CHAPTER 4

CHEMICAL REACTION EFFECTS ON MHD FREE CONVECTION FLOW THROUGH POROUS MEDIUM WITH CONSTANT SUCTION AND HEAT FLUX

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CHAPTER 4

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4.1: INTRODUCTION:

Fluid flows through porous medium are of principal interest, because these are quite prevalent in nature, such flows have attracted the attention of a number of scholars due to their applications in many branches of science and technology, viz. in the fields of agriculture engineering to study the underground water resources, in Petroleum technology to study the movement of natural gas, oil and water through the reservoirs, in chemical engineering for filtration and purification process.

From the technical point of view, MHD-free convection flows have great significance for the applications in the fields of Stellar and Planetary magnetospheres, Aeronautics, Chemical engineering and Electronics. The effect of chemical reaction depends on whether the reaction is homogeneous or heterogeneous; this depends on whether they occur at an interface or a single phase volume reaction. In most cases of chemical reactions, the reaction rate depends on the concentration of the species itself. Porous media are considered to be useful in diminishing the natural free convection which would otherwise occur intensely on a vertical heated surface. In order to make heat insulation of surface move effective, it is necessary to study the free convection flow through a porous medium and to estimate its effect in heat and mass transfer.

Three dimensional free convection flow and heat transfer along a plate was discussed by Singh et.al.[1-2]. Again, Singh et.al.[3] has studied heat and mass transfer flow of a viscous fluid past an infinite porous plate with time dependent suction and heat flux. A problem on unsteady free convection and mass transfer flow of an incompressible viscous liquid through a porous medium past an infinite vertical porous plate subject to time dependent suction velocity normal to the plate using perturbation technique was investigated by Singh and Ajay kumar [4].
Chamkha [5] studied MHD flow past a uniformly stretched vertical permeable surface in the presence of heat generation/absorption and a chemical reaction. Apelblat [6] presented analytical solution for effects of mass transfer on flow past an impulsively started infinite vertical plate with constant heat flux and chemical reaction. Again, mass transfer with a chemical reaction of the first order was discussed by Alexander and Apelblat [7]. Das et al.[8] have studied Effects of mass transfer on flow past an impulsively started infinite vertical plate with constant heat flux and chemical reaction. Chambre and Young [9] have analyzed on the diffusion of chemical reactive species in a laminar boundary layer flow. Effects of chemical reaction and radiation absorption on free convection flow through porous medium with variable suction in presence of uniform magnetic field was investigated by Sudheerbabu, M and Satyanarayana, P.V [10]. Muthucumarswamy, R. and Ravi Shanker,M[11] discussed first order chemical reaction and thermal radiation effects on unsteady flow past an accelerated isothermal infinite vertical plate. Kumar, A.G. V, Varma, S.V.K. and Ram Mohan [12] studied chemical reaction and radiation effects on MHD free convective flow past an exponentially accelerated vertical plate with variable temperature and variable mass diffusion. Effects of chemical reactions on free convection MHD flow past an exponentially accelerated infinite vertical plate through porous medium with variable temperature and mass diffusion was discussed by Rajput, U.S. and Sahu, P.K[13].

Though several authors made a contribution on free convection with mass transfer, in this chapter an attempt is made to study the effects of mass transfer on free convection boundary layer flow of a viscous incompressible and electrically conducting fluid through a porous medium bounded by vertical infinite surface with constant suction velocity and constant heat flux under the action of uniform magnetic field applied normal to the direction of flow.

4.2: NOMENCLATURE:

\[ B' \]  \begin{equation} \text{The volumetric coefficient expansion with species concentration} \end{equation}

\[ B_0 \]  Magnetic field constant

\[ C \]  Species Concentration

\[ C_\infty \]  The species concentration at infinity

\[ C_p \]  Specific heat at constant pressure
D Chemical molecular diffusivity
D T Coefficient of thermal diffusion
g Acceleration due to gravity
Gr Grashof number for heat transfer
G T Grashof number for mass transfer
M Magnetic parameter
N G Nusselt number
Pr Prandtl number
q Constant heat flux
S c Schmidt number
S h Sherwood number
T The fluid temperature
T e The fluid temperature at infinity
V o Scale of suction velocity

Greek symbols:
α Permeability of porous medium
β Coefficient of the volume expansion due to temperature
γ Dimensional distance from the plate
κ Thermal conductivity
μ Dynamic viscosity
ν Coefficient of viscosity
ρ The density of the fluid
σ Electrical conductivity
θ Dimensionless temperature

4.3: MATHEMATICAL FORMULATION:

Two dimensional flow of a viscous incompressible, electrically conducting fluid through a porous medium occupying semi-infinite region of space bounded by a vertical infinite surface, under the action of uniform magnetic field applied normal to
the direction of flow is studied in this chapter. The plate is taken along x-axis in
vertical upward direction against to the gravitational field and y-axis is taken normal
to the plate. The fluid properties are assumed to be constant except for the influence
density in the body force term. As the bounding surface is infinite in length, all the
variables are functions of y only.

