 m_3 - A_2 m_1 \]

\[ A_{32} = m_4 A_3 + m_4 A_4 + m_4 A_5 - m_3 A_3 - m_3 A_4 - m_1 A_5 \]

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