Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 57 Issue: 02:2024
DOI: 10.5281/zenodo.10669873

HEAT AND MASS TRANSFER THROUGH THREE DIMENSIONAL ROTATING FREE CONVECTIVE FLOW PAST A VERTICAL POROUS PLATE WITH HEAT SOURCE

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Abstract

This work aims to analyze the effects of unsteady three-dimensional rotating convection of an infinitely vertical porous plate filled with a viscous, electrically conducting, rotating incompressible fluid. A transverse sinusoidal suction velocity that varies over time is applied to the plate, creating a three-dimensional flow. The series expansion approach was used to generate the expressions for the temperature of the mass flow and cross flow, species concentration, skin friction, and the rate of heat and mass transfer. **Introduction:** Because of its many applications in a variety of engineering problems, including MHD generators, plasma studies, nuclear reactors, oil exploration, geothermal energy extraction, and boundary layer control in the field of aerodynamics, the phenomenon of hydromagnetic flow with heat and mass transfer in an electrically conducting fluid past a porous plate embedded in a porous medium has drawn the attention of a good number of investigators. **Objectives:** Heat and mass transfer via a three-dimensional rotating free convective flow over a vertical porous plate with a heat source is the subject of the problem you mentioned. Problems of this kind are commonly seen in the domains of heat transfer and fluid dynamics. **Methods:** Conduction, Convection, radiation **Conclusion:** The main flow velocity decreases with the increase of Reynolds number and Prandtl number. The cross flow velocity increases with the increase of Schmidt number and rotation number. Increasing Grashof number decreases the skin friction and rate of Heat transfer. Rate of mass transfer at the plate increase with increase in Grashof number and Schmidt number

Keywords: Convective Flows, MHD, Heat and Mass Transfer, Porous Medium, Viscous Dissipation, Heat Generation/Absorptio.

1. INTRODUCTION

The phenomenon of hydro-magnetic flow with heat and mass transfer in an electrically conducting fluid past a porous plate embedded in a porous medium has attracted the attention of a good number of investigators because of its varied applications in many engineering problems such as MHD generators, plasma studies, nuclear reactors, oil exploration, geothermal energy extractions and in the boundary layer control in the field of aerodynamics. The study of convection in rotating porous medium is a subject of fundamental and practical interest because it exists in numerous applications such as centrifugal filtration processes, food engineering, geophysics in the field of agriculture engineering to study the underground water resources, in the field of chemical engineering for filtration and purification processes, in petroleum technology to study the movement of natural gas, oil and water through the oil channels/reservoirs etc. In view of these applications we have extended the work of Das *et al* (2011) to a three dimensional, electrically conducting and rotating flow past porous plate.

It is assumed that fluid is homogeneous so that a complicated problem of the flow through a porous medium gets reduced to the flow problem of a homogeneous fluid with some additional resistance. In view of above applications, a series of investigations have been made by different researchers. Ahmadi and Manvi (1971) have derived the equation of motion and applied the result to some basic flow problems. Gersten and Gross (1974) have studied the three dimensional flow and heat transfer along a flat plate by applying periodic suction. Yamamoto and Iwamura (1976) explained the flow of a viscous fluid with convective acceleration through a porous medium. Gulab Ram and Mishra (1977) have obtained an exact solution of the unsteady motion of an electrically conducting, incompressible and viscous fluid through a porous medium under the action of a transverse magnetic field. Singh, Sharma and Misra (1978) have investigated the free convection flow along a vtical porous plate with transverse sinusolidal suction velocity distribution. Due to this type of suction velocity at the place the flow becomes three-dimensional one. Varshney (1979) analysed an oscillating two-dimensional flow through porous medium bounded by a horizontal porous plate subjected to a variable suction velocity. Rapits (1983) discussed unsteady two dimensional free convective flows through a porous medium bounded by an infinite vertical plate, when the temperature of the plate is oscillating with the time about a constant mean value. Raptis and Peridiks (1985) have studied the problem of free convection flow through a porous medium bounded by a vertical porous plate with constant suction when the free stream velocity oscillates with the time about a constant non-zero mean value. Yan, Tsay and Lin (1989) have investigated the role of vaporization or condensation of the water vapour on the wetted channel walls in laminar mixed convection flows under the simultaneous influences of combined buoyancy effects of thermal and mass diffusion. Chandran and his associates (1998) have discussed the unsteady free convection flow of an electrically conducting fluid with heat flux and accelerated boundary layer motion in presence of a transverse magnetic field. Acharya *et al.* (1999) reported the problem of heat and mass transfer over an accelerating surface with heat source in presence of suction and blowing. The unsteady free convective MHD flow with heat transfer past a semi-infinite vertical porous

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DOI: 10.5281/zenodo.10669873

moving plate with variable suction has been studied by Kim (2000). Singh (1999) have analysed the coquette flow between two horizontal parallel porous flat plates with transverse sinusoidal injection of the fluid at the stationary plate and its corresponding removal by constant suction through the plate in uniform motion. Singh and Sharma (2001) have analysed viscous incompressible couette fluid through a porous medium between two infinite horizontal parallel porous flat plates and also analysed the couette flow between two horizontal parallel porous flat plates of an electrically conducting, viscous, incompressible. Sharma and Pareek (2002) explained the behaviour of steady free convective MHD flow past a vertical porous moving surface. Makinde *et al.* (2003) discussed the unsteady free convective flow with suction on an accelerating porous plate. Sharma and Yadav (2005) have investigated the heat transfer through three dimensional couette flow of a viscous incompressible fluid through a stationary porous plate bounded by a porous medium and a porous plate moving with uniform motion Das and Mitra (2009) discussed the unsteady mixed convective MHD flow and mass transfer past an accelerated infinite vertical plate with suction. Das and his co-workers (2009) analyzed the effect of mass transfer on MHD flow and heat transfer past a vertical porous plate through a porous medium under oscillatory suction and heat source. Das *et al.* (2011) investigated the hydromagnetic convective flow past a vertical porous plate through a porous medium with suction and heat source. In this paper, we have extended the work of Das *et al.* (2011) to a three dimensional rotating free convective flow past a vertical porous plate through a porous medium. The flow becomes three dimensional by subjecting the plate to a transverse sinusoidal suction velocity fluctuating with time. The porous plate is assumed to be adiabatic.

FORMULATION OF THE PROBLEM

We have unsteady free convective mass transfer flow of a viscous electrically conducting, incompressible fluid past an infinite vertical porous plate in the presence of heat source. A uniform magnetic field is introduced normal to the plane of the plate. The porous plate is assumed to be lying horizontally on x*z* plane and y* axis is taken perpendicular to the planes of plates. Transverse sinusoidal injection velocity of the following form is applied at the plate which is unbounded by a porous medium.

$v^* = -\left(1 + \varepsilon e^{i\left(\sigma^* t^* - \frac{\pi^* z^*}{d}\right)}\right)$ Where $0 < \varepsilon < 1$. The flow remains three dimensional due to sinusoidal injection velocity given in the above equation. All the physical quantities are independent of $x*$ for this problem of fully developed laminar flow.

Assuming velocity components $u*, v*, w*$ in $x*, y*, z*$ direction respectively and temperature $T*$, the flow through porous medium is governed by the following governing equations of continuity, motion and energy in dissipation function. The plate temperature is taken spannise cosinusoidally fluctuating with time.

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Continuity Equation:

$$\frac{\partial v^*}{\partial y^*}+\frac{\partial w^*}{\partial z^*}=0 \quad \dots (1)$$

Momentum Equation $\rho\left(\frac{\partial u^*}{\partial t^*}+v^*\frac{\partial u^*}{\partial y^*}+w^*\frac{\partial u^*}{\partial z^*}-2\Omega v^*\right)=\rho g[\beta_T(T^*-T_\infty)+\beta_c(C^*-C_\infty)]+ \dots (2)$

$$\mu(\frac{\partial^2 u^*}{\partial y^{*2}}+\frac{\partial^2 u^*}{\partial z^{*2}})-\frac{\mu}{k^*}u^*-\sigma B_o^2 u^*$$

$$\rho\left(\frac{\partial v^*}{\partial t^*}+v^*\frac{\partial v^*}{\partial y^*}+w^*\frac{\partial v^*}{\partial z^*}+2\Omega u^*\right)=-\frac{\partial p^*}{\partial y^*}+\mu(\frac{\partial^2 v^*}{\partial y^{*2}}+\frac{\partial^2 v^*}{\partial z^{*2}})-\frac{\mu}{k^*}v^* \quad \dots (3)$$

$$\rho\left(\frac{\partial w^*}{\partial t^*}+v^*\frac{\partial w^*}{\partial y^*}+w^*\frac{\partial w^*}{\partial z^*}\right)=-\frac{\partial p^*}{\partial z^*}+\mu(\frac{\partial^2 w^*}{\partial y^{*2}}+\frac{\partial^2 w^*}{\partial z^{*2}})-\frac{\mu}{k^*}w^*-\sigma B_o^2 w^* \quad \dots. (4)$$

Energy Equation: $\rho C_p\left(\frac{\partial T^*}{\partial t^*}+v^*\frac{\partial T^*}{\partial y^*}+w^*\frac{\partial T^*}{\partial z^*}\right)=k(\frac{\partial^2 T^*}{\partial y^{*2}}+\frac{\partial^2 T^*}{\partial z^{*2}})-S^*(T^*-T_\infty) \quad \dots (5)$

Concentration Equation: $\left(\frac{\partial C^*}{\partial t^*}+v^*\frac{\partial C^*}{\partial y^*}+w^*\frac{\partial C^*}{\partial z^*}\right)=D(\frac{\partial^2 C^*}{\partial y^{*2}}+\frac{\partial^2 C^*}{\partial z^{*2}})-R^*(C^*-C_\infty) \quad \dots (6)$

The boundary conditions are $y^* = 0$; $\quad u^*=0, \quad w^*=0, \quad v^*=-v(1+\varepsilon e^{i(\sigma^* t^*-\frac{\pi^* z^*}{d})}),$

$$T^*=T_0+\varepsilon e^{i(\sigma^* t^*-\frac{\pi^* z^*}{d})}(T_0-T_\infty),\ C^*=C_0+\varepsilon e^{i(\sigma^* t^*-\frac{\pi^* z^*}{d})}(C_0-C_\infty) \dots (7)$$

At $y^*\to\infty$; $\quad u^*=0, \quad v^*=-v, \quad w^*=0, \quad T^*=T_\infty, \quad C^*=C_\infty$

Where, ε is a very small positive constant.