In this study the following assumptions are made.

i. A uniform magnetic field is applied normal to the direction of the flow.

ii. The fluid properties are assumed to be constant except for the influence of
density in the body force term.

iii. As the bounding surface is infinite in length, all the variables are functions of y only.

Under the above assumptions and by usual the Boussinesq's approximation, the
steady flow is governed by the following set of equations.

\[
\frac{\partial u}{\partial y} = 0 \\
\nu \frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + g\beta(T_e - T_e) + g\beta^*(C_e - C_e) - \left(\frac{\alpha_{1k}}{\rho}\right) u - \frac{\rho}{\rho} u \\
\nu \frac{\partial T}{\partial y} = \left(\frac{k}{\mu c_p}\right) \frac{\partial^2 T}{\partial y^2} + \left(\frac{\alpha}{\alpha_{1k}}\right) \left(\frac{\partial u}{\partial y}\right)^2 \\
\nu \frac{\partial c}{\partial y} = \frac{d c}{\partial c_{in}} - D_k(C_e - C_e)
\]

The equation of continuity (1) gives \( \nu = \text{constant} = -\nu_0 \)

Where \( \nu_0 > 0 \) corresponds to steady suction velocity (normal at the surface).

In view of equation (5), equation (2), (3) and (4) are reduced to

\[
-\nu \frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + g\beta(T_e - T_e) + g\beta^*(C_e - C_e) - \left(\frac{\alpha_{1k}}{\rho}\right) u - \frac{\rho}{\rho} u \\
-\nu \frac{\partial T}{\partial y} = \left(\frac{k}{\mu c_p}\right) \frac{\partial^2 T}{\partial y^2} + \left(\frac{\alpha}{\alpha_{1k}}\right) \left(\frac{\partial u}{\partial y}\right)^2 \\
-\nu \frac{\partial c}{\partial y} = \frac{d c}{\partial c_{in}} - D_k(C_e - C_e)
\]
The relevant boundary conditions are:

\[ t \leq 0 \quad u = 0, \quad T = T_m, \quad C = C_m \quad \text{for all} \quad y \]

\[ t > 0 : \quad u = 0, \quad T = \frac{u}{v}, \quad C = \frac{m}{v}, \quad \text{for} \quad y = 0 \quad \text{and} \quad y \to \infty \]  

(9)

Introducing the following non-dimensional parameters

\[ f(\eta) = \frac{u}{v}, \quad \eta = \frac{y}{v}, \quad P_r = \frac{\mu r}{k}, \quad S_c = \frac{\theta}{d}, \quad \theta = \frac{(T-T_m)kD}{v} \]

\[ \alpha = \frac{v_k}{\sigma}, \quad C = \frac{(C-C_s)kD}{m}, \quad C_r = \frac{g \beta \phi \theta^2}{v_k}, \quad G_m = \frac{g \beta \phi \theta^2}{v_k} \]

\[ M = \frac{\sigma \beta \phi \theta^2}{\nu k}, \quad E = \frac{1/2}{\sigma \beta \phi \theta^2} \]  

(10)

Where, \( q \) is the heat flux per unit area and \( M \) is the mass flux per unit area, using equation (10) in set of equations (6) to (8), we get

\[ f'' + f' - (\alpha + M) = G, \quad \theta - G_c \]

(11)

\[ \theta' + P_r \theta' = -P_r(f^2)E \]  

(12)

\[ C'' + S_c C' + S_c C = 0 \]  

(13)

Where the primes denotes differentiation with respect to \( \eta \)

The corresponding boundary conditions become:

\[ \eta = 0 \quad f = 0, \quad \theta = -1, \quad C = -1 \]

\[ \eta \to \infty \quad f \to 0, \quad \theta \to 0, \quad C \to 0 \]  

(14)

