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EFFECT OF MAGNETIC FIELD ON DOUBLE DIFFUSIVE MARANGONI CONVECTION WITH CHEMICAL REACTION IN A SQUARE CAVITY

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ABSTRACT

The effect of chemical reaction in the presence of a magnetic field on the onset of double diffusive Marangoni convection in a square cavity is numerically studied. ADI method together with the SOR technique is used to solve the governing equations. The effect of buoyancy ratio *W*, diffusocapillary ratio *w*, Schmidt number *Sc*, and Hartmann number *Ha*, is investigated. The results show that both the average Nusselt number and the average Sherwood number decrease with the increase in Hartmann number, whereas both the average heat and mass transfer rates increase with the increase in chemical reaction parameter. More over the effect of concentration buoyancy on flow is stronger than the one due to thermal buoyancy

Keywords: Double Diffusion, Chemical Reaction, Magnetic Field, Marangoni, Convection, Cavity

1. INTRODUCTION

There are many physical phenomenon in which buoyancy evolves from both the thermal and concentration diffusion of species contained in the fluid. Atmospheric convection, earth warming, and the removal of contaminant from a solution are some of the examples of such phenomena. Moreover, in the presence of a free surface, thermal and concentration buoyancy can also be induced by the variation of surface tension. Double-diffusive Marangoni convection is the phenomena in which density and surface tension vary with both temperature and concentration gradient. From the view point of engineering, a wide range of such phenomena occurs in geothermal engineering, removal of nuclear waste and electro-chemical processes.

Earlier studies of double diffusive convection and chemical reaction include the works Lee and Lee [1], Vafai et al. [2] and Costa [3]. Jue [5] discussed the aiding and opposing effects of thermosolutal Marangoni Convection in a cavity. Gelfgat and Yoseph [6] showed that the natural convection flow can be suppressed by an externally applied magnetic field. Hossain and Wilson [7] showed that the uniform internal heat generation increases the local heat transfer rate. An investigation of double diffusive convection with chemical reaction around a sphere is also made by Hossain et al. [8]. Hossain et al. [9] also investigated the effect of magnetic field on thermocapillary driven convection flow of a fluid in an enclosure.

It follows that the presence of a chemical reaction can have a significant impact on double-diffusive flow and heat and mass fluxes, particularly when the heat equation is also complemented with internal heat generation, which may occur as a result of a chemical reaction. The application of magnetic field may serve the purpose of maintaining the stability of such kind of fluid flow. The study of magnetic field effect on thermocapillary flow with internal heat generation has already been made by the same authors [9]. The investigation of the buoyancy parameters in the presence of magnetic field, in combined thermocapillary and diffusocapillary flow is now carried out. A detailed description of the model and the solution method is given in the subsequent sections.

2. MATHEMATICAL FORMULATION

Consider the transient double diffusive flow of a Newtonian fluid contained in a square cavity of height *H*. The temperature and mass concentration of right and left vertical walls are kept at $\bar{T}_H, \bar{C}_H$ and $\bar{T}_L, \bar{C}_L$, where $\bar{T}_H > \bar{T}_L,\ \bar{C}_H > \bar{C}_L$. The density ρ of the fluid with temperature and concentration follows the Boussinesq's approximation. The surface tension variation at the fluid surface with temperature and concentration given by (see [5])

$$\begin{aligned}\sigma &= \sigma_0\left[1-\gamma_T\left(\bar{T}-\bar{T}_0\right)-\gamma_C\left(\bar{C}-\bar{C}_0\right)\right]\\ \rho &= \rho_0\left[1-\beta_T\left(\bar{T}-\bar{T}_0\right)-\beta_C\left(\bar{C}-\bar{C}_0\right)\right]\end{aligned} \tag{1}$$

where $\bar{T}_0 = (\bar{T}_H+\bar{T}_L)/2, \bar{C}_0 = (\bar{C}_H+\bar{C}_L)/2$ are reference temperature and concentration. The temperature and concentration coefficients of surface tension and volume expansion are defined as

