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ORIGINAL ARTICLE

Free convection flow with chemical reaction effect between oscillating parallel plates

F. Zulkiflee[1], S. Shafie[1], A. Ali[1,*], A.Q. Mohamad[1]

[1]Department of Mathematical Sciences, Faculty of Science, Universiti Teknologi Malaysia, Skudai, 81310 Johor bahru, Johor, Malaysia.

ABSTRACT – This research purpose is to investigate the exact solutions for unsteady free convection flow between oscillating parallel plates with mass diffusion and chemical reaction. The governing equations are modelled and reduced using non-dimensional variables. The method used is Laplace transform method. Solutions for velocity, temperature, and concentration fields as well as skin friction, Nusselt and Sherwood number are obtained. For physical understanding, analytical results for velocity, temperature and concentration profile are plotted graphically with respect to the Schmidt number, Prandtl number, oscillating parameter, Grashof number, mass Grashof number and chemical reaction parameter. Increasing Prandtl number and Schmidt number decreases the concentration, velocity, temperature, and skin friction but increases the Sherwood and Nusselt numbers.

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INTRODUCTION

Free convection in vertical parallel plates has been a popular topics to be discussed as it has many contributions to science and technology. Simple example of free convection occurs in our everyday life so that there has been a great interest and research activity in free convection in vertical parallel plates [1]. Problems of free convection flows in parallel plates are generally modeled under the assumptions of ramped wall temperature, constant surface temperature or constant heat flux [2-3]. Vocale et al. [4] studied transient free convection in open-ended vertical channels. The research investigates heat transfer between two plates when one of the plates have sudden change of temperature. An investigation of free convection flow in vertical parallel plates with mass diffusion were also has received a great deal of attention. Narahari [5] investigate free convection flow between two vertical parallel plates with constant temperature. The research also considered mass diffusion in the problem. The results showed that the skin friction increases through time but decreases when the value of the Schmidt and Prandtl numbers increase. Also, skin friction increases in the presence of aiding flows and decreases with opposing flows. Besides that Jha et al. [5] investigated free convection heat and mass transfer flow in a vertical channel with Dufour effects. The study showed that the transient solution at a higher time coincides with the steady-state solution derived separately.

Different physical effects also considered analysing the problem in free convection between two parallel plates. Some of those effects are radiation, chemical reaction, magnetic fields and porousity [6-8]. Moreover, Alagoa [9] investigate radiative and free convective effects of a MHD flow through a porous medium between infinite parallel plates with time-dependent suction. The research shows that the flow in porous media bathed in high temperatures differs from cold media. Therefore, it is important to consider thermal parameters when investigating processes of flow in porous media in such environments as geothermal and geophysical and even astrophysical regions. In contrast, Singh et al. [10] investigated magnetohydrodynamics free convection between vertical parallel porous plates in the presence of an induced magnetic field. The results show that the effect of a suction parameter is to decrease the velocity field and induced current density. At the same time, it has an increasing effect on the induced magnetic field.

The study of oscillating parallel plates plays important role in many science technology and engineering applications such as petroleum engineering and MHD generators [11]. Some of the researchers considered oscillation in their research study but only considering oscillating vertical plates [12-14]. Chen et al. studied the heat transfer characteristics of the oscillating flow regenerator filled with circular tubes [15]. The study shows that the mean temperature gradient contributes to the heat transfer performance of oscillating flow. Narahari et al [16] investigates soret, heat generation, radiation and porous effects on MHD free convection flow past an infinite plate with oscillating temperature while Sasikumar [17] investigates effect of heat and mass transfer on unsteady MHD flow through porous medium with oscillating temperature. There are many researchers study oscillations problems but only few focused on oscillating parallel plates.

Motivated by the above research, the present investigations is to analyse the effect of chemical reaction on free convection flow between oscillating parallel plates with mass diffusion. Laplace Transform will be used in this study to obtain exact solution results.