4.4: METHOD OF SOLUTION:

In order to obtain a solution of above coupled non-linear system of equations (11) - (13) we expand \( f, \theta \) and \( C \) can be expanded in powers of \( \text{Eckert number} \).
assuming that it is very small (E→0), this is justified in low speed incompressible flow. Hence we assume

\[ f(\eta) = f_0(\eta) + E f_1(\eta) + o(E^2) \]

\[ \theta(\eta) = \theta_0(\eta) + EF_1(\eta) + o(E^2) \]

\[ C(\eta) = C_0(\eta) + EC_1(\eta) + o(E^2) \]  \hspace{1cm} (15)

Substituting equation (15) into equations (11) - (13) and equating coefficients of like powers of \( E \), and neglecting higher order terms in \( E \), the equations (11), (12) and (13) become

\[ f_0'' + f_0 - f_0(\alpha^{-1} + M) = -G_0\theta_0 - G_mC_0 \]  \hspace{1cm} (16)

\[ f_1'' + f_1 - f_1(\alpha^{-1} + M) = -G_0\theta_1 - G_mC_1 \]  \hspace{1cm} (17)

\[ \theta_0'' + P_r\theta_0 = 0 \]  \hspace{1cm} (18)

\[ \theta_1'' + P_r\theta_1 = -P_r \left( f_1' \right) \]  \hspace{1cm} (19)

\[ C_0 + S_cC_0 + K_fC_0 = 0 \]  \hspace{1cm} (20)

\[ C_1 + S_cC_1 + K_fC_1 = 0 \]  \hspace{1cm} (21)

The corresponding boundary conditions are

\[ f_0 = 0, \quad f_1 = 0, \quad \theta_0 = -1, \quad \theta_1 = 0, \quad C_0 = -1, \quad C_1 = 0 \quad \text{at} \quad \eta = 0 \]

\[ f_0 \to 0, \quad f_1 \to 0, \quad \theta_0 \to 0, \quad \theta_1 \to 0, \quad C_0 \to 0, \quad C_1 \to 0 \quad \text{at} \quad \eta \to 0 \]  \hspace{1cm} (22)

Solving equations (16) - (21), under boundary conditions (22), we obtain

\[ f_0 = K_4e^{-m_0\eta} - \frac{K_2}{P_r}e^{-P_r\eta} - \frac{K_3}{m_4}e^{-m_4\eta} \]  \hspace{1cm} (23)

\[ f_1 = N_6e^{-m_0\eta} - N_7e^{-P_r\eta} + N_5e^{-2m_0\eta} + N_2e^{-2P_r\eta} + N_4e^{-2m_4\eta} + N_3e^{-(m_2+P_r)\eta} + N_6e^{-(m_2+P_r)\eta} + N_7e^{-(m_2+P_r)\eta} \]  \hspace{1cm} (24)
\theta_0 = \frac{1}{P_r} e^{-\frac{\theta_0}{P_r}} \tag{25}

\theta_1 = a_2 e^{-\frac{\theta_1}{P_r}} - a_2 e^{-2\mu_1 \eta} + a_2 e^{-2\mu_1 \eta} - a_2 e^{-\frac{\theta_1}{P_r}} - a_5 e^{-\frac{(m_1 + P_r)\eta}{m_2}} + a_6 e^{-\frac{(m_1 + m_2)\eta}{m_2}} \tag{26}

C_0 = \frac{1}{m_2} e^{-m_2 \eta} \tag{27}

C_1 = 0 \tag{28}

Substituting the solutions of equations (23) to (28) in equation (11), we obtain

\begin{align*}
f(\eta) &= K_4 e^{-m_4 \eta} - K_4 e^{-\frac{\theta_0}{P_r}} - K_3 e^{-\frac{\theta_1}{P_r}} + E(N_4 e^{-m_4 \eta} - N_4 e^{-\frac{(m_1 + P_r)\eta}{m_2}} + N_2 e^{-2\mu_1 \eta} + N_2 e^{-2\mu_2 \eta} + N_2 e^{-\frac{(m_1 + m_2)\eta}{m_2}}) \tag{29}
f(\eta) &= \frac{1}{P_r} e^{-\frac{\theta_0}{P_r}} + E(a_4 e^{-\frac{\theta_1}{P_r}} - a_5 e^{-2\mu_1 \eta} + a_6 e^{-2\mu_2 \eta} - a_5 e^{-\frac{(m_1 + P_r)\eta}{m_2}} + a_6 e^{-\frac{(m_1 + m_2)\eta}{m_2}}) \tag{30}
C(\eta) &= \frac{1}{m_2} e^{-m_2 \eta} \tag{31}
\end{align*}