Now Introducing the following non - dimensional quantities into (1) – (6):

$$y^*=yd;\ z^*=zd;\ u^*=uU;\ v^*=vV;\ w^*=wV;\ p^*=\rho v^2 p^*$$
$$T^*-T_\infty=(T_0-T_\infty)\theta;\ C^*-C_\infty=(C_0-C_\infty)C;\ \ t^*=\frac{d}{V}t$$
$$k^*=kd^2;\ \tau=\frac{2\Omega d}{v};\ \lambda=\frac{V}{U};\ \mathrm{Re}=\frac{Vd\rho}{\mu} \quad \dots(8)$$

Substituting (8) in (1) – (6),

then the equation reduces to the non dimensional form: $\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad \dots (9)$

$$\frac{\partial u}{\partial t}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=\lambda Gr\theta+\lambda GmC-\frac{1}{\mathrm{Re}}\frac{u}{k}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)-M^2\frac{1}{\mathrm{Re}}u+\lambda\tau v \dots (10)$$

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$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{\partial p}{\partial y}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)-\frac{1}{\mathrm{Re}}\frac{v}{k}-\frac{\tau}{\lambda}u \quad \text{... (11)}$$

$$\frac{\partial w}{\partial t}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{\partial p}{\partial z}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)-\frac{1}{\mathrm{Re}}\frac{w}{k}-M^2\frac{1}{\mathrm{Re}}w \quad \text{... (12)}$$

$$\frac{\partial \theta}{\partial t}+v\frac{\partial \theta}{\partial y}+w\frac{\partial \theta}{\partial z}=\frac{1}{\mathrm{Pr}\,\mathrm{Re}}\left(\frac{\partial^2 \theta}{\partial y^2}+\frac{\partial^2 \theta}{\partial z^2}\right)-S\theta \quad \text{... (13)}$$

$$\frac{\partial C}{\partial t}+v\frac{\partial C}{\partial y}+w\frac{\partial C}{\partial z}=\frac{1}{Sc\,\mathrm{Re}}\left(\frac{\partial^2 C}{\partial y^2}+\frac{\partial^2 C}{\partial z^2}\right)-RC \quad \text{.... (14)}$$

Conditions are:At y = 0; $u=0,\ w=0, v=-\left(1+\in e^{i(\sigma t-\pi z)}\right),\ \theta=1+\in e^{i(\sigma t-\pi z)},\quad C=1+\in e^{i(\sigma t-\pi z)}$

At $y\to\infty$; $\quad u=0,\quad v=-1,\quad w=0,\quad \theta=0,\quad C=0$ ... (15)

In order to solve the system of Equations (9)–(14) subject to the above boundary conditions, it is assumed

$$\begin{aligned} u&=u_0(y)+\in u_1(y,z,t)+...\\ v&=v_0(y)+\in v_1(y,z,t)+...\\ w&=w_0(y)+\in w_1(y,z,t)+...\\ T&=T_0(y)+\in T_1(y,z,t)+...\\ C&=C_0(y)+\in C_1(y,z,t)+...\\ p&=p_0(y)+\in p_1(y,z,t)+... \end{aligned} \quad \text{...(16)}$$

Substituting (16) into the equations (9) – (14) we get: $\frac{\partial v_0}{\partial y}+\varepsilon\frac{\partial v_1}{\partial y}+\varepsilon\frac{\partial w_1}{\partial z}=0$ ... (17)

$$\varepsilon\frac{\partial u_1}{\partial t}+(v_0+\varepsilon v_1)\frac{\partial}{\partial y}(u_0+\varepsilon u_1)+\in(w_0+\varepsilon w_1)\frac{\partial u_1}{\partial z} = \lambda Gr(\theta_0+\varepsilon\theta_1)+\lambda Gm(C_0+\varepsilon C_1)-\frac{1}{\mathrm{Re}}\frac{1}{k}(u_0+\varepsilon u_1)+\frac{1}{\mathrm{Re}}\left[\frac{\partial^2 u_0}{\partial y^2}+\varepsilon\frac{\partial^2 u_1}{\partial y^2}+\varepsilon\frac{\partial^2 u_1}{\partial z^2}\right]$$
$$-\frac{M^2}{\mathrm{Re}}(u_0+\varepsilon u_1)+\lambda\tau(v_0+\varepsilon v_1) \quad \text{....(18)}$$

$$\varepsilon\frac{\partial v_1}{\partial t}+(v_0+\varepsilon v_1)\frac{\partial}{\partial y}(v_0+\varepsilon v_1)+\varepsilon(w_0+\varepsilon w_1)\frac{\partial v_1}{\partial z} = -\frac{\partial P_0}{\partial y}-\varepsilon\frac{\partial P_1}{\partial y}+\frac{1}{\mathrm{Re}}\left[\frac{\partial^2 v_0}{\partial y^2}+\varepsilon\frac{\partial^2 v_1}{\partial y^2}+\varepsilon\frac{\partial^2 v_1}{\partial z^2}\right]-\frac{1}{\mathrm{Re}}\frac{1}{k}(v_0+\varepsilon v_1)-\frac{\tau}{\lambda}(u_0+\varepsilon u_1) \quad \text{.... (19)}$$

$$= \quad -\varepsilon\frac{\partial P_1}{\partial y}+\frac{1}{\mathrm{Re}}\left[\frac{\partial^2 w_0}{\partial y^2}+\varepsilon\frac{\partial^2 w_1}{\partial y^2}+\varepsilon\frac{\partial^2 w_1}{\partial z^2}\right]-\frac{1}{\mathrm{Re}}\frac{1}{k}(w_0+\varepsilon w_1)-\frac{M^2}{\mathrm{Re}}(w_0+\varepsilon w_1) \quad \text{...(20)}$$

$$\varepsilon\frac{\partial \theta_1}{\partial t}+(v_0+\varepsilon v_1)\frac{\partial}{\partial y}(\theta_0+\varepsilon\theta_1)+\varepsilon(w_0+\varepsilon w_1)\frac{\partial \theta_1}{\partial z} = \frac{1}{\mathrm{Pr}\,\mathrm{Re}}\left[\frac{\partial^2 \theta_0}{\partial y^2}+\varepsilon\frac{\partial^2 \theta_1}{\partial y^2}+\varepsilon\frac{\partial^2 \theta_1}{\partial z^2}\right]-S(\theta_0+\varepsilon\theta_1) \quad \text{... (21)}$$

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$$\varepsilon\frac{\partial C_1}{\partial t}+(v_0+\varepsilon v_1)\frac{\partial}{\partial y}(C_0+\varepsilon C_1)+\varepsilon(w_0+\varepsilon w_1)\frac{\partial C_1}{\partial z} = \frac{1}{Sc\,\mathrm{Re}}\left[\frac{\partial^2 C_0}{\partial y^2}+\varepsilon\frac{\partial^2 C_1}{\partial y^2}+\varepsilon\frac{\partial^2 C_1}{\partial z^2}\right]-R(C_0+\varepsilon C_1) \quad \text{... (22)}$$

When $\varepsilon = 0$,the problem reduces to two dimensional flow through porous medium with constant injection at the plate, $\frac{\partial v_0}{\partial y}=0$ ... (23)

$$v_0\frac{\partial u_0}{\partial y}=\lambda Gr\theta_0+\lambda GmC_0-\frac{u_0}{\mathrm{Re}\,k}+\frac{1}{\mathrm{Re}}\frac{\partial^2 u_0}{\partial y^2}+\lambda\tau v_0-\frac{M^2}{\mathrm{Re}}u_0 \quad \text{.... (24)}$$

$$v_0\frac{\partial v_0}{\partial y}=-\frac{\partial p_0}{\partial y}+\frac{1}{\mathrm{Re}}\frac{\partial^2 v_0}{\partial y^2}-\frac{v_0}{\mathrm{Re}\,k}-\frac{\tau}{\lambda}u_0 \text{.... (25)},\; v_0\frac{\partial w_0}{\partial y}=\frac{1}{\mathrm{Re}}\frac{\partial^2 w_0}{\partial y^2}-\frac{w_0}{\mathrm{Re}\,k}-\frac{M^2}{\mathrm{Re}}w_0 \text{.... (26)}$$

$$v_0\frac{\partial\theta_0}{\partial y}=\frac{1}{\mathrm{Pr\,Re}}\frac{\partial^2\theta_0}{\partial y_2}-S\theta_0 \text{ .... (27)},\quad v_0\frac{\partial C_0}{\partial y}=\frac{1}{Sc\,\mathrm{Re}}\frac{\partial^2 C_0}{\partial y_2}-RC_0 \text{ ... (28)}$$