*CORRESPONDING AUTHOR | A.Ali | ✉ anati@utm.my

MATHEMATICAL FORMULATION

Unsteady free convection flow between two parallel plates with mass diffusion are considered with oscillating plate at $y' = 0$. The configuration problem of the flow is presented in Figure 1.

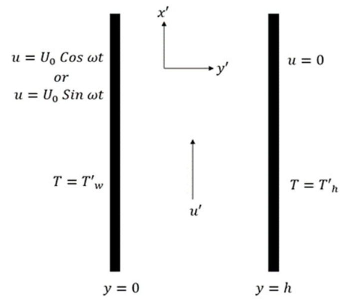

Figure 1. Flow configuration of the problem.

The following equations govern the flow under the usual Boussinesq's approximations:

$$\frac{\partial u'}{\partial t'} = \nu \frac{\partial^2 u'}{\partial y'^2} + g\beta(T' - T'_h) + g\beta^*(C' - C'_h) \tag{1}$$

$$\rho C_\rho \frac{\partial T'}{\partial t'} = k \frac{\partial^2 T'}{\partial y'^2} \tag{2}$$

$$\frac{\partial C'}{\partial t'} = D \frac{\partial^2 C'}{\partial y'^2} - K_c(C' - C'_h) \tag{3}$$

$$t \leq 0 \ : u' = 0 \qquad T' = T'_h \qquad C' = C'_h \qquad for \qquad 0 \leq y' \leq h$$

$$t > 0 : \ u' = U_0 \cos \omega t \ \ and \ \ U_0 \sin \omega t \ T' = T'_W \ C' = C'_w \ \ at \ y' = 0$$

$$u' = 0 \qquad T' = T'_h \qquad C' = C'_h \qquad at \qquad y' = h \tag{4}$$

where u' is velocity of the fluid, β is the volumetric coefficient of thermal expansion, t' is the time, h is the distance between two vertical plates, g is the acceleration due to gravity, T' is the temperature of the fluid. T'_h is the temperature of the plate at $y' = h$, β^* is the volumetric coefficient of concentration expansion, C' is the species concentration in the fluid, C'_h species concentration at $y' = h$, ν is the kinematic viscosity, y' is the coordinate axis normal to the plates, ρ is the density, C'_p is the specific heat at constant pressure, k is the thermal conductivity of the fluid, K_c is the chemical reaction coefficient, D is the mass diffusion coefficient, T'_w and C'_w are the temperature and concentration of the plate at $y' = 0$. ω is the frequency of velocity of the wall.

Next, we introduce the following non-dimensional quantities:

$$y = \frac{y'}{h} \qquad t = \frac{t'}{h^2} \qquad u = \frac{u'}{U_0}$$

$$\mu = \rho\nu \qquad T' = \frac{T' - T'_h}{T'_w - T'_h} \qquad C' = \frac{C' - C'_h}{C'_w - C'_h} \tag{5}$$

Then, from equation (1)-(3) and boundary conditions (4) becomes:

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + Gr\theta + GmC \tag{6}$$

$$\frac{\partial \theta}{\partial t} = \left(\frac{1}{Pr}\right)\frac{\partial^2 \theta}{\partial y^2} \tag{7}$$

$$\frac{\partial C}{\partial t} = \left(\frac{1}{Sc}\right)\frac{\partial^2 C}{\partial y^2} - \frac{A_2 C}{Sc} \tag{8}$$

$$t \le 0 \ : u = 0 \quad \theta = 0 \quad C = 0 \quad for \quad 0 \le y \le 1$$

$$t > 0 \ : u = \cos\omega t \ and \ \sin\omega t \quad \theta = 1 \ \ C = 1 \ \ at \ \ y = 0$$

$$u = 0 \quad \theta = 0 \quad C = 0 \quad at \quad y = 1 \tag{9}$$

where,

$$Gr = \frac{g\beta h^2}{\nu U_0}(T'_w - T'_h) \qquad Gm = \frac{g\beta^* h^2}{\nu U_0}(C'_w - C'_h) \qquad Sc = \frac{\nu}{D}$$

$$Pr = \frac{\mu C_p}{k} \qquad A_2 = \frac{K_c h^2}{D} \tag{10}$$

Here, Gr is the thermal Grashof number, Gm is the mass Grashof number, Pr is the Prandtl number, Sc the Schmidt number, A_2 is the chemical reaction parameter and ω is the oscillating parameter. Cosine and sine are considered in this study as oscillations can occur either in sine or cosine form.