$$\begin{aligned}\gamma_T &= -\frac{1}{\sigma_0}\frac{\partial\sigma}{\partial\bar{T}},\ \ \gamma_C = -\frac{1}{\sigma_0}\frac{\partial\sigma}{\partial\bar{C}}\\ \beta_T &= -\frac{1}{\rho_0}\frac{\partial\rho}{\partial\bar{T}},\ \ \beta_C = -\frac{1}{\rho_0}\frac{\partial\rho}{\partial\bar{C}}\end{aligned} \tag{2}$$

where $\bar{T}$ and $\bar{C}$ are the temperature and concentration of the fluid. Throughout the discussion, the subscript '0' corresponds to the reference state and the subscripts 'T' and 'C' respectively refer to the thermal and concentration properties. Now further assume that the cavity subject to a uniform magnetic field $\mathbf{B}=B_x e_x+B_y e_y$ of constant magnitude B_0, where e_x and e_y are unit vectors along the coordinate axis, and ξ be the orientation of magnetic field. Let σ_e and φ respectively be the electrical conductivity and electric potential of the fluid, then the electric current density $\mathbf{j}$ and the electromagnetic force $\mathbf{F}$ for electrically non conducting boundaries are given by the relation (see also [9])

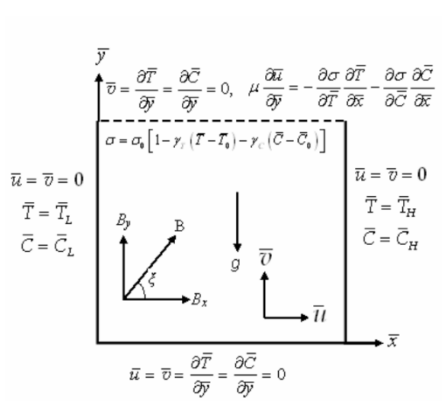

Fig 1. Physical model of the problem

$$\begin{aligned}\mathbf{J} &= \sigma_e(\mathbf{V}\times\mathbf{B})\\ \mathbf{F} &= \sigma_e(\mathbf{V}\times\mathbf{B})\times\mathbf{B}\end{aligned} \tag{3}$$

Where $\mathbf{V} = \bar{u}e_x + \bar{v}e_y$ the velocity vector is in two dimensions in which $\bar{u}$ and $\bar{v}$ are the velocity components of the fluid along the coordinate axes. The flow configuration is shown in figure 1. Here the symbol 'g' stands for the acceleration due to gravity. Now the stream vorticity formulation of the governing equations in terms of non dimensional variables is given by

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2} = -\omega \tag{4}$$

$$\begin{aligned}&\frac{\partial\omega}{\partial t}+u\frac{\partial\omega}{\partial x}+v\frac{\partial\omega}{\partial y} = \nabla^2\omega+\frac{Gr}{2}\left[(1-W)\frac{\partial\theta}{\partial x}+W\frac{\partial\phi}{\partial x}\right]\\ &+Ha^2\left[\sin\xi\cos\xi\left(\frac{\partial u}{\partial x}-\frac{\partial v}{\partial y}\right)+\left(\sin^2\xi\frac{\partial u}{\partial y}-\cos^2\xi\frac{\partial v}{\partial x}\right)\right]\end{aligned} \tag{5}$$

$$\frac{\partial\theta}{\partial t}+u\frac{\partial\theta}{\partial x}+v\frac{\partial\theta}{\partial y} = \frac{1}{\Pr}\left(\nabla^2\theta+\lambda\right) \tag{6}$$

$$\frac{\partial\phi}{\partial t}+u\frac{\partial\phi}{\partial x}+v\frac{\partial\phi}{\partial y} = \frac{1}{Sc}\nabla^2\phi-\gamma\phi \tag{7}$$