The corresponding boundary conditions are:

At y = 0; $u_0=0, v_0=-1, w_0=0, \theta_0=1, C_0=1$, At $y\to\infty$; $u_0=0, v_0=-1, w_0=0, \theta_0=0, C_0=0$ .... (29)

Solving (22) – (27) by using the boundary conditions (28) we get:

$u_0=A_3e^{-m_3y}-A_1e^{-m_1y}-A_2e^{-m_2y}$ ... (30) $v_0=-1$ ... (31) $w_0=0$ ... (32) $\theta_0=e^{-m_1y}$ ... (33)

$\theta_0=e^{-m_1y}$ ... (33) $C_0=e^{-m_2y}$ ... (34) Equating the coefficient of (ε), we get $\frac{\partial w_1}{\partial z}+\frac{\partial v_1}{\partial y}=0$ ... (35)

$$\frac{\partial u_1}{\partial t}-\frac{\partial u_1}{\partial y}+v_1\frac{\partial u_0}{\partial y} = \lambda Gr\theta_1+\lambda GmC_1-\frac{u_1}{\mathrm{Re}\,k}+\frac{1}{\mathrm{Re}}\left[\frac{\partial^2 u_1}{\partial y^2}+\frac{\partial^2 u_1}{\partial z^2}\right]-\frac{\tau M^2}{\mathrm{Re}}u_1+\lambda\tau v_1 \quad \text{....(36)}$$

$$\frac{\partial v_1}{\partial t}-\frac{\partial v_1}{\partial y}=-\frac{\partial p_1}{\partial y}+\frac{1}{\mathrm{Re}}\left[\frac{\partial^2 u_1}{\partial y^2}+\frac{\partial^2 u_1}{\partial z^2}\right]-\frac{v_1}{\mathrm{Re}\,k}-\frac{\tau}{\lambda}u_1 \text{... (37)} = -\frac{\partial p_1}{\partial z}+\frac{1}{\mathrm{Re}}\left[\frac{\partial^2 w_1}{\partial y^2}+\frac{\partial^2 w_1}{\partial z^2}\right]-\frac{w_1}{\mathrm{Re}\,k}-\frac{\tau M^2}{\mathrm{Re}}w_1 \text{.... (38)}$$

$$\frac{\partial\theta_1}{\partial t}-\frac{\partial\theta_1}{\partial y}+v_1\frac{\partial\theta_0}{\partial y}=\frac{1}{\mathrm{Pr\,Re}}\left[\frac{\partial^2\theta_1}{\partial y^2}+\frac{\partial^2\theta_1}{\partial z^2}\right]-S\theta_1 \text{...(39)}\; \frac{\partial C_1}{\partial t}-\frac{\partial C_1}{\partial y}+v_1\frac{\partial C_0}{\partial y}=\frac{1}{Sc\,\mathrm{Re}}\left[\frac{\partial^2 C_1}{\partial y^2}+\frac{\partial^2 C_1}{\partial z^2}\right]-RC_1 \text{ (40)}$$

Boundary conditions are : At y = 0; $u_1=0, v_1=-e^{i(\sigma t-\pi z)}, w_1=0, \theta_1=e^{i(\sigma t-\pi z)}, C_1=e^{i(\sigma t-\pi z)}$

At $y\to\infty$; $u_1=0, v_1=0, w_1=0, \theta_1=0, C_1=0$ ... (41)

In order to solve the system of equations (34) – (39) subject to the boundary conditions (40), it is assumed

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$$u_1 = e^{i(\sigma t-\pi z)} u_{11}(y), v_1 = e^{i(\sigma t-\pi z)} v_{11}(y), w_1 = e^{i(\sigma t-\pi z)} w_{11}(y), \theta_1 = e^{i(\sigma t-\pi z)} \theta_{11}(y), C_1 = e^{i(\sigma t-\pi z)} C_{11}(y) \cdots (42)$$

Solving (34) – (39) by using the boundary conditions (40) and the substitution (41) we get

$$u_{11} = A_{31}e^{-m_{11}y} - A_{21}e^{-m_5 y} + ... - A_{18}e^{-m_{13}y} + \tau\{A_{167}e^{-m_{11}y} - A_{77}e^{-m_3 y} ... + A_{166}e^{-m_{10}y}\} ..... (43)$$

$$v_{11} = A_7 e^{-m_4 y} + A_8 e^{-\pi y} + \tau\{A_{44}e^{-m_4 y} + A_{43}e^{-\pi y} - ... + A_{42}ye^{-\pi y}\} ..... (44)$$

$$w_{11} = \frac{1}{\pi i}\{-m_4 A_7 e^{-m_4 y} - \pi A_8 e^{-\pi y} + \tau\{-m_4 A_{446} e^{-m_4 y} - \pi A_{43}e^{-\pi y} + ... - \pi A_{42}ye^{-\pi y}\} .... (45)$$

$$\theta_{11} = \left(A_{11}e^{-m_5 y} - A_9 e^{-m_6 y} - A_{10}e^{-m_7 y}\right) + \tau\{A_{60}e^{-m_5 y} - A_{45}e^{-m_6 y} + ... - A_{59}e^{-m_7 y}\} .... (46)$$

$$C_{11} = A_{14}e^{-m_8 y} - A_{12}e^{-m_9 y} - A_{13}e^{-m_{10}y} + \tau\{A_{76}e^{-m_8 y} - A_{61}e^{-m_9 y} + ... - A_{75}e^{-m_{10}y}\} ... (47)$$

Substituting the equations (43) – (47) in (42) we get

$$u_1 = e^{i(\sigma t-\pi z)}\{A_{31}e^{-m_{11}y} - A_{21}e^{-m_5 y} + ... - A_{18}e^{-m_{13}y} + \tau\{A_{167}e^{-m_{11}y} + ... - A_{165}e^{-m_9 y}\}\} ...(48)$$

$$v_1 = e^{i(\sigma t-\pi z)}\{A_7 e^{-m_4 y} + A_8 e^{-\pi y} + \tau\{A_{44}e^{-m_4 y} + A_{43}e^{-\pi y} ... - A_{42}ye^{-\pi y}\}\} ... (49)$$

$$w_1 = e^{i(\sigma t-\pi z)}\frac{1}{\pi i}\{-m_4 A_7 e^{-m_4 y} - \pi A_8 e^{-\pi y} + \tau\{-m_4 A_{446} e^{-m_4 y} - \pi A_{43}e^{-\pi y} + ... - \pi A_{42}ye^{-\pi y}\}\} ... \quad (50)$$

$$\theta_1 = e^{i(\sigma t-\pi z)}\left(A_{11}e^{-m_5 y} - A_9 e^{-m_6 y} - A_{10}e^{-m_7 y}\right) + \tau\{A_{60}e^{-m_5 y} - A_{45}e^{-m_6 y} - ... + A_{59}e^{-m_7 y}\} ...(51)$$

$$C_1 = e^{i(\sigma t-\pi z)} A_{14}e^{-m_8 y} - A_{12}e^{-m_9 y} - A_{13}e^{-m_{10}y} + \tau\{A_{76}e^{-m_8 y} - A_{61}e^{-m_9 y} + ... - A_{75}e^{-m_{10}y}\} .... (52)$$

The physical quantities of interest are the wall shear stress τ_w is given by

$$\tau_w = \mu\left(\frac{\partial u^*}{\partial y^*}\right)_{y=0} = \rho v_0^2 u'(0) \qquad ... (53)$$

Therefore, the local skin friction factor C_{f_x} is given by

$$C_{f_x} = \frac{\tau_w}{\rho v_0^2} = u'(0) \qquad .... (54)$$

Using (16), (29) and (47) in (53), we get

$$C_{f_x} = (-m_3 A_3 + m_1 A_1 + m_2 A_2 + \varepsilon e^{i(\sigma t-\pi z)}\{(-m_{11}A_{31} + m_5 A_{21} - m_6 A_{27} - m_7 A_{28} + m_8 A_{24} - m_9 A_{29} - m_{10}A_{30} + m_{12}A_{15} + m_{13}A_{18}) + \tau\{(-m_{11}A_{167} - m_3 A_{77} + ... - m_{10}A_{166})\} \quad .... (55)$$

The local Nusselt number Nu_x can be written as

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$$\frac{Nu_x}{\mathrm{Re}_x} = \theta'(0) \qquad \text{... (56)}$$

Using (16), (32) and (50) in (55), we get

$$\frac{Nu_x}{\mathrm{Re}_x} = -m_1 + \varepsilon e^{i(\sigma t - \pi z)}\{(-m_5A_{11} + m_6A_9 + m_7A_{10}) + \tau(-m_5A_{60} + m_6A_{45} + m_7A_{46} - m_{14}A_{47} + m_{15}A_{48} - m_{16}A_{49} - m_{17}A_{50}$$
$$+m_{18}A_{51} - m_{19}A_{52} - m_{20}A_{53} + m_{21}A_{54} + m_{22}A_{55} - A_{56} - m_6A_{57} + A_{58} + m_7A_{59})\} \text{ ...(57)}$$

The local surface mass flux is given by

$$\frac{Sh_x}{\mathrm{Re}_x} = C'(0) \qquad \text{... (58)}$$

Using (16), (33) and (51) in (57), we get

$$\frac{Sh_x}{\mathrm{Re}_x} = -m_2 + \varepsilon e^{i(\sigma t - \pi z)}\{(-m_8A_{14} + m_9A_{12} + m_{10}A_{13}) + \tau(-m_8A_{76} + m_9A_{61} + m_{10}A_{62} - m_{23}A_{63} + m_{24}A_{64} - m_{25}A_{65}$$
$$-m_{26}A_{66} + m_{27}A_{67} - m_{28}A_{68} - m_{29}A_{69} + m_{30}A_{70} + m_{31}A_{71} - A_{72} - m_9A_{73} + A_{74} + m_{10}A_{75})\}$$

RESULTS AND DISCUSSION

The numerical values of the main flow velocity, cross flow, concentration temperature, skin friction, Nusselt number and Sherwood number are computed for different parameters like Prandtl number, Schmidt number, rotation number, frequency parameter, Grashof number ete. The effects of the pertinent parameters on the flow fields are analyzed and discussed with the help of main flow velocity profiles (Figures 1-5), cross flow velocity profiles (Figures 6-10), concentration profiles (Figures 11-15), Temperature profiles (Figures 16-20), skin friction (Figures 21-23), Rate of heat transfer (Figures 24-26) and Rate of mass transfer (Figures 27-30).