Solutions to the problem

The governing equations (6)-(8) with boundary conditions (9) were solved in exact form by the Laplace transform technique and their solutions in the transform (y, q) plane are given by

$$\begin{aligned}\bar{u}_c = \sum_{n=0}^{\infty} \Bigg\{ & \frac{a_1}{q^2}e^{-a\sqrt{q}} - \frac{a_1}{q^2}e^{-b\sqrt{q}} + \frac{a_2}{q}e^{-a\sqrt{q}} - \frac{a_2}{q}e^{-b\sqrt{q}} - \frac{a_2}{\left(q + \frac{A_2}{Sc-1}\right)}e^{-a\sqrt{q}} + \frac{a_2}{\left(q + \frac{A_2}{Sc-1}\right)}e^{-b\sqrt{q}} \\ & + \frac{1}{2(q - i\omega)}e^{-a\sqrt{q}} - \frac{1}{2(q - i\omega)}e^{-b\sqrt{q}} + \frac{1}{2(q + i\omega)}e^{-a\sqrt{q}} - \frac{1}{2(q + i\omega)}e^{-b\sqrt{q}} - \frac{a_1}{q^2}e^{-a\sqrt{Prq}} \\ & + \frac{a_1}{q^2}e^{-b\sqrt{Prq}} - \frac{a_2}{q}e^{-a\sqrt{Sc\,q + A_2}} + \frac{a_2}{q}e^{-b\sqrt{Sc\,q + A_2}} + \frac{a_2}{\left(q + \frac{A_2}{Sc-1}\right)}e^{-a\sqrt{Sc\,q + A_2}} \\ & - \frac{a_2}{\left(q + \frac{A_2}{Sc-1}\right)}e^{-b\sqrt{Sc\,q + A_2}} \Bigg\}\end{aligned} \tag{11}$$

$$\bar{\theta} = \sum_{n=0}^{\infty}\left\{\frac{1}{q}e^{-a\sqrt{Prq}} - \frac{1}{q}e^{-b\sqrt{Prq}}\right\} \tag{12}$$

$$\bar{C} = \sum_{n=0}^{\infty}\left\{\frac{1}{q}e^{-a\sqrt{Scq + A_2}} - \frac{1}{q}e^{-b\sqrt{Scq + A_2}}\right\} \tag{13}$$

where the subscripts c in equations (11) – (13) refer to cosine oscillations of the plate and while

$$a_1 = \frac{Gr}{Pr - 1} \qquad a_2 = \frac{Gm}{A_2} \qquad a = 2n + y \qquad b = 2n + 2 - y$$

