ISSN (Online) 2456 -1304

International Journal of Science, Engineering and Management (IJSEM)
Vol 2, Issue 4, April 2017

Effect of Chemical Reaction on Convective Instability in a Ferromagnetic Liquid

[1] Dr. Annamma Abraham, [2] Sreelakshmi T K, [3] Dr. Chethan A S, [4] Dr. Jojy Joseph Idicula
[1][2][3][4] BMS Institute of Technology & Management, Bengaluru, IndiaMIT College of Food Technology, Pune

***Abstract*— Convective instability in fluids arises due to thermo-mechanical interactions induced by externally applied temperature gradients. The problem of Rayleigh-Benard convection in a chemically reacting ferromagnetic fluid layer permeated by a uniform vertically magnetic field is investigated. A linear stability analysis is performed. The fluid is assumed to be undergoing zero-order exothermic reactions. The horizontal ferromagnetic fluid layer is cooled from the upper boundary while two different thermal boundary conditions are imposed at the lower boundary i.e. isothermal wall and an adiabatic wall. The resulting eigenvalue problems will be solved approximately using a single-term Galerkin method that gives the critical Rayleigh number and the associate wave number at a given Frank-Kamennetskii number. It is shown that the critical Rayleigh number decreases as the value of FK is increased. Thus, chemical reaction in a horizontal ferrofluid layer enhances instability. This is reasonable because chemical reaction leads to non-linear temperature distribution. The onset of convection is delayed in a chemically reacting ferrofluid as compared to the case of a chemically reacting liquid. The problem has relevance in many ferromagnetic fluid applications wherein regulation of thermal convection is called for.**

***Key words:* Chemical reaction, convective instability, ferromagnetic liquid, Galerkin method**

INTRODUCTION

Natural convection in a horizontal Newtonian fluid heated from below and cooled from above, called Rayleigh-Benard (RB) convection, has received considerable attention owing to its applications in diverse areas. The study of it is well understood and documented in the works of Chandrasekhar [1], Turner [2], Drazin and Reid [3] and Platten and Legros [4]. Convective instability in fluids arises due to thermo-mechanical interactions induced by externally applied temperature gradients. The most familiar thermo-mechanical interaction is buoyancy induced convection also referred to as the Rayleigh-Benard convection where the driving force is the body force. The problem of the onset of convective instability in a horizontal layer of fluid heated from below has its origin in the experimental observations of Benard [5]. Lord Rayleigh [6] was the first person to give an analytical treatment of the problem aimed at determining the conditions delineating the break down of the basic state. As a consequence of these works the thermal instability problem is now referred to as Rayleigh-Benard convection problems. For a chemically reacting ferromagnetic fluid a thermo-mechanical interaction is predicted in the presence of a uniform vertical magnetic field provided the magnetisation is a function of temperature and magnetic filed and a temperature gradient is established across the fluid layer.

The Rayleigh-Benard convection in ferromagnetic fluids has been considered by Finlayson [7], Rosensweig [8], Rudraiah and Shekar [9], Siddheshwar [10], Qin and Kaloni [11], Annamma Abraham [12], P. G. Siddheshwar and Annamma Abraham [13,14], Mustafa Alsaady et al [15].

Kordylewski and Krajewski [16] were the first to perform a stability analysis based on Darcy's law with the Boussinesq approximation and a zero-order exothermic reaction. Numerical studies of systems under similar conditions were carried out by Vilijoen and Hlavacek [17] and Subramanian and Balakotaiah [18]. A linear stability analysis to study the onset of convective instability in a horizontal inert porous layer saturated with a fluid undergoing a zero-order exothermic chemical reaction was carried out by Malashetty et al. [19]. Mubeen et al. [20] investigated the problem of onset of convective instability in a horizontal inert porous layer saturated with a couple-stress fluid subject to zero-order chemical reaction.