In the absence of the magnetic field and rotation, our results are found to be in good agreement with the results of Singh *et al* (1978).

From figures 1 – 5, it can be observed that the main flow velocity u decreases with the increase of Reynolds number, Prandtl number, Schmidt number and Hartmann number. However, Grashof number, modified Grashof number and frequency parameter have opposite effect on velocity profiles.

These results are qualitatively in agreement with the results obtained by Singh and Kumar (2001) in the absence of magnetic field and rotation. From figures 6 – 10, it can be deduced that the cross flow velocity w decreases with the Reynolds number, Prandtl number, and Hartmann number whereas increase in Schmidt number and rotation number results in increase of cross flow velocity.

Figures 11 – 15 depict the behaviour of the concentration. It is found that the species concentration decreases with the increase in the Reynolds number and Schmidt number. Rotation number and Grashof number are found to play no significant role on the

Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 57 Issue: 02:2024
DOI: 10.5281/zenodo.10669873

concentration profiles. Near the plate increase in the Prandtl number increase the species concentration whereas in the fully developed flow, increase in the Prandtl number does not affect the species concentration significantly.

In figures 16 – 20 temperature profiles are plotted as the function of y for various parameters. Increase in Prandtl number, Reynolds number, Schmidt number and Hartmann number decrease in temperature whereas increase in the rotation number and Grashof number increase the temperature profiles.

The values of Skin friction coefficient, Nusselt number and Sherwood number as shown in the figures (21 - 30). It is clear from these figure that both coefficient of Skin friction and Nusselt number decreases with increase of Grashof number, modified Grashof number and frequency parameter. However, Hartmann number, Prandtl number and Schmidl number have opposite effect on coefficient of Skin friction, Heat transfer and Mass transfer at the plate.

CONCLUSION

In this paper, we have extended the work of Das et al (2011) to a three dimensional rotating electrically conducting free convective flow past a vertical porous plate through a porous medium.

The plate temperature is spannise cosinusoidally fluctuating with time. The governing equations for unsteady MHD three dimensional free convective heat and mass transfer flow past a vertical porous plate with heat source formulated.

The resulting partial differential equations were transformed into a set of ordinary differential equations using perturbation technique and solved in closed form.

It was found that

- The main flow velocity decreases with the increase of Reynolds number and Prandtl number
- The cross flow velocity increases with the increase of Schmidt number and rotation number
- Increasing Grashof number decreases the skin friction and rate of Heat transfer.
- Rate of mass transfer at the plate increase with increase in Grashof number and Schmidt number

This work basically throws light on the effect of mass transfer on rotating hydro magnetic flow past a porous plate with sinusoidal suction and heat source.

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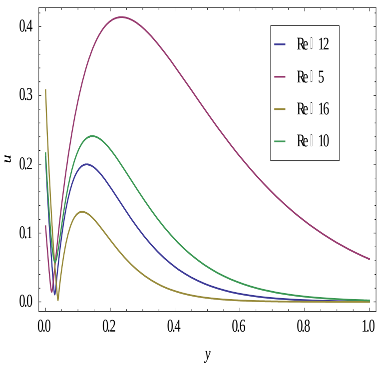
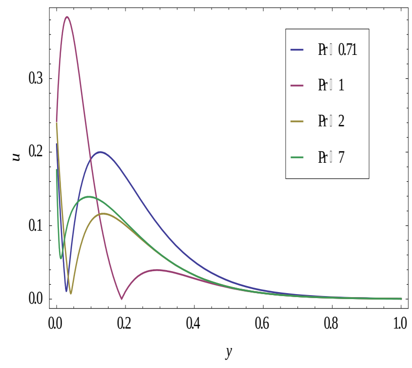




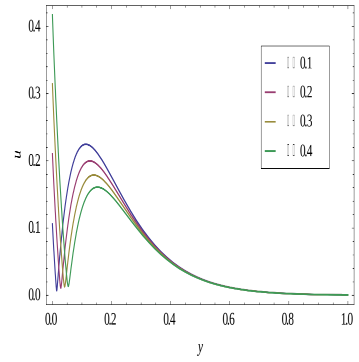
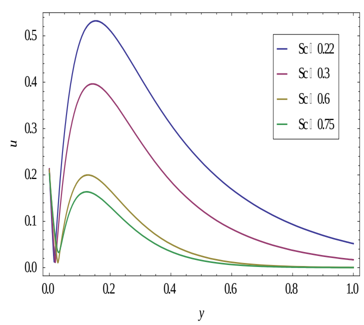
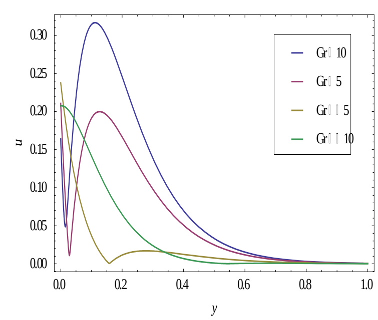


Fig 1: Mass flow velocity u as a function of y for varying Reynolds number

Fig 2: Mass flow velocity u as a function of y for varying Prandtls number

Fig 3: Mass flow velocity u as a function of y for varying τ





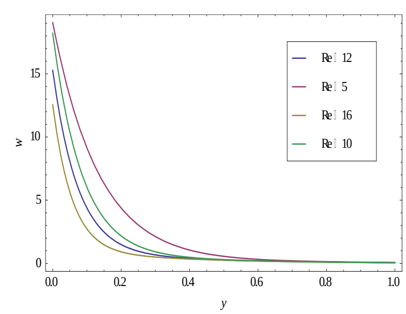
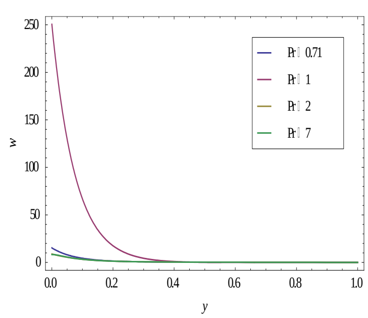
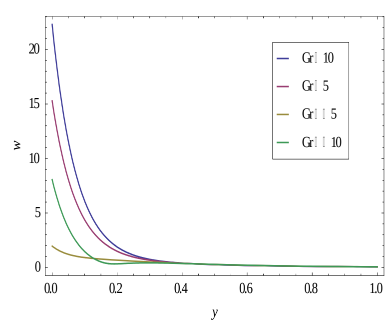


Fig 4: Mass flow velocity u as a function of y for varying Schmidts number

Fig 5: Mass flow velocity u as a function of y for varying Grashop number

Fig 6: Cross flow velocity was a function of y for different values of Reynolds number





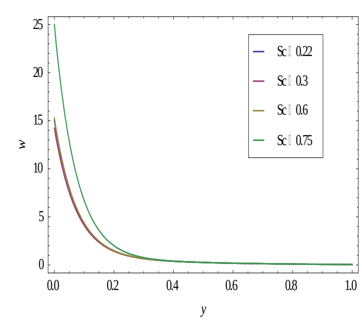


Fig 7: cross flow velocity was a function of y for different values of Prandtl number

Fig 8: cross flow velocity was a function of y for varying Grashof number

Fig 9: cross flow velocity was a function of y for varying Schmidt number

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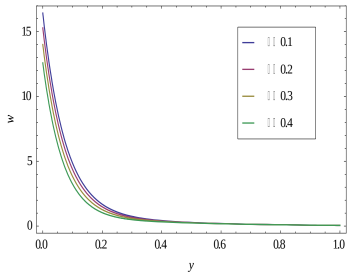
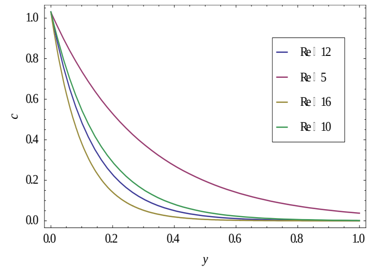