Laplace inversion of the above equationis as follows,

$$
\begin{aligned}
u_c = \sum_{n=0}^{\infty} \Bigg\{ & a_1 \left(\left(\frac{a^2}{2}+t\right) Erfc\left(\frac{a}{2\sqrt{t}}\right) - a\sqrt{\frac{t}{\pi}} e^{-\frac{a^2}{4t}} - \left(\frac{b^2}{2}+t\right) Erfc\left(\frac{b}{2\sqrt{t}}\right) + b\sqrt{\frac{t}{\pi}} e^{-\frac{b^2}{4t}} \right) + \\
& a_2 \Bigg(\frac{1}{2} \Bigg(-e^{a\sqrt{A_2}}\, Erfc\left(\frac{a}{2}\sqrt{\frac{Sc}{t}} + \sqrt{\frac{A_2}{Sc}t}\right) - e^{-a\sqrt{A_2}} Erfc\left(\frac{a}{2}\sqrt{\frac{Sc}{t}} - \sqrt{\frac{A_2}{Sc}t}\right) + e^{b\sqrt{A_2}}\, Erfc\left(\frac{b}{2}\sqrt{\frac{Sc}{t}} + \sqrt{\frac{A_2}{Sc}t}\right) + \\
& e^{-b\sqrt{A_2}} Erfc\left(\frac{b}{2}\sqrt{\frac{Sc}{t}} - \sqrt{\frac{A_2}{Sc}t}\right) \Bigg) + \frac{e^{-\left(\frac{A_2}{Sc-1}\right)t}}{2} \Bigg(e^{a\sqrt{Sc\left(\frac{A_2}{Sc}+\frac{A_2}{Sc-1}\right)}} Erfc\left(\frac{a}{2}\sqrt{\frac{Sc}{t}} + \sqrt{\left(\frac{A_2}{Sc}-\frac{A_2}{Sc-1}\right)t}\right) + \\
& e^{-a\sqrt{Sc\left(\frac{A_2}{Sc}+\frac{A_2}{Sc-1}\right)}} Erfc\left(\frac{a}{2}\sqrt{\frac{Sc}{t}} - \sqrt{\left(\frac{A_2}{Sc}-\frac{A_2}{Sc-1}\right)t}\right) - e^{b\sqrt{Sc\left(\frac{A_2}{Sc}+\frac{A_2}{Sc-1}\right)}} Erfc\left(\frac{b}{2}\sqrt{\frac{Sc}{t}} + \sqrt{\left(\frac{A_2}{Sc}-\frac{A_2}{Sc-1}\right)t}\right) - \\
& e^{-b\sqrt{Sc\left(\frac{A_2}{Sc}+\frac{A_2}{Sc-1}\right)}} Erfc\left(\frac{b}{2}\sqrt{\frac{Sc}{t}} - \sqrt{\left(\frac{A_2}{Sc}-\frac{A_2}{Sc-1}\right)t}\right) \Bigg) \Bigg) + \frac{1}{2}\Bigg(\frac{e^{i\omega t}}{2} \Bigg(e^{a\sqrt{i\omega}} Erfc\left(\frac{a}{2\sqrt{t}} + \sqrt{i\omega t}\right) + e^{-a\sqrt{i\omega}} Erfc\Bigg(\frac{a}{2\sqrt{t}} - \\
& \sqrt{i\omega t}\Bigg)\Bigg) - \frac{e^{i\omega t}}{2} \left(e^{b\sqrt{i\omega}} Erfc\left(\frac{b}{2\sqrt{t}} + \sqrt{i\omega t}\right) + e^{-b\sqrt{i\omega}} Erfc\left(\frac{b}{2\sqrt{t}} - \sqrt{i\omega t}\right)\right)\Bigg) + \frac{1}{2}\Bigg(\frac{e^{-i\omega t}}{2} \Bigg(e^{a\sqrt{-i\omega}} Erfc\left(\frac{a}{2\sqrt{t}} + \sqrt{-i\omega t}\right) + \\
& e^{-a\sqrt{-i\omega}} Erfc\left(\frac{a}{2\sqrt{t}} - \sqrt{-i\omega t}\right)\Bigg) - \frac{e^{-i\omega t}}{2} \left(e^{b\sqrt{-i\omega}} Erfc\left(\frac{b}{2\sqrt{t}} + \sqrt{-i\omega t}\right) + e^{-b\sqrt{-i\omega}} Erfc\left(\frac{b}{2\sqrt{t}} - \sqrt{-i\omega t}\right)\right)\Bigg) + \\
& a_1 \Bigg(\left(Erfc\left(\frac{a}{2\sqrt{t}}\right) - Erfc\left(\frac{b}{2\sqrt{t}}\right)\right) + \frac{e^{-\left(\frac{A_2}{Sc-1}\right)t}}{2} \Bigg(-e^{a\sqrt{-\left(\frac{A_2}{Sc-1}\right)}} Erfc\left(\frac{a}{2\sqrt{t}} + \sqrt{-\left(\frac{A_2}{Sc-1}\right)t}\right) - e^{-a\sqrt{-\left(\frac{A_2}{Sc-1}\right)}} Erfc\Bigg(\frac{a}{2\sqrt{t}} - \\
& \sqrt{-\left(\frac{A_2}{Sc-1}\right)t}\Bigg) + e^{b\sqrt{-\left(\frac{A_2}{Sc-1}\right)}} Erfc\left(\frac{b}{2\sqrt{t}} + \sqrt{-\left(\frac{A_2}{Sc-1}\right)t}\right) + e^{-b\sqrt{-\left(\frac{A_2}{Sc-1}\right)}} Erfc\left(\frac{b}{2\sqrt{t}} - \sqrt{-\left(\frac{A_2}{Sc-1}\right)t}\right)\Bigg)\Bigg) + \\
& a_2 \left(\left(\frac{a^2 Sc}{2}+t\right) Erfc\left(\frac{a\sqrt{Sc}}{2\sqrt{t}}\right) - a\sqrt{Sc}\sqrt{\frac{t}{\pi}} e^{-\frac{a^2 Sc}{4t}} - \left(\frac{b^2 Sc}{2}+t\right) Erfc\left(\frac{b\sqrt{Sc}}{2\sqrt{t}}\right) + b\sqrt{Sc}\sqrt{\frac{t}{\pi}} e^{-\frac{b^2 Sc}{4t}} \right) \Bigg\}
\end{aligned} \tag{14}
$$