In the present paper, we investigate the effect of non-uniform basic temperature gradient on the onset of convection driven by buoyancy forces in a chemically reacting ferromagnetic liquid. We assume that the fluid is undergoing a zero-order exothermic chemical reaction. A linear stability analysis is performed and the resulting eigenvalue problem is solved by the Galerkin technique.

IFERP
connecting engineers... developing research

ISSN (Online) 2456 -1304

International Journal of Science, Engineering and Management (IJSEM)
Vol 2, Issue 4, April 2017

II. MATHEMATICAL FORMULATION

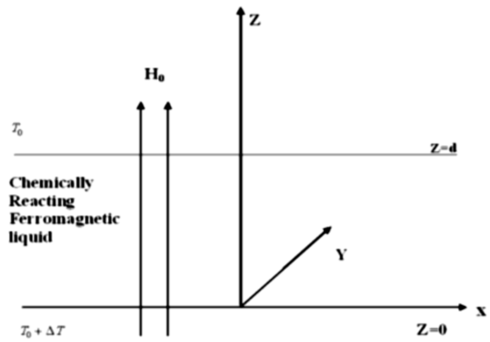

Fig. 1 : Schematic of the Rayleigh Benard situation for a chemically reacting ferromagnetic liquid

We consider a horizontal layer of chemically reacting ferromagnetic liquid of finite thickness bounded between $z = 0$ and $z = d$ (with z-axis directed vertically upward) and of infinite extent in the horizontal xy plane. We assume a temperature drop ΔT across the boundaries. Provided ΔT is not too large we can invoke the Boussinesq approximation. The Navier–Stokes Eqs. describing flow in an incompressible ferromagnetic fluid are:

$$\nabla.\vec{q} = 0 \quad (1)$$

$$\rho_0 \frac{D\vec{q}}{Dt} = -\nabla p + \rho\vec{g} + \nabla.\left(\vec{H}\vec{B}\right) + \eta\nabla^2\vec{q} \quad (2)$$

$$\left[\rho_0 C_{V,H} - \mu_o H.\left(\frac{\partial \bar{M}}{\partial T}\right)_{V,H}\right]\frac{dT}{dt} + \mu_0 T\left(\frac{\partial \bar{M}}{\partial T}\right)_{V,H}\frac{d\bar{H}}{dt} = K_1\nabla^2 T + QBY_F^a Y_o^b \exp\left(-\frac{E}{RT}\right) \quad (3)$$

$$\rho = \rho_0\left[1 - \alpha\left(T - T_0\right)\right] \quad (4)$$

In the above equations, $\vec{q}$ is the velocity, T is the temperature, p is the pressure, n is the shear kinematic viscosity co-efficient, α is the co-efficient of thermal expansion, ρ is the density, ρ_0 is the density of the fluid at temperature $T=T_0$, K_1 is the thermal conductivity, μ_0 is the magnetic permeability , C_{VH} is the specific heat at constant volume and constant magnetic field, $\vec{g}$ is the acceleration due to gravity, Q is the product of the heat of reaction, a preexponential factor and reactant concentration, E is the activation energy, R is the universal gas constant, $\vec{M}$ is the magnetisation, $\vec{B}$ is the magnetic induction and $\vec{H}$ is the magnetic field. Maxwell's equations, simplified for a non conducting fluid with no displacement current become

$$\nabla.\vec{B} = 0 \quad , \quad \nabla \times \vec{H} = 0 \quad (5)$$

and

$$\vec{B} = \mu_0\left(\vec{M} + \vec{H}\right) \quad (6)$$

We assume that the magnetisation $\vec{M}$ is aligned with the magnetic field, but allow a dependence on the magnitude of the magnetic field as well as the temperature

$$\vec{M} = \frac{\vec{H}}{H} M(H,T) \quad (7)$$

The magnetic equation of state is linearized about the magnetic field H_0 and an average temperature T_0 to give

$$M = M_0 + \chi(H - H_0) - K_m(T - T_0), \quad (8)$$

where χ is the magnetic susceptibility and K_m is the pyromagnetic coefficient.