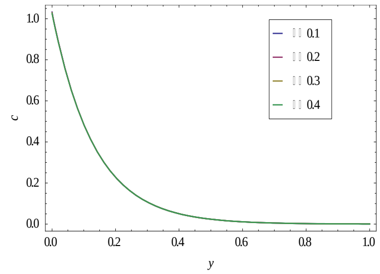
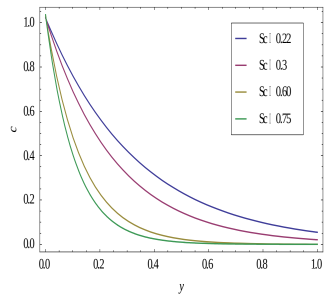
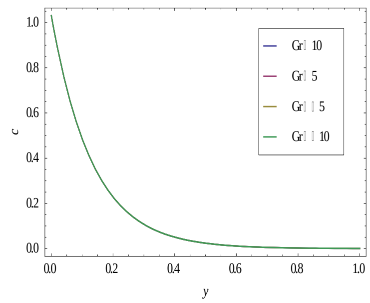


Fig 10: cross flow velocity was a function of y for varying τ

Fig 11: Concentration C as a function of y for varying Reynolds number

Fig 12: Concentration C as a function of y for different values of τ





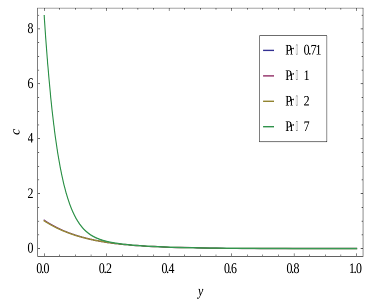
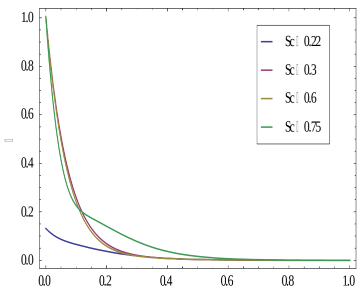
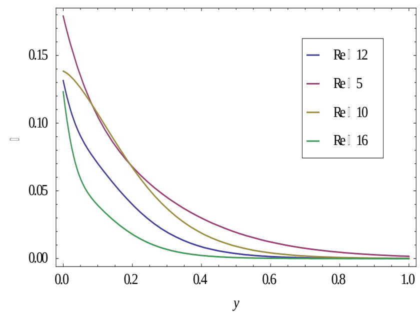


Fig 13: Concentration C as a function of y for different values of Schmidt number

Fig 14: Concentration C as a function of y for different values of Grashof number

Fig 15: Concentration C as a function of y for different values of Prandtl number





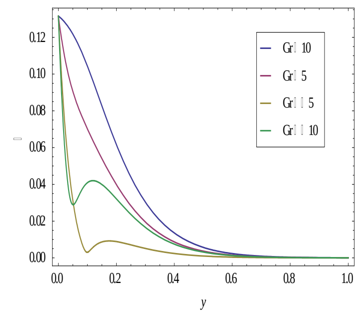


Fig 16: Temperature profile as a function of y for different values of Schmidt number

Fig 17: Temperature profile as a function of y for different values of Reynolds number

Fig 18: Temperature profile as a function of y for different values of Grashof number

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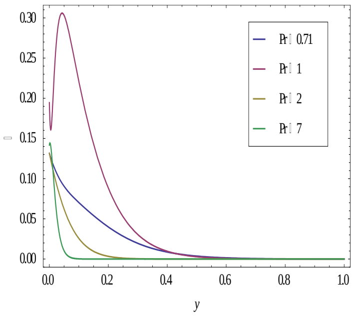
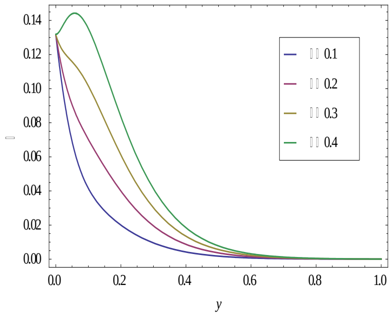




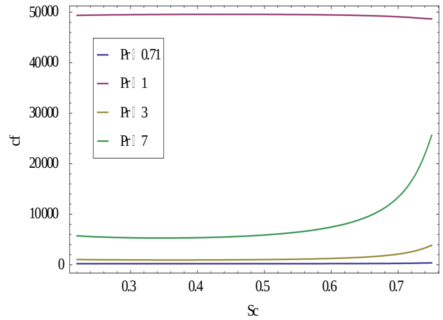
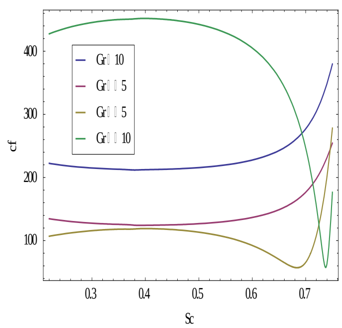
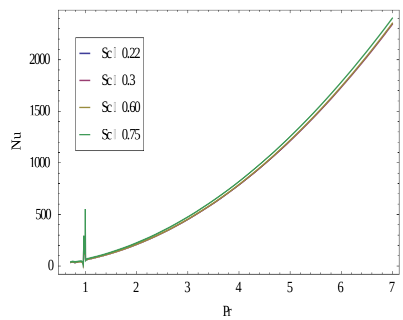


Fig 19: Temperature profile as a function of y for different values of Prandtl number

Fig 20: Temperature profile as a function of y for different values of τ

Fig 21: Skin friction as a function of Re for different values of Sc





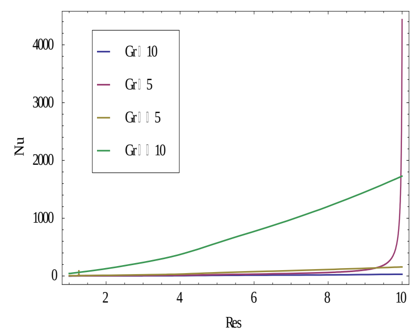
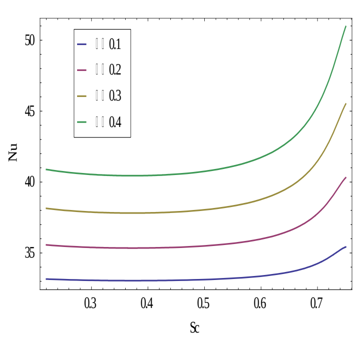
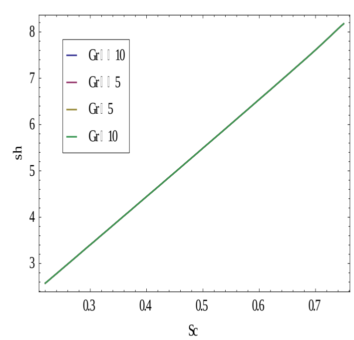


Fig 22: Skin friction as a function of Sc for different values of Pr

Fig 23: Skin friction as a function of Sc for different values of Gr

Fig 24: Rate of Heat transfer as a function of Pr for different values of Sc





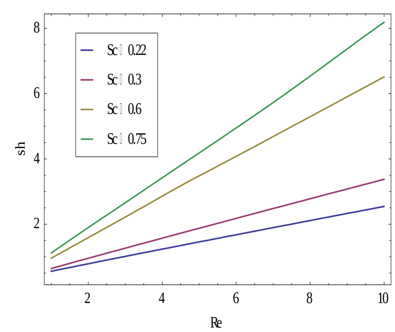


Fig 26: Rate of Heat transfer as a function of Sc for different values of τ

Fig 27: Rate of mass transfer as a function of Sc for different values of Gr

Fig 28: Rate of mass transfer as a function of re for different values of Sc

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Journal of Tianjin University Science and Technology
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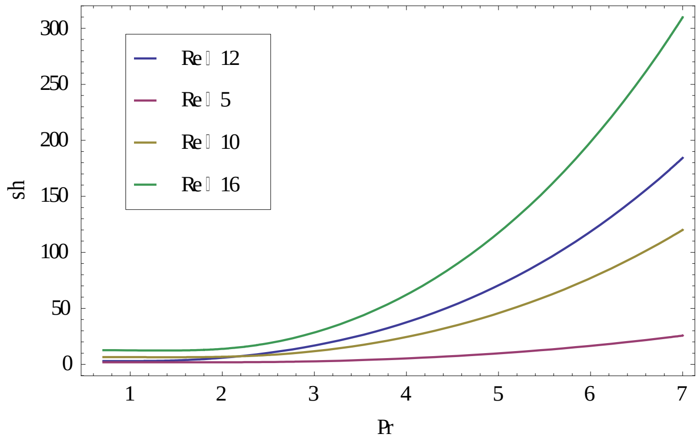