4.5: SKIN-FRICTION:

Skin-friction coefficient (τ) at the plate is given by

\[ \tau = \frac{d(f(\eta))}{d\eta} \bigg|_{\eta=0} = \tau_0 + E(\tau_1) \tag{32} \]

Where \( \tau_0 = -K_4 m_4 + K_3 \)

\[ \tau_1 = m_{12} N_4 - N_4 P_r - 2N_2 m_4 - 2N_2 P_r - 2N_4 m_2 - N_4 (P_r + m_4) - N_4 (P_r + m_2) - N_4 (m_2 + m_4) \tag{33} \]
4.6: NUS Alternate Number:

The rate of heat transfer coefficient ($Nu$) at the plate is given by

$$Nu = \left( \frac{\partial x}{\partial n} \right)_{\eta=0}$$

$$-1 + E \left(-a_3P + 2m_6a_1 + 2P, a_2 + 2m_2a_3 + a_4(P + m_9) + a_5(P + m_2) + a_6(m_2 + m_9)\right)$$ (35)

4.7: SHERWOOD NUMBER:

The rate of mass transfer coefficient ($Sh$) at the plate is given by

$$Sh = \left( \frac{\partial \tilde{x}}{\partial n} \right)_{\eta=0} = -1$$ (36)

4.8: RESULTS AND DISCUSSION:

An analysis is forformed for different values of Prandil number($Pr$), Magnetic parameter($M$), Grashof number for heat transfer($Gr$), Grashof number for mass transfer($G_m$), Permeability parameter($\alpha$), Chemical reaction parameter($K_r$), Schmidt number($Sc$) on Velocity, Temperature and Concentration fields are displayed through the figures and tables.

Figures (1) & (2) display the effects of Chemical reaction parameter ($K_r$) and Eckert number ($E_c$) on the velocity field for the cases of cooling and heating of the plate respectively. In the case of cooling of the plate, the velocity increases near the plate and attains the maximum velocity at $\eta = 0.05$, then decreases rapidly for $\eta > 0.1$, also noticed that the velocity increases with decrease in Chemical reaction parameter ($K_r$) values and the velocity increases with an increase in Eckert number($E_c$). While an opposite phenomenon is noted in case of heating of the plate.

Figure (3) and (4) display the effects of modified Grashof number ($G_m$) and magnetic parameter ($M$) on the velocity field for the cases of externally cooling and heating of plates. It is observed from figure(3) that velocity increases with an increase in the values of ($G_m$). also it is noticed that the velocity increases near the plate attains the maximum velocity at $\eta = 0.1$, then decreases tends to zero as $\eta \to \infty$, for increasing values of magnetic parameter($M$) the velocity decreases. And a reverse effect is observed in case of heating of the plate.
Figures (5) and (6) display the effects of modified Grashof number \((G_m)\) and magnetic parameter \((M)\) on the velocity field for the cases of externally cooling and heating of plates. It is observed from figure (5) that velocity increases with an increase in the values of \((G_m)\), also it is noticed that the velocity increases near the plate attains the maximum velocity at \(\eta = 0.1\) and then decreases then tends to zero as \(\eta \rightarrow \infty\), for increasing values of magnetic parameter \((M)\) the velocity increases. And the trend is just reversed in case of heating of the plate.

Figures (7) and (8) reveal the effect of Schmidt number \((S_c)\) and Eckert number \((E_e)\) on the velocity field for the cases of cooling and heating of the plate. It is noticed from figure (7) that the velocity increases with an increase in Eckert number and it decreases with an increase in Schmidt number \((S_c)\), also seen that the velocity increases near the plate attains the maximum velocity and then decreases tends to zero. An opposite phenomenon is observed in case of heating of the plate.

From figures (9) and (10), we observe the effects of Grashof number for heat transfer \((G_r)\), Prandtl number \((P_r)\) on the velocity field for the cases of cooling and heating of the plates. It is observed from figure (9) that velocity increases with an increase in Grashof number for heat transfer \((G_r)\), it decreases with decrease in Prandtl number \((P_r)\), also observed that the velocity increases near the plate attains the maximum velocity and then decreases tends to zero. And an opposite phenomenon is observed in case of heating of the plate.