Basic state:
The basic state is one in which

$$\vec{q}_b = (0,0,0,), \ p = p_b(z), \ \rho = \rho_b(z), \ T_b = T_b(z), \ \vec{H}_b = H_b\hat{k}, \ \vec{M}_b = M_b\hat{k}. \quad (9)$$

The quiescent state solutions are therefore given by the following equations:

$$\nabla p_b = \rho_b\vec{g} + \left(\vec{B}_b.\nabla\right)\vec{H}_b \quad (10)$$

$$K_1\frac{d^2T_b}{dz^2} + Ce^{T_b} = 0 \quad (11)$$

$$\vec{H}_b = \left[H_0 - \frac{K_m}{(1+\chi)}\left(\frac{\Delta T}{d}\right)z\right]\hat{k}, \quad (12)$$

$$\vec{M}_b = \left[M_0 + \frac{K_m}{(1+\chi)}\left(\frac{\Delta T}{d}\right)z\right]\hat{k} \quad (13)$$

where $C = QBY_F^a Y_o^b \exp\left(-\frac{E}{RT}\right)$

$$\exp\left(-\frac{E}{RT}\right)=\exp\left(\frac{-ET_c-ET+ET_c}{RT_c^2}\right)$$

Where $\theta=\frac{T-T_c}{T_r}$ and $T_r=\frac{RT_c^2}{E}$

$$=\exp\left(\frac{-E}{RT_c}\right)\exp(-\theta)$$

Where T_C is temperature of cold boundary

Therefore C = $QBY_F^aY_o^b\ \exp\left(\frac{-E}{RT_c}\right)\exp(-\theta)$

$$C\exp(-\theta)\ =\ QBY_F^aY_o^b\exp\left(\frac{-E}{RT_c}\right)$$

Let the basic state be slightly perturbed by an Infinitesimal perturbation, indicated by primes. We now have,

$$\vec{q}=\vec{q}_b+\vec{q}\,',p=p_b+p',\rho=\rho_b+\rho',$$
$$T=T_b+\theta,\vec{H}=H_b\hat{k}+\vec{H}',\vec{M}=M_b\hat{k}+\vec{M}'. \tag{14}$$

Since the effect of ferrite suspended particles is to stabilize the system, the principle of exchange of stability can be assumed to be valid and hence we consider only stationary convection. Substituting equations (14) into equation (1) to (8), using the basic state equations, neglecting the nonlinear terms and operating curl twice on the resulting momentum equation we get

$$\left(1+\frac{M_0}{H_0}\right)\nabla_1^2\phi+(1+\chi)\frac{\partial^2\phi}{\partial z^2}-K_m\frac{\partial T}{\partial z}=0\ , \tag{15}$$

$$\left(\frac{\partial}{\partial t}-\upsilon\nabla^2\right)\nabla^2 w=\alpha g\nabla_1^2 T-\frac{\mu_0K_m}{\rho_0}\left(\frac{\Delta T}{d}\right)\frac{\partial(\nabla_1^2\phi)}{\partial z}+\frac{\mu_0K_m^2}{\rho_0(1+\chi)}\left(\frac{\Delta T}{d}\right)\nabla_1^2 T \tag{16}$$

$$\left[\rho_0C_{V,H}-\mu_0K_mH_b\right]\left(\frac{\partial T}{\partial t}+w\frac{\partial T_b}{\partial z}\right)-\mu_0K_mT_b\left(\frac{\partial H_3'}{\partial t}+w\frac{\partial H_b}{\partial z}\right)$$
$$=K_1\nabla^2(T_b+\theta)+C\exp(T_b+\theta) \tag{17}$$

where $H'=\nabla\phi'$, $\gamma=\frac{\mu}{\rho_0}$ = Kinematic viscosity,

$$\rho_0C_0=\rho_0C_{V,H}+\mu_0K_mH_0$$

According to the normal mode analysis, convective motion is assumed to exhibit horizontal periodicity [1]. Thus the perturbed quantities can be expressed as follows:

$$\left[w,T,\phi\right]=\left[W(z),T(z),\phi(z)\right]\exp\left[\sigma\ t+i(lx+my)\right] \tag{18}$$

$$\left.\begin{aligned}
&k^2=l^2+m^2\\
&\nabla^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}=-l^2-m^2+D^2=D^2-k^2\\
&\nabla_1^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}=-l^2-m^2=-k^2
\end{aligned}\right\} \tag{19}$$