Fig 29: Rate of mass transfer as a function of Pr for different values of Re

Appendix:

$$m_1 = \frac{\Pr \mathrm{Re} + \sqrt{\Pr^2 \mathrm{Re}^2 + 4 \Pr \mathrm{Re}\, S}}{2}, \qquad m_2 = \frac{Sc \mathrm{Re} + \sqrt{Sc^2 \mathrm{Re}^2 + 4 \mathrm{Re}\, Sc R}}{2}$$

$$m_3 = \frac{\mathrm{Re} + \sqrt{\mathrm{Re}^2 + 4(M^2 + \frac{1}{k})}}{2}, \; m_4' = \frac{-\mathrm{Re} + \sqrt{\mathrm{Re}^2 + 4(\mathrm{Re}\, i\sigma + \pi^2 + \frac{1}{k})}}{2}$$

$$m_5 = \frac{\Pr \mathrm{Re} + \sqrt{\Pr^2 \mathrm{Re}^2 + 4(\Pr \mathrm{Re}\, i\sigma + \pi^2 + \Pr \mathrm{Re}\, S)}}{2}, \; m_6 = m_4 + m_1 \; m_7 = m_1 + \pi,$$

$$m_8 = \frac{Sc \mathrm{Re} + \sqrt{Sc^2 \mathrm{Re}^2 + 4(Sc \mathrm{Re}\, i\sigma + \pi^2 + Sc \mathrm{Re}\, R)}}{2}$$

$$m_9 = m_2 + m_4, \; m_{10} = m_2 + \pi, \; m_{11} = \frac{\mathrm{Re} + \sqrt{\mathrm{Re}^2 + 4(\pi^2 + \mathrm{Re}\, i\sigma)}}{2}$$

$$m_{12} = m_3 + m_4, \; m_{13} = m_3 + \pi, \; A_1 = \frac{\lambda \mathrm{Re}\, Gr}{m_1^2 - m_1 \mathrm{Re} - (M^2 + \frac{1}{k})}, \; A_2 = \frac{\lambda \mathrm{Re}\, Gm}{m_2^2 - m_2 \mathrm{Re} - (M^2 + \frac{1}{k})}$$

$$A_3 = A_1 + A_2 - k\lambda\tau \mathrm{Re}, \quad A_4 = \frac{\tau \mathrm{Re}\, A_3}{\lambda m_3}, \; A_5 = \frac{\tau \mathrm{Re}\, A_1}{\lambda m_1}, \; A_6 = \frac{\tau \mathrm{Re}\, A_2}{\lambda m_2}, \; A_7 = \frac{\pi}{m_4 - \pi}$$

$$A_8 = \frac{m_4}{\pi - m_4}, \; A_9 = \frac{\Pr \mathrm{Re}\, m_1 A_1}{m_6^2 - m_6 \Pr \mathrm{Re} - (\Pr \mathrm{Re}\, i\sigma + \pi^2 + \Pr \mathrm{Re}\, S)}$$

$$A_{10} = \frac{\Pr \mathrm{Re}\, m_1 A_8}{m_7^2 - m_7 \Pr \mathrm{Re} - (\Pr \mathrm{Re}\, i\sigma + \pi^2 + \Pr \mathrm{Re}\, S)}, \; A_{11} = 1 - A_9 - A_{10}$$

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$$A_{12}=\frac{Sc\,\mathrm{Re}\,m_2A_7}{m_9^2-m_9Sc\,\mathrm{Re}-(Sc\,\mathrm{Re}\,i\sigma+\pi^2+Sc\,\mathrm{Re}\,R)},$$

$$A_{13}=\frac{Sc\,\mathrm{Re}\,m_2A_8}{m_{10}^2-m_{10}Sc\,\mathrm{Re}-(Sc\,\mathrm{Re}\,i\sigma+\pi^2+Sc\,\mathrm{Re}\,R)},\ A_{14}=1-A_{12}-A_{13}$$

$$A_{15}=\frac{\mathrm{Re}\,m_3A_3A_7}{m_{12}^2-m_{12}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)},\ A_{16}=\frac{\mathrm{Re}\,m_1A_1A_7}{m_6^2-m_6\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)}$$

$$A_{17}=\frac{\mathrm{Re}\,m_2A_2A_7}{m_9^2-m_9\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)},\ A_{18}=\frac{\mathrm{Re}\,m_3A_3A_8}{m_{13}^2-m_{13}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)}$$

$$A_{19}=\frac{\mathrm{Re}\,m_1A_1A_8}{m_7^2-m_7\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)},\ A_{20}=\frac{\mathrm{Re}\,m_2A_2A_8}{m_{10}^2-m_{10}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)}$$

$$A_{21}=\frac{\lambda Gr\,\mathrm{Re}\,A_{11}}{m_5^2-m_5\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)},\ A_{22}=\frac{\lambda Gr\,\mathrm{Re}\,A_9}{m_6^2-m_6\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)}$$

$$A_{23}=\frac{\lambda Gr\,\mathrm{Re}\,A_{10}}{m_7^2-m_7\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)},\ A_{24}=\frac{\lambda Gm\,\mathrm{Re}\,A_{14}}{m_8^2-m_8\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)}$$

$$A_{25}=\frac{\lambda Gm\,\mathrm{Re}\,A_{12}}{m_9^2-m_9\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)},\quad A_{24}=\frac{\lambda Gm\,\mathrm{Re}\,A_{13}}{m_{10}^2-m_{10}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)}$$

$$A_{27}=A_{16}+A_{22},\ A_{28}=A_{19}+A_{23},\ A_{29}=A_{17}+A_{25},\ A_{30}=A_{20}+A_{26}$$

$$A_{31}=A_{21}-A_{27}-A_{28}+A_{24}-A_{29}-A_{30}+A_{15}+A_{18}$$

$$A_{32}=\frac{\pi^2\,\mathrm{Re}\,A_{31}}{\lambda(-m_{11}+m_4)(-m_{11}-m_4')(-m_{11}+\pi)(-m_{11}-\pi)}$$

$$A_{33}=\frac{\pi^2\,\mathrm{Re}\,A_{21}}{\lambda(-m_5+m_4)(-m_5-m_4')(-m_5+\pi)(-m_5-\pi)},$$

$$A_{35}=\frac{\pi^2\,\mathrm{Re}\,A_{28}}{\lambda(-m_7+m_4)(-m_7-m_4')(-m_7+\pi)(-m_7-\pi)},$$

$$A_{34}=\frac{\pi^2\,\mathrm{Re}\,A_{27}}{\lambda(-m_6+m_4)(-m_6-m_4')(-m_6+\pi)(-m_6-\pi)},$$

$$A_{37}=\frac{\pi^2\,\mathrm{Re}\,A_{29}}{\lambda(-m_9+m_4)(-m_9-m_4')(-m_9+\pi)(-m_9-\pi)},$$

$$A_{38}=\frac{\pi^2\,\mathrm{Re}\,A_{30}}{\lambda(-m_{10}+m_4)(-m_{10}-m_4')(-m_{10}+\pi)(-m_{10}-\pi)},$$

$$A_{39}=\frac{\pi^2\,\mathrm{Re}\,A_{15}}{\lambda(-m_{12}+m_4)(-m_{12}-m_4')(-m_{12}+\pi)(-m_{12}-\pi)},$$

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$$A_{40}=\frac{\pi^2\operatorname{Re}A_{18}}{\lambda(-m_{13}+m_4)(-m_{13}-m_4')(-m_{13}+\pi)(-m_{13}-\pi)},\ A_{41}=\frac{\pi^2\operatorname{Re}M^2m_4^2A_7}{\lambda(-m_4-m_4')(-m_4+\pi)(-m_4-\pi)},$$

$$A_{42}=\frac{\pi^4\operatorname{Re}M^2A_8}{\lambda(-\pi-m_4')(m_4-\pi)(-2\pi)}$$

$$A_{43}=\frac{1}{(m_4-\pi)}\{(m_4-m_{11})A_{32}-(m_4-m_5)A_{33}+(m_4-m_6)A_{34}+(m_4-m_7)A_{35}$$
$$-(m_4-m_8)A_{36}+(m_4-m_9)A_{37}+(m_4-m_{10})A_{38}-(m_4-m_{12})A_{39}$$
$$-(m_4-m_{13})A_{40}-A_{41}-A_{42}\}$$

$$A_{44}=A_{32}-A_{33}+A_{34}+A_{35}-A_{36}+A_{37}+A_{38}-A_{39}-A_{40}-\frac{1}{(m_4-\pi)}\{(m_4-m_{11})A_{32}$$
$$-(m_4-m_5)A_{33}+(m_4-m_6)A_{34}+(m_4-m_7)A_{35}-(m_4-m_8)A_{36}+(m_4-m_9)A_{37}$$
$$+(m_4-m_{10})A_{38}-(m_4-m_{12})A_{39}-(m_4-m_{13})A_{40}-A_{41}-A_{42}\}$$

$$A_{45}=\frac{\Pr\operatorname{Re}m_1A_{44}}{m_6^2-m_6\operatorname{Re}\Pr-K_1},\ A_{46}=\frac{\Pr\operatorname{Re}m_1A_{32}}{m_7^2-m_7\operatorname{Re}\Pr-K_1},\ A_{47}=\frac{\Pr\operatorname{Re}m_1A_{32}}{m_{14}^2-m_{14}\operatorname{Re}\Pr-K_1},$$

$$A_{48}=\frac{\Pr\operatorname{Re}m_1A_{33}}{m_{15}^2-m_{15}\operatorname{Re}\Pr-K_1},\ A_{49}=\frac{\Pr\operatorname{Re}m_1A_{34}}{m_{16}^2-m_{16}\operatorname{Re}\Pr-K_1},\ A_{50}=\frac{\Pr\operatorname{Re}m_1A_{35}}{m_{17}^2-m_{17}\operatorname{Re}\Pr-K_1}$$

$$A_{51}=\frac{\Pr\operatorname{Re}m_1A_{36}}{m_{18}^2-m_{18}\operatorname{Re}\Pr-K_1},\ A_{52}=\frac{\Pr\operatorname{Re}m_1A_{37}}{m_{19}^2-m_{19}\operatorname{Re}\Pr-K_1},\ A_{53}=\frac{\Pr\operatorname{Re}m_1A_{38}}{m_{20}^2-m_{20}\operatorname{Re}\Pr-K_1}$$