$$
\theta = \sum_{n=0}^{\infty} \left\{ Erfc\left(\frac{a\sqrt{Pr}}{2\sqrt{t}}\right) - Erfc\left(\frac{b\sqrt{Pr}}{2\sqrt{t}}\right) \right\} \tag{15}
$$

$$
\begin{aligned}
C = \sum_{n=0}^{\infty} \frac{1}{2} \Bigg\{ & e^{a\sqrt{A_2}}\, Erfc\left(\frac{a\sqrt{Sc}}{2\sqrt{t}} + \sqrt{\frac{A_2 t}{Sc}}\right) + e^{-a\sqrt{A_2}}\, Erfc\left(\frac{a\sqrt{Sc}}{2\sqrt{t}} - \sqrt{\frac{A_2 t}{Sc}}\right) - e^{b\sqrt{A_2}}\, Erfc\left(\frac{b\sqrt{Sc}}{2\sqrt{t}} + \sqrt{\frac{A_2 t}{Sc}}\right) \\
& - e^{-b\sqrt{A_2}}\, Erfc\left(\frac{b\sqrt{Sc}}{2\sqrt{t}} - \sqrt{\frac{A_2 t}{Sc}}\right) \Bigg\}
\end{aligned} \tag{16}
$$

From the solution (14) – (16), expressions for Skin friction, Nusselt number and Sherwood number were calculated by using the following relations,

Skin friction

$$
\tau = -\left.\frac{\partial u}{\partial y}\right|_{y=0} \tag{17}
$$

Nusselt number

$$
Nu = -\frac{1}{\theta(0,t)} \left.\frac{\partial \theta}{\partial y}\right|_{y=0} \tag{18}
$$

Sherwood number

$$
Sh = \left.\frac{\partial C}{\partial y}\right|_{y=0} \tag{19}
$$

RESULTS AND DISCUSSION

In this section, the exact solutions (14) – (16) are studied numerically to determine the different effects of several involved parameter such as Prandtl number Pr, Grashof number Gr, Mass Grashof number Gm, Schmidt number Sc, chemical reaction parameter A_2 and oscillating parameter ω. Skin friction, Nusselt number and Sherwood number are also studied with different parameters.