Where

$$\begin{aligned}&Ha^2 = \frac{\sigma_e B_0^2 H^2}{\mu},\ Gr_T = \frac{g\beta_T(\bar{T}_H-\bar{T}_L)H^3}{\nu^2},\\ &Gr_C = \frac{g\beta_C(\bar{C}_H-\bar{C}_L)H^3}{\nu^2},\ Gr = Gr_T+Gr_C,\\ &W = \frac{N}{1+N},\ N = \frac{\beta_C\Delta\bar{C}}{\beta_T\Delta\bar{T}},\ \Pr = \frac{\nu}{\alpha},\\ &Gr_I = \frac{g\beta_T SH^5}{k\nu^2},\ \lambda = \frac{Gr_I}{Gr_T},\ Sc = \frac{\nu}{D},\ \gamma = \frac{KH^2}{\nu}\end{aligned} \tag{8}$$

Here *Ha* is the Hartmann number, Gr_T and Gr_C are respectively the Grashof numbers due to thermal and solutal buoyancies, *Gr* is the total Grashof number, *N* is the ratio of concentration and thermal buoyancies, W is a parameter that shows relative impact of concentration and thermal buoyancies. Obviously W=0 represents the case of only thermal buoyancy, whereas W=1 represents only the solutal buoyancy effects. Pr is the Prandtl number, Gr_I is the Grashof number due to internal heat in which *S* is the volumetric heat generation rate. The constant λ is the heat generation parameter, *Sc* is Schmidt number, which is the ratio of viscous and concentration diffusivities. Fineally γ is the dimensionless chemical reaction parametr, in which *K* is the rate of chemical reaction. The dimensionless form was obtained by defining the following transformations

$$x=\frac{\bar{x}}{H},\ y=\frac{\bar{y}}{H},\ \psi=\frac{\bar{\psi}}{\nu},t=\frac{\bar{t}\,\nu}{H^2},$$
$$u=\frac{\bar{u}H}{\nu},\ v=\frac{\bar{v}H}{\nu},\ p=\frac{\bar{p}H^2}{\rho\nu^2},\ \omega=\frac{\bar{\omega}H^2}{\nu}, \qquad (9)$$
$$\theta=\frac{\bar{T}-\bar{T}_0}{\bar{T}_H-\bar{T}_0},\ \phi=\frac{\bar{C}-\bar{C}_0}{\bar{C}_H-\bar{C}_0}$$

whereas the bar represents the variables in dimensional form. The stream vorticity formulation was given by

$$\bar{\omega}=\frac{\partial\bar{v}}{\partial\bar{x}}-\frac{\partial\bar{u}}{\partial\bar{y}},\ \bar{v}=-\frac{\partial\bar{\psi}}{\partial\bar{x}},\ \bar{u}=\frac{\partial\bar{\psi}}{\partial\bar{y}} \qquad (10)$$

Using the transformations given in (9), the boundary conditions are given by

$t<0$, $u=v=\psi=\theta=\omega=\varnothing=0$, $0\le x\le 1$, $0\le y\le 1$
$t\ge 0$
$u=v=\psi=0$, $\theta=\varnothing=-1$, $\omega=\partial v/\partial x$, $x=0$, $0\le y\le 1$
$u=v=\psi=0$, $\theta=\varnothing=1$, $\omega=-\partial v/\partial x$, $x=0$, $0\le y\le 1$ (11)
$u=v=\psi=0$, $\partial\theta/\partial y=\partial\varnothing/\partial y=0$,
$\omega=-\partial u/\partial y$, $y=0$, $0\le x\le 1$

The boundary conditions at the free surface become

$$\omega=\frac{\partial u}{\partial y}=-\frac{Ma}{2\Pr}\left[(1-w)\frac{\partial\theta}{\partial x}+w\frac{\partial\phi}{\partial x}\right], \qquad (12)$$
$$v=\frac{\partial\theta}{\partial y}=\frac{\partial\phi}{\partial y}=0,\ y=1,\ 0\le x\le 1$$