Substituting (18) and (19) in (15) to (17) we get,

$$(1+\chi)D^2\phi-\left(1+\frac{M_0}{H_0}\right)k^2\phi-k_mDT\ =0 \tag{20}$$

$$\rho_0\,\sigma\left(D^2-k^2\right)w=\frac{\mu_0\,K_m}{(1+\chi)}\left(\frac{\Delta T}{d}\right)\left[(1+\chi\ )D\phi-K_m\,T\right]k^2$$
$$-\rho_0\,\alpha\,gk^2\,T+\mu\left(D^2-k^2\right)^2w \tag{21}$$

$$\left[\rho_0C_0-\frac{\mu_0K_m^2}{(1+\chi)}\left(\frac{\Delta T}{d}\right)z\right]\sigma t-\rho_0C_0w\left(\frac{\Delta T}{d}\right)-\mu_0K_m\left[T_0-\frac{\Delta T}{d}z\right]\sigma D\phi$$
$$+\frac{\mu_0K_m^2T_0}{(1+\chi)}\left(\frac{\Delta T}{d}\right)w=K_1\left(D^2-k^2\right)T+C(\exp T_b)T \tag{22}$$

The linearised equations (20) to (22) are non dimensionalized using the following definitions:

$$\left(x^*,y^*,z^*\right)=\left(\frac{x}{d},\frac{y}{d},\frac{z}{d}\right),T^*=\frac{\rho_0C_0\alpha gd^3}{\gamma K_1R},$$
$$\phi^*=\frac{\phi}{\left(\frac{\gamma K_mK_1R}{\rho_0C_0(1+\chi)\alpha gd^2}\right)},\sigma^*=\frac{\sigma}{\left(\frac{K_1}{\rho_0C_0d^2}\right)}$$
$$T_b^*=\frac{T_b}{\left(\frac{E}{RT_c^2}\right)},\qquad w^*=\frac{w}{\left(\frac{K_1}{\rho_0C_0d}\right)}$$
$$\left(a^*\right)^2=k^2d^2,\quad D^*=Dd \tag{23}$$

Using equation (23) in equations (20) to (22) we obtain (after suppressing the asterisks) the equations in the following dimensionless form

$$\left(D^2-a^2\right)^2 w - Ra\left(1+M_1\right)a^2 T + Ra\, M_1 a^2 D\phi = 0 \tag{24}$$

$$D^2\phi - M_3 a^2\phi - DT = 0 \tag{25}$$

$$\left(D^2-a^2\right)T + FK\exp\left(\theta_b\right)T = w\frac{d\theta_b}{dz} \tag{26}$$

where the non – dimensional parameters are the Frank-Kamennetskii number, Rayleigh number and magnetization parameters given respectively by

$$FK = \frac{Cd^2}{K_1}\left(\frac{E}{RT_c^2}\right), \qquad Ra = \frac{\rho_0 C_0\,\alpha\, g\,\Delta T\, d^{\,3}}{\nu\, K_1}$$

$$M_1 = \frac{\mu_0 K_m^2 \Delta T}{(1+\chi)\alpha\, g\rho_0 d}, \qquad M_3 = \frac{\left(1+\dfrac{M_0}{H_0}\right)}{(1+\chi)}$$