Figures 2 and 3 show concentration profiles with different parameters. The graphs show that increasing Sc number and A_2 parameter causes the concentration to decrease. It was found that a higher number of chemical reaction parameters causes the concentration of the fluid flow to become lower. Meanwhile, Figure 4 show the effect of temperature for different numbers of Pr. A higher number of Pr will caused the temperature to decrease. When the Pr number increases, the viscosity of the fluid increases causing the fluid to become thicker and decreases the heat transfer.

In Figures 5-8, the impact of various parameters on velocity profiles were discussed. Figure 5 illustrates the effects of different Sc numbers on the velocity profile. Increasing the Sc number would cause the fluid flow velocity to decrease as higher Sc number causes the thickness of the boundary layer to increase and velocity to decrease. Figure 6 shows the velocity profile with different numbers of Pr in the fluid flow. It is clear from Figure 6 that increasing the Pr number would cause the velocity to decrease. Meanwhile, increasing the chemical reaction parameter will cause the velocity to decrease in Figure 7. Figure 8 shows the velocity profile graph against different oscillating parameter. Here, increasing the oscillating parameter will decrease the velocity of the fluid flow. When the plates oscillates, it will cause the velocity of the fluid flow become slower.

Tables 1-3 will shows solutions for skin friction, Sherwood number and Nusselt number against different parameters. The solutions of skin friction, Sherwood and Nusselt are derived from equations (17) - (19). Table 1 shows the Sherwood number with different parameters. From Table 1, increasing the Schmidt number and chemical reaction parameter will cause the Sherwood number to increase. Table 2 shows Nusselt number with different Pr numbers. Increasing the Prandtl number will cause the Nusselt number to increase. Since Nusselt number is a measure of the ratio between heat convection and heat conduction, higher Nusselt number means that the fluid flow have very efficient convection. Table 3 potrays the results of skin friction against different parameters. By increasing the Prandtl number, Schmidt number and chemical reaction parameter, would decrease the skin friction. Meanwhile, for the oscillating parameter, Grashof and mass Grashof number, increasing the parameters would increase the skin friction. All of the solutions satisfy the boundary conditions.

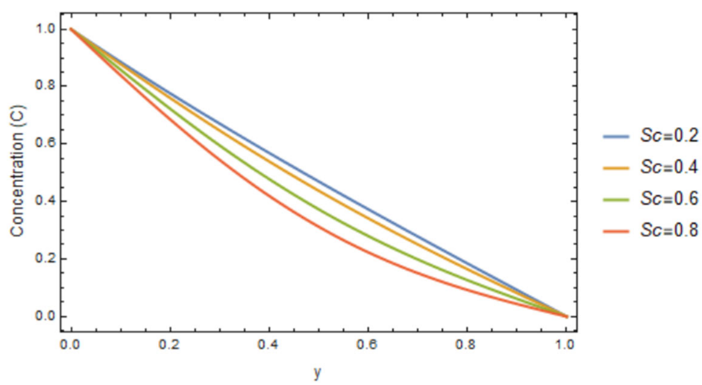

Figure 2. Concentration profile with different Sc when $t = 0.2,\ A_2 = 0.1$.

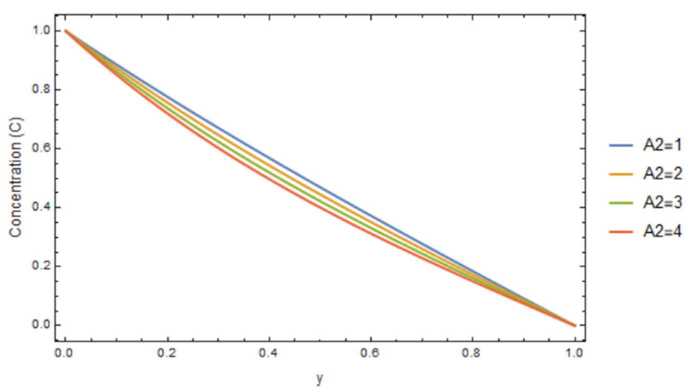

Figure 3. Concentration profile with different A_2 when $t = 0.2,\ Sc = 0.1$.