Where

$$Ma_T=\left.\frac{\partial\sigma}{\partial\bar{T}}\right|_C\frac{\left(\bar{T}_H-\bar{T}_L\right)H}{\alpha\mu},\quad Ma_C=\left.\frac{\partial\sigma}{\partial\bar{C}}\right|_T\frac{\left(\bar{C}_H-\bar{C}_L\right)H}{\alpha\mu},$$
$$Ma=Ma_T+Ma_C,\quad r=\frac{\left.\frac{\partial\sigma}{\partial\bar{C}}\right|_T\left(\bar{C}_H-\bar{C}_L\right)}{\left.\frac{\partial\sigma}{\partial\bar{T}}\right|_C\left(\bar{T}_H-\bar{T}_L\right)},\quad w=\frac{r}{1+r} \qquad (13)$$

are respectively the thermal Marangoni number at constant concentration Ma_T, the concentration Marangoni number at constant temperature Ma_C, whereas Ma is the total Marangoni number, r is a dimensionless parameter that defines the relative impact of solutal and thermal Marangoni numbers, and w defines the relative strength of thermal and solutal Marangoni effects on the free surface.(8). For w=0, only thermocapillary effect comes into account whereas w=1 shows the dominance of diffusocapillary effect. We now define the local Nusselt number and local Sherwood number in dimensionless form, along the wall at higher temperature and concentration level by the relation

$$Nu=-\left(\frac{\partial\theta}{\partial x}\right)_{x=1},\qquad Sh=-\left(\frac{\partial\phi}{\partial x}\right)_{x=1} \qquad (14)$$

where x is the coordinate perpendicular to the wall. Now the average Nusselt number and average Sherwood number in dimensionless form, along the right wall is given by

$$\bar{N}u=\int_0^1 Nu\,dy,\qquad \bar{S}h=\int_0^1 Sh\,dy \qquad (15)$$

where dy is the element of length H along the right wall. Equations (4) - (7) along with boundary conditions given by equations (11) and (12) are solved numerically to study the flow properties of the proposed physical model.

3. METHOD OF SOLUTION

The stream function equation (4) is solved using the SOR method with residual tolerance of order 10^{-5}. From these values of stream function, the velocity at each time step is updated using the non dimensional form of equation (10). For transient equations (5), (6) and (7), given the values of flow variables at any time step, we used the ADI method to find the values of these variables at the next time step. FTCS descretization is used for the unsteady, diffusion and source terms in the ADI method. For non linear terms, we used the second upwind differencing technique. For the entire computation we take H=1. The time step for the entire computation is taken to be 10^{-6} (see also [4]). For convergence, it was considered that for any variable F

$$\left|\frac{F_{i,j}^{m+1}-F_{i,j}^{m}}{F_{i,j}^{m}}\right|<10^{-6}$$

where i,j is the grid location along the coordinate axes and the superscript m refers to the number of time step. Intel 1.83 G.Hz Core 2 Duo processing machine is used for the entire computation.

4. RESULTS AND DISCUSSION

We have considered the interaction of magnetic field and double-diffusive Marangoni convection in a square cavity, in the presence of internal heat generation and chemical reaction. A temperature and concentration difference is maintained at the side walls. The results are presented in terms of streamlines, isohalines and heat and mass transfer rates for different values of physical parameters.

4.1 The Effect of Hartmann number

An externally applied magnetic field can be used to suppress the instability and reduce the convective flow up to a desired level of practical interest (see [6] and [9]). Similar effects are observed in the presence of mass transfer. That is, for certain values of chemical reaction parameter and Schmidt number, the average Nusselt number and average Sherwood number both decrease with effect of increasing strength of magnetic field. These results are shown in Figure 2 at Gr=2×10^6, Pr=0.054, Ma=4000, ξ=0^o, λ=γ=1, Sc=10, W=w=0.5 for different values of Hartmann number Ha. In figure 2 (a), the decrease in the heat transfer rate was now expected, however due to suppression of flow instability, the mass transfer rate also decreases as shown in figure 2 (b).