$$A_{54}=\frac{\Pr\operatorname{Re}m_1A_{39}}{m_{21}^2-m_{21}\operatorname{Re}\Pr-K_1},\ A_{55}=\frac{\Pr\operatorname{Re}m_1A_{40}}{m_{22}^2-m_{22}\operatorname{Re}\Pr-K_1},\ A_{56}=\frac{\Pr\operatorname{Re}m_1A_{41}}{K_3}$$

$$A_{57}=\frac{\Pr\operatorname{Re}m_1A_{41}K_2}{K_3^2},\ A_{58}=\frac{\Pr\operatorname{Re}m_1A_{42}}{K_5},\ A_{59}=\frac{\Pr\operatorname{Re}m_1A_{42}K_4}{K_5^2}$$

$$A_{60}=A_{45}+A_{46}-A_{47}+A_{48}-A_{49}-A_{50}+A_{51}$$
$$-A_{52}-A_{53}+A_{54}-A_{55}-A_{57}+A_{59}$$

$$A_{61}=\frac{Sc\operatorname{Re}m_2A_{44}}{m_9^2-m_9\operatorname{Re}Sc-K_6},\ A_{62}=\frac{Sc\operatorname{Re}m_2A_{43}}{m_{10}^2-m_{10}\operatorname{Re}Sc-K_6},\ A_{63}=\frac{Sc\operatorname{Re}m_2A_{32}}{m_{23}^2-m_{23}\operatorname{Re}Sc-K_6}$$

$$A_{64}=\frac{Sc\operatorname{Re}m_2A_{33}}{m_{24}^2-m_{24}\operatorname{Re}Sc-K_6},\ A_{65}=\frac{Sc\operatorname{Re}m_2A_{34}}{m_{25}^2-m_{25}\operatorname{Re}Sc-K_6},\ A_{66}=\frac{Sc\operatorname{Re}m_2A_{35}}{m_{26}^2-m_{26}\operatorname{Re}Sc-K_6}$$

$$A_{67}=\frac{Sc\operatorname{Re}m_2A_{36}}{m_{27}^2-m_{27}\operatorname{Re}Sc-K_6},\ A_{68}=\frac{Sc\operatorname{Re}m_2A_{37}}{m_{28}^2-m_{28}\operatorname{Re}Sc-K_6},\ A_{69}=\frac{Sc\operatorname{Re}m_2A_{38}}{m_{29}^2-m_{29}\operatorname{Re}Sc-K_6}$$

$$A_{70}=\frac{Sc\operatorname{Re}m_2A_{39}}{m_{30}^2-m_{30}\operatorname{Re}Sc-K_6},\ A_{71}=\frac{Sc\operatorname{Re}m_2A_{40}}{m_{31}^2-m_{31}\operatorname{Re}Sc-K_6},\ A_{72}=\frac{Sc\operatorname{Re}m_2A_{41}}{K_7}$$

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$$A_{73}=\frac{Sc\,\mathrm{Re}\,m_2A_{41}K_3}{K_7^2},\ A_{74}=\frac{Sc\,\mathrm{Re}\,m_2A_{42}}{K_9},\ A_{75}=\frac{Sc\,\mathrm{Re}\,m_2A_{42}K_{10}}{K_9^2}$$

$$A_{76}=A_{61}+A_{62}-A_{63}+A_{64}-A_{65}-A_{66}+A_{67}-A_{68}$$
$$-A_{69}+A_{70}+A_{71}+A_{72}-A_{74}+A_{75}$$

$$K_1=\mathrm{Pr}\,\mathrm{Re}\,S+\pi^2+i\sigma\,\mathrm{Pr}\,\mathrm{Re},\ K_2=-m_6+\mathrm{Pr}\,\mathrm{Re},\ K_3=m_6^2-\mathrm{Pr}\,\mathrm{Re}\,m_6-K_1$$

$$K_4=-2m_7+\mathrm{Pr}\,\mathrm{Re},\ K_5=m_7{}^2-\mathrm{Pr}\,\mathrm{Re}\,m_7-K_1,\ K_6=Sc\,\mathrm{Re}\,S+\pi^2+i\sigma Sc\,\mathrm{Re}$$

$$K_7=-2m_9+Sc\,\mathrm{Re},\ K_8=m_7{}^2-Sc\,\mathrm{Re}\,m_7-K_6,\ K_9=-2m_{10}+Sc\,\mathrm{Re}$$

$$K_{10}=m_{10}{}^2-Sc\,\mathrm{Re}\,m_{10}-K_6,\ K_{11}=\sigma T^2+i\sigma\,\mathrm{Re},\ K_{12}=-2m_{32}+\mathrm{Re}$$

$$K_{13}=m_{32}{}^2-\mathrm{Re}\,m_{32}-K_{11},\ K_{14}=-2m_{33}+\mathrm{Re},\ K_{15}=m_{33}{}^2-\mathrm{Re}\,m_{33}-K_{11}$$

$$K_{17}=m_6{}^2-\mathrm{Re}\,m_6-K_{11},\ K_{18}=-2m_7+\mathrm{Re},\ K_{19}=m_7{}^2-\mathrm{Re}\,m_7-K_{11}$$

$$K_{20}=-2m_9+\mathrm{Re},\ K_{21}=m_9{}^2-\mathrm{Re}\,m_9-K_{11},\ K_{22}=-2m_{10}+\mathrm{Re}$$

$$K_{23}=m_{10}{}^2-\mathrm{Re}\,m_{10}-K_{11},\ K_{24}=-2m_6+\mathrm{Re},\ K_{25}=m_6{}^2-\mathrm{Re}\,m_6-K_{11}$$

$$K_{26}=-2m_7+\mathrm{Re},\ K_{27}=m_7{}^2-\mathrm{Re}\,m_7-K_{11},\ K_{28}=-2m_9+\mathrm{Re}$$

$$K_{29}=m_9{}^2-\mathrm{Re}\,m_9-K_{11},\ K_{30}=-2m_{10}+\mathrm{Re},\ K_{31}=m_{10}{}^2-\mathrm{Re}\,m_{10}-K_{11}$$

$$A_{77}=\frac{A_3M^2}{m_3^2-m_3\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)},\ A_{78}=\frac{A_1M^2}{m_1^2-m_1\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)}$$

$$A_{79}=\frac{A_2M^2}{m_2^2-m_2\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)},\ A_{80}=\frac{\mathrm{Re}\,m_3A_3A_{44}}{m_{32}^2-m_{32}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)}$$

$$A_{81}=\frac{\mathrm{Re}\,m_3A_3A_{43}}{m_{33}^2-m_{33}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)},\ A_{82}=\frac{\mathrm{Re}\,m_3A_3A_{32}}{m_{34}^2-m_{34}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)}$$

$$A_{83}=\frac{\mathrm{Re}\,m_3A_3A_{33}}{m_{35}^2-m_{35}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)},\ A_{84}=\frac{\mathrm{Re}\,m_3A_3A_{34}}{m_{36}^2-m_{36}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)}$$

$$A_{85}=\frac{\mathrm{Re}\,m_3A_3A_{35}}{m_{37}^2-m_{37}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)},\ A_{86}=\frac{\mathrm{Re}\,m_3A_3A_{36}}{m_{38}^2-m_{38}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)}$$

$$A_{87}=\frac{\mathrm{Re}\,m_3A_3A_{37}}{m_{39}^2-m_{39}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)},\ A_{88}=\frac{\mathrm{Re}\,m_3A_3A_{38}}{m_{40}^2-m_{40}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)}$$

$$A_{89}=\frac{\mathrm{Re}\,m_3A_3A_{39}}{m_{41}^2-m_{41}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)},\ A_{90}=\frac{\mathrm{Re}\,m_3A_3A_{40}}{m_{42}^2-m_{42}\,\mathrm{Re}-(\mathrm{Re}\,i\sigma+\pi^2)}$$

$$A_{91}=\frac{\mathrm{Re}\,m_3A_3A_{41}}{K_{12}},\ A_{92}=\frac{\mathrm{Re}\,m_3A_3A_{41}K_{13}}{K_{12}^2},\ A_{93}=\frac{\mathrm{Re}\,m_3A_3A_{42}}{K_{14}},\ A_{94}=\frac{\mathrm{Re}\,m_3A_3A_{42}K_{15}}{K_{14}^2}$$