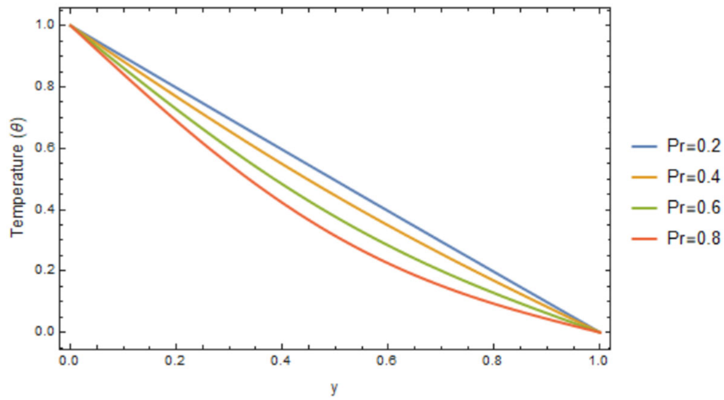

Figure 4. Temperature profile with different Pr when $t = 0.2$.

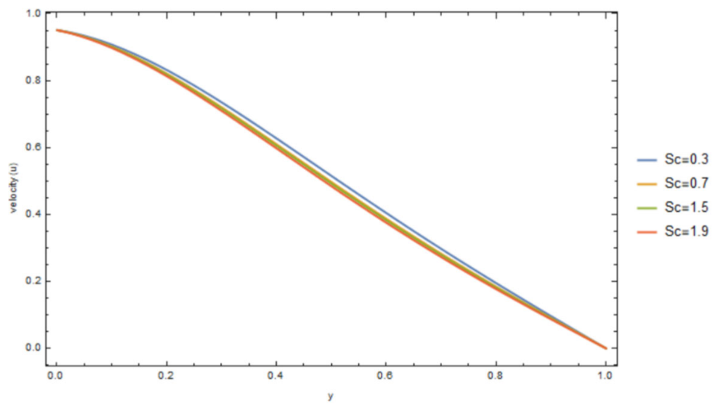

Figure 5. Velocity profile with different Sc when $t = 0.2, Pr = 0.3, Gm = 2, Gr = 2, \omega = \frac{\pi}{2},\ A_2 = 1$.

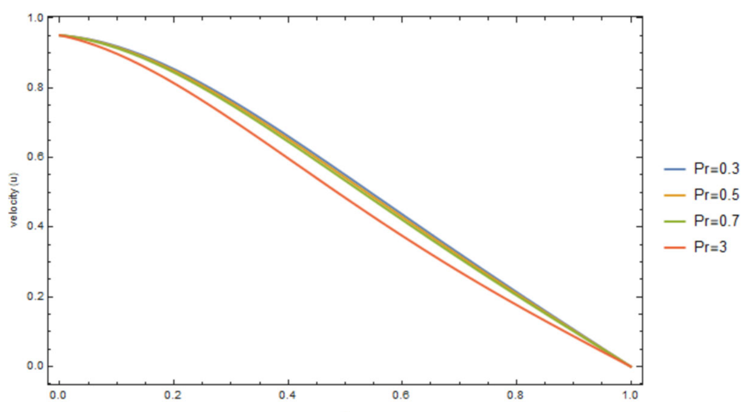

Figure 6. Velocity profile for different Pr when $t = 0.2, Sc = 0.7, Gm = 2, Gr = 2, \omega = \frac{\pi}{2},\ A_2 = 1$.