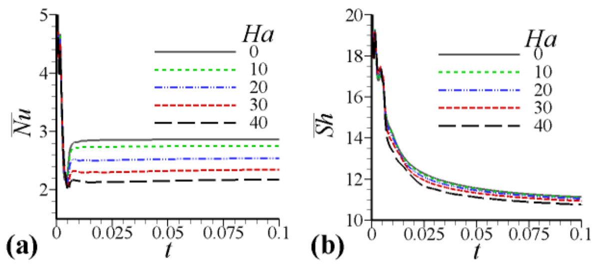

Fig 2. (a) Average Nusselt number (b) average Sherwood number against time at Gr=2×10^6, Pr=0.054, Ma=4000, ξ=0^o, λ=γ=1, Sc=10, W=w=0.5 for different values of Hartmann number Ha.

4.2 Effect of Chemical Reaction Parameter

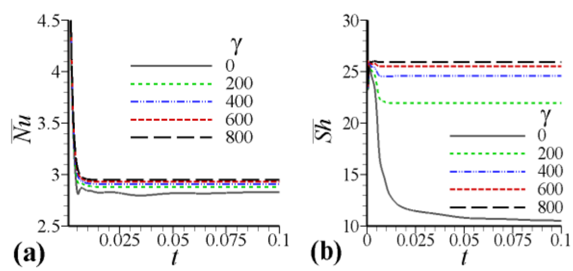

Fig 3. Time evolution of (a) Average Nusselt number (b) average Sherwood number at Gr=10^6, Pr=0.054, Ma=5000, Ha=50, ξ=0^o, λ=2, Sc=5, W=w=0.5 for different values chemical reaction parameter γ.

Figure 3 (a) shows the results of average Nusselt, and figure 3 (b) shows the average Sherwood number against time at Gr=10^6, Pr=0.054, Ma=5000, Ha=50, ξ=0^o, Sc=5, λ=2, W=w=0.5 for different values of chemical reaction parameter γ. Both heat and mass transfer rates increase for increasing values of γ. The increase in Sherwood number may be due to the reason that the increase of the values of γ implies more impact of species concentration on momentum and buoyancy. However, as can be seen from equation (6), the heat equation does not directly depend upon the species concentration; the increase in heat transfer is not much pronounced.

4.3 The Effect of *W*

Figure 4 shows the selected results of steady state pattern of streamlines at Gr=5×10^5, Pr=0.054, Ma=2000, Ha=20, ξ=0^o, Sc=γ=λ=5, w=0.5 for W=0,0.5,1.0 respectively. The cell adjacent to top surface in Figure 4(a) indicates the presence of counteracting mechanism due to thermocapillary effects on buoyancy at W=0. Figure 4(b) shows that the flow in the buoyancy cell decreases due to opposing flow induced by mass transfer in this flow at W=0.5. However at W=1.0, the concentration buoyancy is solely responsible for the counteracting flow and the flow in the buoyancy cell further decreases, as shown in Figure 4(c). Comparing the strength of Marangoni cell in Figures 4 (a)-(c), we discern that the Marangoni effects that appear due to concentration are more pronounced than that of thermal effects. This suggests that the contribution of mass diffusion is much pronounced, as compared to that of thermal buoyancy. This might well be attributed to the presence of chemical reaction parameter, which adds to the instability of flow mechanism in the diffusion