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$$A_{95} = \frac{\mathrm{Re}\, m_1 A_1 A_{44}}{m_6^2 - m_6\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{96} = \frac{\mathrm{Re}\, m_1 A_1 A_{43}}{m_7^2 - m_7\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

$$A_{97} = \frac{\mathrm{Re}\, m_1 A_1 A_{32}}{m_{14}^2 - m_{14}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{98} = \frac{\mathrm{Re}\, m_1 A_1 A_{33}}{m_{15}^2 - m_{15}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

$$A_{99} = \frac{\mathrm{Re}\, m_1 A_1 A_{34}}{m_{16}^2 - m_{16}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{100} = \frac{\mathrm{Re}\, m_1 A_1 A_{35}}{m_{17}^2 - m_{17}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

$$A_{101} = \frac{\mathrm{Re}\, m_1 A_1 A_{36}}{m_{18}^2 - m_{18}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{102} = \frac{\mathrm{Re}\, m_1 A_1 A_{37}}{m_{19}^2 - m_{19}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

$$A_{103} = \frac{\mathrm{Re}\, m_1 A_1 A_{38}}{m_{20}^2 - m_{20}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{104} = \frac{\mathrm{Re}\, m_1 A_1 A_{39}}{m_{21}^2 - m_{21}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

$$A_{105} = \frac{\mathrm{Re}\, m_1 A_1 A_{40}}{m_{22}^2 - m_{22}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{106} = \frac{\mathrm{Re}\, m_1 A_1 A_{41}}{K_{16}},\ A_{107} = \frac{\mathrm{Re}\, m_1 A_1 A_{41} K_{17}}{K_{16}^2}$$

$$A_{108} = \frac{\mathrm{Re}\, m_3 A_3 A_{42}}{K_{18}},\ A_{109} = \frac{\mathrm{Re}\, m_3 A_3 A_{42} K_{19}}{K_{18}^2},\ A_{110} = \frac{\mathrm{Re}\, m_2 A_2 A_{44}}{m_9^2 - m_9\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

$$A_{111} = \frac{\mathrm{Re}\, m_2 A_2 A_{43}}{m_{10}^2 - m_{10}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{112} = \frac{\mathrm{Re}\, m_2 A_2 A_{32}}{m_{23}^2 - m_{23}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

$$A_{113} = \frac{\mathrm{Re}\, m_2 A_2 A_{33}}{m_{24}^2 - m_{24}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{114} = \frac{\mathrm{Re}\, m_2 A_2 A_{34}}{m_{25}^2 - m_{25}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

$$A_{115} = \frac{\mathrm{Re}\, m_2 A_2 A_{35}}{m_{26}^2 - m_{26}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{116} = \frac{\mathrm{Re}\, m_2 A_2 A_{36}}{m_{27}^2 - m_{27}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

$$A_{116} = \frac{\mathrm{Re}\, m_2 A_2 A_{36}}{m_{27}^2 - m_{27}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{117} = \frac{\mathrm{Re}\, m_2 A_2 A_{37}}{m_{28}^2 - m_{28}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

$$A_{118} = \frac{\mathrm{Re}\, m_2 A_2 A_{38}}{m_{29}^2 - m_{29}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{119} = \frac{\mathrm{Re}\, m_2 A_2 A_{39}}{m_{30}^2 - m_{30}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

$$A_{120} = \frac{\mathrm{Re}\, m_2 A_2 A_{40}}{m_{31}^2 - m_{31}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{121} = \frac{\mathrm{Re}\, m_2 A_2 A_{41}}{K_{20}},\ A_{122} = \frac{\mathrm{Re}\, m_2 A_2 A_{41} K_{21}}{K_{20}^2}$$

$$A_{123} = \frac{\mathrm{Re}\, m_2 A_2 A_{42}}{K_{22}},\ A_{124} = \frac{\mathrm{Re}\, m_2 A_2 A_{42} K_{23}}{K_{22}^2},\ A_{125} = \frac{\lambda\,\mathrm{Re}\, Gr A_{60}}{m_3^2 - m_3\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

$$A_{126} = \frac{\lambda\,\mathrm{Re}\, Gr A_{45}}{m_6^2 - m_6\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{127} = \frac{\lambda\,\mathrm{Re}\, Gr A_{46}}{m_7^2 - m_7\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

$$A_{128} = \frac{\lambda\,\mathrm{Re}\, Gr A_{47}}{m_{14}^2 - m_{14}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{129} = \frac{\lambda\,\mathrm{Re}\, Gr A_{48}}{m_{15}^2 - m_{15}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

$$A_{130} = \frac{\lambda\,\mathrm{Re}\, Gr A_{49}}{m_{16}^2 - m_{16}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)},\ A_{131} = \frac{\lambda\,\mathrm{Re}\, Gr A_{50}}{m_{17}^2 - m_{17}\,\mathrm{Re} - (\mathrm{Re}\, i\sigma + \pi^2)}$$

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$$A_{132}=\frac{\lambda \operatorname{Re} Gr A_{51}}{m_{18}^2-m_{18}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)},\ A_{133}=\frac{\lambda \operatorname{Re} Gr A_{52}}{m_{19}^2-m_{19}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)}$$

$$A_{134}=\frac{\lambda \operatorname{Re} Gr A_{53}}{m_{20}^2-m_{20}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)},\ A_{135}=\frac{\lambda \operatorname{Re} Gr A_{54}}{m_{21}^2-m_{21}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)}$$

$$A_{136}=\frac{\lambda \operatorname{Re} Gr A_{55}}{m_{22}^2-m_{22}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)},\ A_{137}=\frac{\lambda \operatorname{Re} Gr A_{56}}{K_{24}},\ A_{138}=\frac{\lambda \operatorname{Re} Gr A_{56} K_{25}}{K_{24}^2}$$

$$A_{139}=\frac{\lambda \operatorname{Re} Gr A_{57}}{m_{6}^2-m_{6}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)},\ A_{140}=\frac{\lambda \operatorname{Re} Gr A_{58}}{K_{26}},\ A_{141}=\frac{\lambda \operatorname{Re} Gr A_{58} K_{27}}{K_{26}^2}$$

$$A_{142}=\frac{\lambda \operatorname{Re} Gr A_{59}}{m_{7}^2-m_{7}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)},\ A_{143}=\frac{\lambda \operatorname{Re} Gr A_{57}}{m_{8}^2-m_{8}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)}$$

$$A_{144}=\frac{\lambda \operatorname{Re} Gm A_{61}}{m_{9}^2-m_{9}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)},\ A_{145}=\frac{\lambda \operatorname{Re} Gm A_{62}}{m_{10}^2-m_{10}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)}$$

$$A_{146}=\frac{\lambda \operatorname{Re} Gm A_{63}}{m_{23}^2-m_{23}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)},\ A_{147}=\frac{\lambda \operatorname{Re} Gm A_{64}}{m_{24}^2-m_{24}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)}$$

$$A_{148}=\frac{\lambda \operatorname{Re} Gm A_{65}}{m_{25}^2-m_{25}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)},\ A_{149}=\frac{\lambda \operatorname{Re} Gm A_{66}}{m_{26}^2-m_{26}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)}$$

$$A_{150}=\frac{\lambda \operatorname{Re} Gm A_{67}}{m_{27}^2-m_{27}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)},\ A_{151}=\frac{\lambda \operatorname{Re} Gm A_{68}}{m_{28}^2-m_{28}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)}$$

$$A_{152}=\frac{\lambda \operatorname{Re} Gm A_{69}}{m_{29}^2-m_{29}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)},\ A_{153}=\frac{\lambda \operatorname{Re} Gm A_{70}}{m_{30}^2-m_{30}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)}$$

$$A_{154}=\frac{\lambda \operatorname{Re} Gm A_{71}}{m_{31}^2-m_{31}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)},\ A_{155}=\frac{\lambda \operatorname{Re} Gm A_{72}}{K_{28}},\ A_{156}=\frac{\lambda \operatorname{Re} Gm A_{72} K_{29}}{K_{28}^2}$$

$$A_{157}=\frac{\lambda \operatorname{Re} Gm A_{73}}{m_{9}^2-m_{9}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)},\ A_{158}=\frac{\lambda \operatorname{Re} Gm A_{74}}{K_{30}},\ A_{159}=\frac{\lambda \operatorname{Re} Gm A_{74} K_{31}}{K_{30}^2}$$

$$A_{160}=\frac{\lambda \operatorname{Re} Gm A_{75}}{m_{10}^2-m_{10}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)},\ A_{161}=\frac{\lambda \operatorname{Re} A_{7}}{m_{4}^2-m_{4}\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)}$$

$$A_{162}=\frac{\lambda \operatorname{Re} A_{8}}{\pi^2-\pi\operatorname{Re}-(\operatorname{Re} i\sigma+\pi^2)},\ A_{163}=A_{95}-A_{107}-A_{126}+A_{138}+A_{139}$$

$$A_{164}=A_{96}+A_{109}-A_{127}-A_{141}-A_{142},\ A_{165}=A_{110}-A_{122}-A_{144}+A_{156}+A_{157}$$

$$A_{164}=A_{111}+A_{124}+A_{145}-A_{159}-A_{160},$$

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$$A_{167} = -A_{77} + A_{78} + A_{79} - A_{80} - A_{81} + A_{82} + A_{83} + A_{84}$$
$$+ A_{85} - A_{86} + A_{87} + A_{88} - A_{89} - A_{90} - A_{91} + A_{92} + A_{93}$$
$$- A_{94} - A_{97} + A_{98} - A_{99} - A_{100} + A_{101} - A_{102} - A_{103}$$
$$+ A_{104} + A_{105} + A_{106} - A_{108} - A_{112} + A_{113} - A_{114} - A_{115}$$
$$+ A_{116} - A_{117} - A_{118} + A_{119} + A_{120} + A_{121} - A_{123} + A_{125}$$
$$+ A_{128} - A_{129} + A_{130} + A_{131} - A_{132} + A_{133} + A_{134} - A_{135}$$
$$- A_{136} - A_{137} + A_{140} + A_{143} + A_{146} - A_{147} + A_{148} + A_{149}$$
$$- A_{150} + A_{151} + A_{152} - A_{153} - A_{154} + A_{158} + A_{161} + A_{162}$$
$$+ A_{164} + A_{165} + A_{166}$$

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