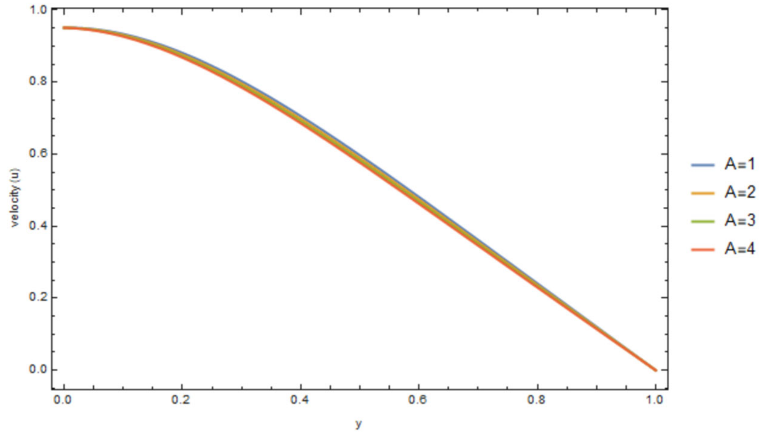

Figure 7. Velocity profile with different A_2 when $t = 0.2, Pr = 0.3,\ Sc = 0.7, Gm = 2, Gr = 2, \omega = \frac{\pi}{2}$.

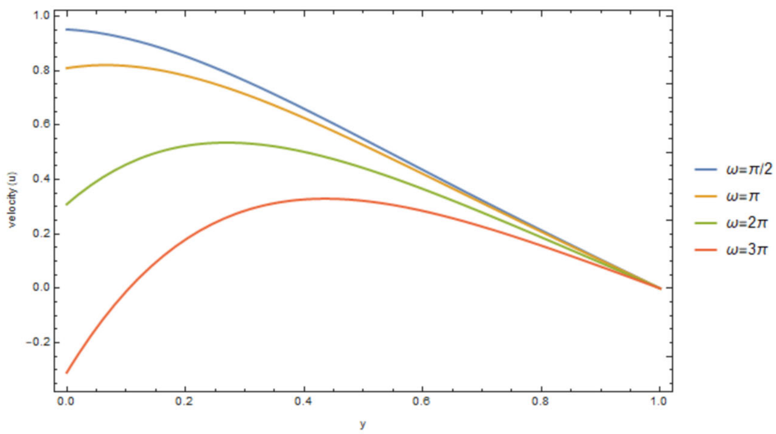

Figure 8. Velocity profile with different ω when $t = 0.2, Sc = 0.7, Pr = 0.3, Gm = 2, Gr = 2,\ A_2 = 1$.

Table 1. Sherwood number against different parameters.

t	Sc	A_2	Sh
0.1	0.3	0.1	1.11280
0.1	0.5	0.1	1.31595
0.1	0.7	0.1	1.52361
0.1	0.3	0.2	1.19814
0.1	0.3	0.3	1.28192

Table 2. Nusselt number with different Pr.

t	Pr	Nu
0.1	0.2	0.9057
0.1	0.4	1.1491
0.1	0.6	1.3854
0.1	0.8	1.5963

Table 3. Skin friction with different parameters.

t	Pr	Sc	Gm	Gr	ω	A_2	τ
0.1	0.3	0.3	3	1	π	1	-0.661287
0.1	0.5	0.3	3	1	π	1	-0.681443
0.1	0.7	0.7	3	1	π	1	-0.752762
0.1	0.3	0.3	3	2	π	1	-0.432377
0.1	0.3	0.3	4	1	π	1	-0.440666
0.1	0.3	0.3	3	1	$\frac{\pi}{2}$	1	-0.834901
0.1	0.3	0.3	3	1	π	3	-0.703939

CONCLUSION

An exact solution to oscillating free convection flows between oscillating parallel plates with chemical reaction and mass diffusion was discussed. The governing equation was reduced to non-dimensional equations, where the solution was solved using Laplace Transform. The solutions were also graphically studied using different parameters. Based on the results, the following conclusions were drawn:

- Increasing chemical reaction parameter would decrease concentration, velocity and skin friction but increase the Sherwood number of the fluid flow.
- Increasing the oscillating parameter would increase the skin friction but decrease the velocity of the fluid flow.
- The solutions to this problem satisfy the boundary conditions.

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