III. APPLICATION OF GALERKIN METHOD

We use the single term Galerkin expansion in solving the eigenvalue equations (24) to (26) that gives general results for the Eigen value of the problem, using simple trial functions for the lowest Eigen value. By choosing suitable trial functions for velocity, temperature perturbations and electric potential that satisfy some of the given boundary conditions, but may not exactly satisfy the differential equations. This results in residuals when the trial functions are substituted into the differential equations. Multiplying equation (24) by W, Equation (26) by T and equation (25) by ∅ and integrating the resulting equations by parts with respect to z from 0 to 1, and taking $W=AW_1$, $T=BT_1$ and $\emptyset = C\,\emptyset 1$ in which A, B and C are constants and W_1, T_1 and $\emptyset_1$ are trial functions, yields the following equation for the eigen value.

$$Ra = \frac{\left\{\left\langle W_1 D^4 W_1\right\rangle - 2a^2\left\langle W_1 D^2 W_1\right\rangle + a^4\left\langle W_1^2\right\rangle\right\}A}{a^2\left\{\left(1+M_1\right)\left\langle W_1 T_1\right\rangle B - M_1\left\langle W_1 D\phi_1\right\rangle C\right\}} \tag{27}$$

where

$$B = \frac{AY}{\left\langle T_1 D^2 T_1 - a^2 T_1^2 + \dfrac{X}{2}\right\rangle}, \quad X = 2FK\left\langle e^{\theta_b} T_1^2\right\rangle, \quad Y = \left\langle W_1 T_1 \frac{d\theta_b}{dz}\right\rangle$$

$$C = \frac{B\left\langle \phi_1 D T_1\right\rangle}{\left\{\left\langle \phi_1 D^2 \phi_1\right\rangle - a^2 M_3\left\langle \phi_1^2\right\rangle\right\}}$$

In the above expression the angular bracket < > denotes the integration with respect to z from 0 to 1. The following trial functions

CASE1: ISOTHERMAL BOUNDARY CONDITIONS

$$W_1 = T_1 = D\phi_1 = 0 \; at\; z = 0,1$$

Choose the trial functions as

$$W_1 = \sin\pi z,\; T_1 = \sin\pi z,\; \phi_1 = \frac{1}{\pi}\cos\pi z$$

Then,

$$Ra = -\frac{\left(\pi^2+a^2\right)^2\left\langle \pi^2+a^2-X\right\rangle\left(\pi^2+a^2M_3\right)}{2a^2Y\left\{\left(1+M_1\right)\left(\pi^2+a^2M_3\right)-M_1\pi^2\right\}} \tag{28}$$

When

M_1 is zero the resulting Raleigh number is same as that obtained by Finlayson [7]. When FK is zero the resulting Raleigh number is same as that obtained by Malashetty et.al [19].

CASE 2 : ADIABATIC BOUNDARY CONDITIONS

$$W_1 = D\phi_1 = 0 \; at\; z = 0,1 \quad T_1 = 0 \; at\; z = 1 \quad DT_1 = 0 \; at\; z = 0$$

Choose the trial functions as

$$W_1 = \sin\pi z,\; T_1 = \cos\frac{\pi}{2}z,\; \phi_1 = \frac{1}{\pi}\cos\pi z$$

Then

$$Ra = -\frac{3\pi\left(\pi^2+a^2\right)^2\left\langle \pi^2+4a^2-4X\right\rangle\left(\pi^2+a^2M_3\right)}{8a^2Y\left\{8\left(1+M_1\right)\left(\pi^2+a^2M_3\right)-3M_1\pi^2\right\}} \tag{29}$$

$$X = 2FK\left\langle \exp(T_b)T_1^2\right\rangle$$

$$Y = \left\langle W_1 T_1 \frac{dT_b}{dz}\right\rangle$$

When

M_1 is zero the resulting Raleigh number is same as that obtained by Finlayson [7]. When FK is zero the resulting Raleigh number is same as that obtained by Malashetty et.al [19].

IFERP connecting engineers... developing research

ISSN (Online) 2456 -1304

International Journal of Science, Engineering and Management (IJSEM)
Vol 2, Issue 4, April 2017

IV. RESULTS AND DISCUSSION

The effect of T_b on the critical value of *FK* is presented in Fig. 2. It is shown that the critical value of *FK* increases to a maximum value of 0.8785 (corresponding to T_b = 1.19) and then decreases as Tb is increased (Table 1). From Fig. 3 it is shown that, at small values of *FK*, the basic temperature profile is almost linear with the vertical coordinate z.