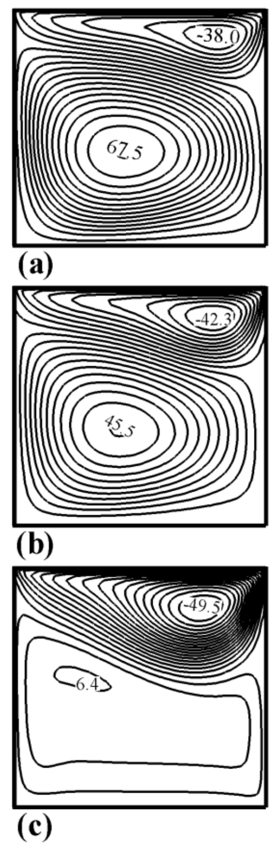

Fig 4. Steady state pattern of streamlines at Gr=5×10^5,Pr=0.054, Ma=2000, Ha=20, ξ=0^o, Sc=γ=λ=5, w=0.5 for (a) W=0 (b) W=0.5 (c) W=1

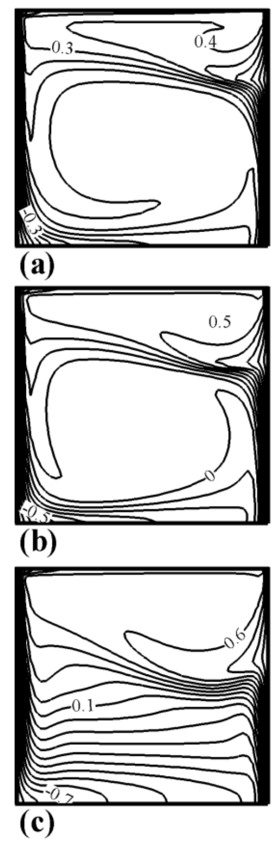

Fig 5. Steady state pattern of isohalines at Gr=5×10^5,Pr=0.054, Ma=2000, Ha=20, ξ=0^o, Sc=γ=λ=5, w=0.5 for (a) W=0 (b) W=0.5 (c) W=1

equation, and is ultimately responsible for the reduction of the flow due to buoyancy. Figure 5 (a)-(c) represent the isolines of concentration at Gr=5×10^5, Pr=0.054, Ma=2000, Ha=20, ξ=0^o, Sc=γ=λ=5, w=0.5 for W=0,0.5,1.0 respectively. Comparing figure 4 and 5, we can see that in Figure 5 (a) and (b), there is an empty region of low concentration isohalines in the lower half where the buoyancy cell was concentrated in the streamlines. However, the isohalines are evenly distributed in Figure 5 (c), in that region because flow is very low. This suggests that the stronger the buoyancy cell, the weaker the iso-concentration lines in this region. Figure 6 now shows the time evolution of Nusselt number and Sherwood number of the right wall at Gr=5×10^5, Pr=0.054, Ma=2000, Ha=20, ξ=0^o, w=0.5, Sc=γ=λ=5 for different values of W. Increase in heat transfer rate occurs from 0.33 to 0.98 due to increase in concentration buoyancy. However average Sherwood number decreases since the concentration of isolines close to the sidewalls decreases.

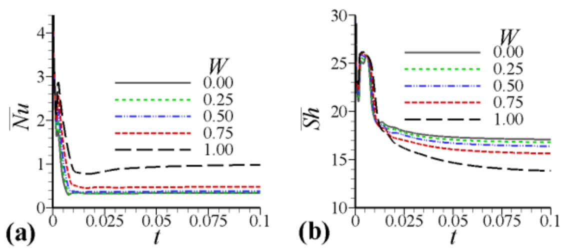

Fig 6. (a) Average Nusselt number (b) average Sherwood number against time at Gr=5×10^5, Pr=0.054, Ma=2000, Ha=20, ξ=0^o, Sc=γ=λ=5, w=0.5 for different values of W

4.4 The Effect of Schmidt number

The phenomenon of Marangoni convection is more common in liquid metals. It is due to this reason that we are considering the Prandtl number as low as 0.054. Such kind of materials has generally high viscous diffusivity. Therefore the heat and mass transfer is studied Gr=4×10^5, Pr=0.054, Ma=4000, Ha=40, ξ=0^o, λ=γ=5, W=w=0.5 for the values of Schmidt number 25≤ Sc≤100, given by figure 7 (a) and 7 (b) respectively. The increase in the value of Schmidt number decrease the concentration diffusion, which slightly reduces the flow and thus heat transfer, whereas the increase in diffusive convection causes mass transfer rate to increase. However both these changes become less significant for increasing values of Schmidt number, rather both the Nusselt number and the Sherwood number nearly remain unchanged for Sc>100.