Figures (11) and (12) represent the effect of Prandtl number \((P_r)\) on the velocity field for cooling and heating of the plates. From figure (11) we find that velocity decreases with increasing values of Prandtl number \((P_r)\) in case of cooling of the plate. The reverse effect is observed in the case of heating of the plate.

Figures (13) and (14) display the effect of permeability parameter \((a)\) on the velocity for the cases of cooling and heating of the plates. From figure (13) we noticed that the velocity decreases with an increase in permeability \((a)\) values in case of cooling of the plate. The trend is just reversed in case of heating of the plate.

Figure (15) displays the effect of permeability parameter \((a)\) on the temperature field. It is noticed that the temperature decreases with an increase in Permeability \((a)\) parameter. The effect of Schmidt number \((S_c)\) on the temperature...
field shown in figure (16), it is noticed that with an increase in Schmidt number the temperature field decreases.

Temperature profiles for various values of Grashof number for heat transfer \( G_r \) are shown in figure (17), it is observed that the temperature increases with an increase in \( G_r \). The effect of Grashof number \( G_m \) on the temperature shown in figure (18), it is noticed that with an increase in \( G_m \), the temperature increases.

Figure (19) shows the effect of chemical reaction parameter \( K_r \) for various values on concentration profiles, it shows the concentration decreases with an increase in \( K_r \). Concentration profiles for various values of Schmidt number \( S_c \) are shown in figure (20), it shows that the concentration increases with an increase in Schmidt number \( S_c \). Finally Skin-friction is presented in Tables (1) and (2) for both cooling and heating of the plate for different values of Grashof number \( G_m \), chemical reaction parameter \( K_r \), Schmidt number \( S_c \), Prandtl number \( P_r \), Grashof number for heat transfer \( G_r \). It is observed that as \( G_r \), \( G_m \), \( K_r \) and \( S_c \) increases the Skin-friction increases, while \( M \) or \( P_r \) increases the Skin-friction decreases in case of cooling of the plate. As \( G_r \), \( G_m \) decreases the Skin-friction decreases and as \( P_r \), \( M \) increases the Skin-friction increase in case of heating of the plate.
Figure 1: The Effects of $K_p$ and $E_c$ parameters on velocity for externally cooled plate

Figure 2: The Effects of $K_p$ and $E_c$ parameters on velocity for externally heated plate
Figure 3: The Effects of $G_e$ and $M$ parameters on velocity for externally cooled plate.

Figure 4: The Effects of $G_e$ and $M$ parameters on velocity for externally heated plate.
Figure 5: The Effects of $G_m$ and $M$ parameters on velocity for externally cooled plate.

Figure 6: The Effects of $G_m$ and $M$ parameters on velocity for externally heated plate.
Figure 7: The Effects of \( S_c \) and \( E_c \) parameters on velocity for externally cooled plate.

Figure 8: The Effects of \( S_c \) and \( E_c \) parameters on velocity for externally heated plate.
Figure 9: The Effects of $G_r$ and $P_r$ parameters on velocity for externally cooled plate.

Figure 10: The Effects of $G_r$ and $P_r$ parameters on velocity for externally heated plate.
Figure 11: The Effect of $P_r$ parameter on velocity for externally heated plate.

Figure 12: The Effect of $P_r$ parameter on velocity for externally cooled plate.
Figure 13: The Effect of permeability parameter $a$ on velocity for externally cooled plate.

Figure 14: The Effect of permeability parameter on velocity for externally heated plate.
Figure 15: The effect of permeability parameter on temperature

Figure 16: The effect of Schmidt number $S_c$ on temperature.
Figure 17: The effect of Grashof number $Gr$ on temperature

Figure 18: The effect of Grashoff number $G_m$ on temperature
Figure 19: The effect of chemical reaction parameter $K_r$ on concentration

Concentration profiles due to various values of Schmidt number $Sc$

Figure 20: The effect of Schmidt number $S_c$ on concentration
### Table 1
The Skin friction coefficient ($\tau$) for cooling of the plate at $\varepsilon = 0.005$

<table>
<thead>
<tr>
<th>$G_r$</th>
<th>$G_m$</th>
<th>$M$</th>
<th>$K_r$</th>
<th>$P_r$</th>
<th>$S_c$</th>
<th>$\alpha$</th>
<th>Skin-friction</th>
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<td>2.0</td>
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### Table 2
The Skin friction coefficient ($\tau$) for heating of the plate at $\varepsilon = 0.005$