Because chemical reactions give rise to heat generation, the basic undisturbed temperature profile becomes more nonlinear as the value of *FK* is increased for a higher heat generation rate. A figure 4 and 5 depicts the variation of R_{ac} as a function of *FK* for different values of the magnetization parameter M_1 and M_3 for a fixed value of Tb in the isothermal case. It is observed that R_{ac} decreases with increasing the magnetization parameter M_1 and M_3. It is shown that the critical Rayleigh number decreases as the value of *FK* is increased and then increases with increase in *FK*. Thus, chemical reaction in a horizontal layer of ferrofluid enhances instability. This is reasonable because chemical reaction leads to non-linear temperature distribution in the undisturbed state.

The value of the wave number at the onset of convection ac as a function of FK for the isothermal case is presented in Fig. 6. The variations of the critical Rayleigh number and the wave number as a function of *FK* are small. The values of R_{ac} and a_c for the isothermal case with $T_b = 1$ are also listed in Table 2.

The critical Rayleigh number as a function of *FK* for the physically realistic cases is presented in Figures. 7 and 8. It is seen that the critical Rayleigh number decreases as the *FK* value increases from zero. The corresponding critical wavenumber decreases as the value of *FK* is increased as shown in Fig. 9. The decrease in the critical wave number is drastic near the ignition point.

The effect of zero-order exothermic chemical reaction on the onset of free convection in a Ferro fluid leads to a distributed heat source which gives rise to a non linear temperature distribution in the undisturbed state. Thus, the effect of chemical reactions is to enhance the onset of free convection compared to the case in which chemical reactions are absent.

The Ferro fluid dampens the onset of free. Thus the effect of magnetization of the Ferro fluid is to delay the onset of free convection compared to the case in which magnetization of the Ferro fluid is absent.

T_b	FK
0	0
0.5	0.6587
1	0.8662
1.08	0.8746
1.19	0.8785
1.2	0.8784
1.22	0.8781
1.5	0.8523
2	0.7425
3	0.4734

Table. 1

T_b =1.0	M_1=1.0	M_3=1.0
FK	a_c^2	Ra_c
0.1	6.27	1648.43
0.2	6.21	1392.05
0.3	6.14	1324.56
0.4	6.08	1318.88
0.5	6.01	1347
0.6	5.95	1401.47
0.7	5.88	1482.61
0.8	5.81	1596.09
0.8662	5.76	1696.86