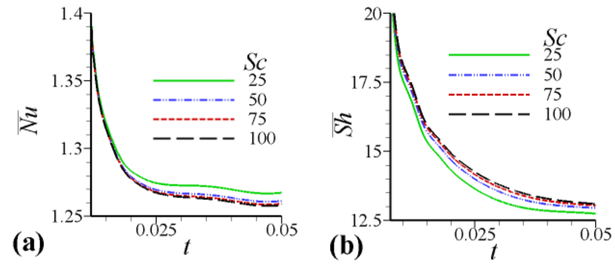

Fig 7. (a) Average heat transfer (b) average mass transfer rate at Gr=4×10^5, Pr=0.054, Ma=4000, Ha=40, ξ=0^o, γ=λ=5, W=w=0.5 for different values of Sc

5. CONCLUSION

An investigation of the effect of magnetic field on double diffusive Marangoni convection in a cavity has been carried out. The vertical walls of the cavity were subject to horizontal temperature and concentration gradients. The results reveal that the concentration buoyancy has a stronger impact on the flow strength, compare to the thermal buoyancy, due to the presence of chemical reaction. Both the heat and mass transfer rate decrease with the increase in Hartmann number, whereas the heat and mass transfer rate increases with the increase in chemical reaction parameter. It should be noted here that this decrease in heat transfer is subject to the values of parameters chosen. That is for large internal heat generation and large chemical reaction parameter, the result would not be the same. That is, the heat transfer will not always decrease with the increase in Hartmann number and its orientation, for all values of internal heat generation and chemical reaction parameters. Thus a detailed investigation will further be made to assume these parameter values for which the magnetic field suppresses the flow in such configurations.

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7. NOMENCLATURE

Symbol	Meaning	Unit
B	uniform magnetic field vector	Tesla
$\bar{C}$	mass concentration	Kgm^{-3}
D	Concentration diffusivity	m^2s^{-1}
F	Electromagnetic force	N
G	acceleration due to gravity	ms^{-2}
Gr	total Grashof number	
H	height of the cavity	m
Ha	Hartmann number	
J	current density	Am^{-2}
K	chemical reaction rate	s^{-1}
K	thermal conductivity	$Wm^{-1}K^{-1}$
Ma	total Marangoni number	
$\overline{Nu}$	Average Nusselt number	
$\bar{p}$	Fluid pressure	Pa
Pr	Prandtl number	
Sc	Schmidt number	
$\overline{Sh}$	Average Sherwood number	
$\bar{T}$	Dimensional temperature	K
$\bar{t}$	Dimensional time	s
$\bar{u}, \bar{v}$	Velocity components	ms^{-1}
W	Solutal buoyancy parameter	
$\bar{x}, \bar{y}$	Dimensional coordinate axes	m
A	Thermal diffusivity	m^2s^{-1}
β_T	thermal expansion coefficient	K^{-1}
β_C	concentration expansion coefficient	m^3Kg^{-1}
γ_C	concentration coefficient of surface tension	m^3Kg^{-1}
γ_T	temperature coefficient of surface tension	K^{-1}
μ	dynamic viscosity	$Kg\ m^{-1}\ s^{-1}$
N	kinematic viscosity	m^2s^{-1}
P	density of fluid	Kgm^{-3}
Σ	surface tension	Nm^{-1}
σ_e	Electrical conductivity	$\Omega^{-1}m^{-1}$

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