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<th>$G_m$</th>
<th>$M$</th>
<th>$K_r$</th>
<th>$P_r$</th>
<th>$S_c$</th>
<th>$\alpha$</th>
<th>Skin-friction</th>
</tr>
</thead>
<tbody>
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4.10: CONCLUSIONS:

An analysis is performed to study the effects of chemical reaction on MHD free convection flow through porous medium with constant suction and heat flux. The coupled non-linear system of partial differential equations is solved by employing a Perturbation technique. The various effects of flow parameters like, Prandtl number \( P_r \), magnetic parameter \( M \), Grashof number for heat transfer \( G_r \), Grashof number for mass transfer \( G_m \), Permeability parameter \( \alpha \), Chemical reaction parameter \( k \), Schmidt number \( S_c \) are discussed through graphs and tables.

In this study we conclude that in case of cooling of the plate, the velocity increases with decrease in Chemical reaction parameter \( K_r \) values and the velocity increases with an increase in Eckert number \( E_r \). While an opposite phenomenon is noted in case of heating of the plate. In case of cooling of the plate velocity increases with an increase in the values of \( G_r \), also it is noticed that the velocity increases near the plate attains the maximum velocity at \( \eta = 0.1 \), then decreases tends to zero as \( \eta \to \infty \), for increasing values of magnetic parameter \( M \) the velocity decreases. And a reverse effect is observed in case of heating of the plate. It is noticed that the temperature decreases with an increase in Permeability \( \alpha \) parameter. It is observed that the concentration increases with an increase in Schmidt number \( S_c \).

It is observed that as \( G_m \), \( G_r \), \( k \), and \( S_c \) increases the Skin-friction increases, while \( M \) or \( P_r \) increases the Skin-friction decreases in case of cooling of the plate. As \( G_r \), \( G_m \) decreases the Skin-friction decreases and as \( P_r \), \( M \) increases the Skin-friction increase in case of heating of the plate.
4.11: REFERENCES:


4.12: APPENDIX:

\[ k_1 = a^{-1} + M, \quad k_3 = \frac{1 + \sqrt{1 + 4k_1}}{2} \]
\[ k_4 = \frac{k_5}{p_r} + \frac{k_6}{s_c}, \quad k_5 = \frac{G_r}{p_r^2 - p_r - k_1} \]

\[ k_6 = \frac{G_m}{s_c^2 - s_c - k_1}, \quad k_7 = -k_3 k_4, \quad k_9 = \frac{1 + \sqrt{1 + 4k_1}}{2} \]

\[ a_1 = \frac{p_r k_1^2}{4k_1 - 2k_3 p_r}, \quad a_2 = \frac{k_1^2}{p_r} \]

\[ a_3 = \frac{p_r k_6^2}{4s_c^2 - 2s_c p_r}, \quad a_4 = \frac{2p_r k_5 k_6}{k_5^2 + k_3 p_r}, \quad a_5 = \frac{2p_r k_6 k_8}{s_c^2 + s_c p_r}, \]

\[ a_6 = \frac{2k_3 k_6 p_r}{(k_5^2 + s_c^2 + 2k_3 s_c) - p_r (k_3 + s_c)} \]

\[ a_7 = \frac{1 + k_2^2}{p_r} + \frac{2k_2}{k_5 - p_r} + \frac{k_2^2}{2s_c - p_r} + \frac{2k_2 k_3}{k_5} + \frac{2k_2 k_6}{s_c} + \frac{2k_2 k_8}{k_5 + s_c - p_r} \]

\[ a_8 = \frac{G_r a_2}{(p_r)^2 - (p_r) - k_1}, \quad a_9 = \frac{G_r a_3}{(2k_3)^2 - (2k_3) - k_1} \]

\[ a_{10} = \frac{G_r a_3}{4s_c^2 - 2s_c - k_1}, \quad a_{11} = \frac{G_r a_4}{(k_3 + p_r)^2 - (k_3 + p_r) - k_1} \]

\[ a_{12} = \frac{G_r a_5}{(s_c + p_r)^2 - (s_c + p_r) - k_1}, \quad a_{13} = \frac{G_r a_6}{(k_3 + s_c)^2 - (k_3 + s_c) - k_1} \]

\[ a_{14} = a_9 + a_{11} + a_{10} + a_{11} + a_{12} + a_{13} - a_8 \]