Table. 2

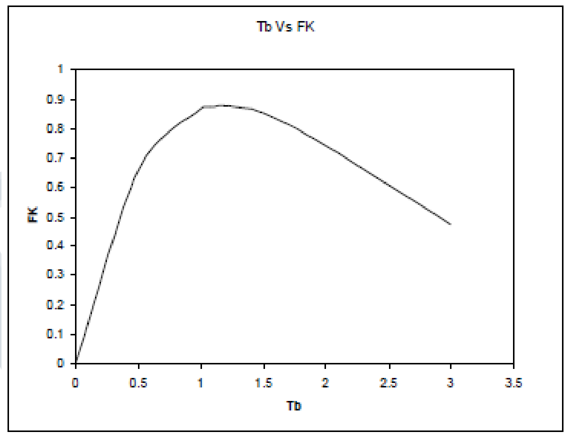

Fig. 2: The effect of T_b on the critical value of FK

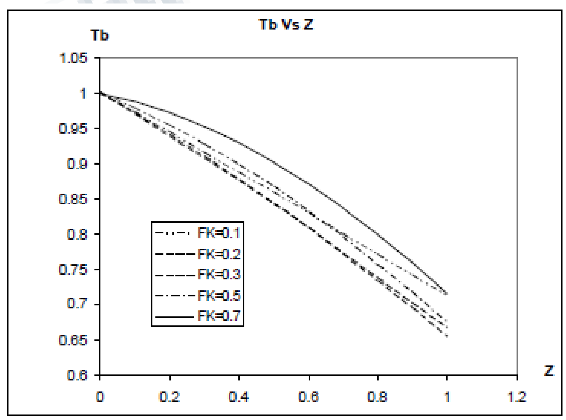

Fig. 3: The effect of T_b on the vertical coordinate z

Isothermal Case

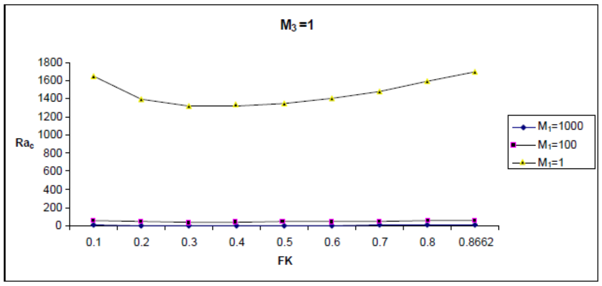

Fig. 4: FK versus critical Rayleigh Number for a fixed value of M_3

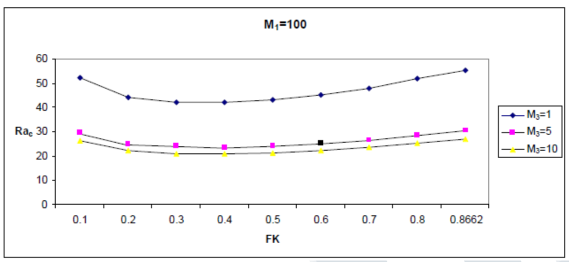

Fig. 5: FK versus critical Rayleigh Number for a fixed value of M_1

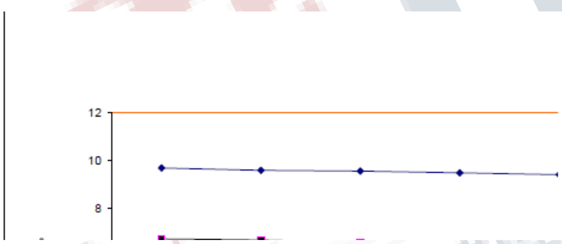

Fig. 6: FK versus critical wave number for a fixed value of M_1

Adiabatic Case

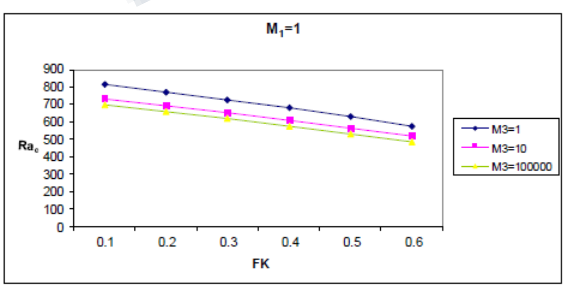

Fig. 7:FK versus R_{ac} for a fixed value of M_1

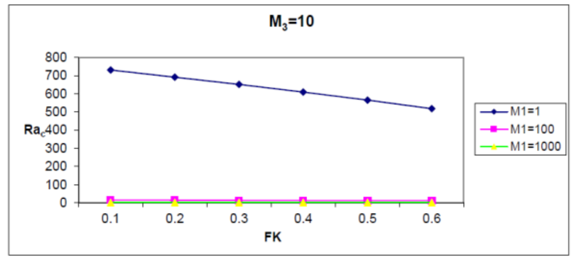

Fig. 8:FK versus R_{ac} for a fixed value of M_3

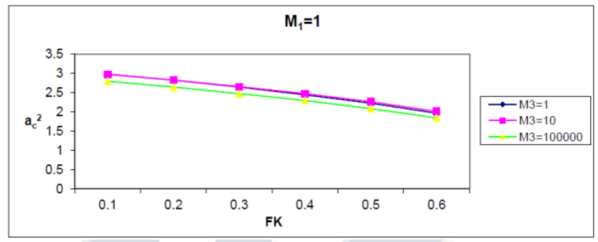

Fig. 9:FK versus a_c^2 for a fixed value of M_1

V. CONCLUSIONS

The effect of zero-order exothermic chemical reaction on the onset of free convection in a ferrofluid has been investigated. The chemical reaction leads to a distributed heat source which gives rise to a nonlinear temperature distribution in the undisturbed state. Thus, the effect of chemical reactions and the magnetization parameters is to enhance the onset of free convection compared to the case in which chemical reactions/ferromagnetic fluids are absent.

ACKNOWLEDGEMENTS

The authors are grateful to the Management of BMS Institute of Technology and Management, Bangalore, India for their encouragement and support.

REFERENCES

[1] Chandrasekhar S, “Hydrodynamic and hydromagnetic stability”, Oxford University Press, 1961.

[2] Turne J. S., “Buoyancy effects in fluids”, Cambridge University Press, Cambridge, 1973.

[3] Drazin, P. and Reid, W., “Hydrodynamic instability”. Cambridge University Press, U. K, 1981.

[4] Platten, J. K, Legros, J.C, "Convection in liquids", Springer, New York, 1984.

[5] Benard, H., " Les tourbillions cellularies dans une nappe liquide transportant de la chaleut par convection en regime permanent", Ann. Che. Phys. 23, 62, 1901.

[6] Rayleigh, Lord, "On convection currents in a horizontal layer of fluid when the higher temperature is on the underside", Phil. Mag. 32, 529, 1916.

[7] Finlayson, B. A., "Convective instability of ferromagnetic fluids", J. Fluid Mech., 40, 753, 1970.

[8] Rosensweig, R. E., "Ferro hydrodynamics", Cambridge Univ. Press, Cambridge, 1985.

[9] Rudraiah, N. and Sekhar, G. N., "Effects of non-uniform temperature gradient on convection in magnetic fluids", Proc. Of CAMS Conference, Canada, Hemisphere Publication, 1988.

[10] Siddheshwar P.G., "Convective instability of ferromagnetic fluids bounded by fluid-permeable boundaries", Journal of Magnetism and Magnetic Materials, 149, 148, 1995.

[11] Qin, Y and Kaloni, P. N., "Non – linear stability problem of a ferromagnetic fluid with surface tension effect", Eur. J. Mech., B/Fluids, 13, 305, 1994.

[12] Annamma Abraham, "Rayleigh-Benard Convection In A Micropolar Ferromagnetic Fluid", International Journal of Engineering Science40, 449-460, 2002.

[13] P. G. Siddheshwar and Annamma Abraham, "Time–Periodic Boundary Temperatures/ Body Force on Rayleigh-Benard Convection in a Ferromagnetic Fluid", Acta Mechanica, 161, 131-150,2003.

[14] P. G. Siddheshwar and Annamma Abraham, "Rayleigh-Benard Convection in a Dielectric Liquid: Imposed Time Periodic Boundary Temperatures", Chamchuri Journal of Mathematics, Bangkok, Vol 1. Number 2, 105-121, ISSN 1906-554X, 2009.

[15] Mustafa Alsaady, Rong Fu, Bo Li, Rabah Boukhanouf, Yuying Yan, "Thermo-physical properties and thermo-magnetic convection of ferrofluid", Applied Thermal Engineering, Volume 88, 5 September, Pages 14–21, 2015

[16] W. Kordylewski and Z. Krajewski, "Convection effects on thermal ignition in porous media", Chem. Engng. Sci., 39, 610-612, 1984.

[17] H. Viljoen and V. Hlavacek, "Chemically driven convection in a porous medium", AIChE Journal, 33, 1344-1350, 1987.

[18] S. Subramanian and V. Balakotaiah, "Convective instabilities induced by exothermic reactions occurring in a porous medium", Phys. Fluids, 6, 2907-2922, 1994.

[19] M.S. Malashetty, P. Cheng and B.H. Chao, "Convective instability in a horizontal porous layer saturated with a chemically reacting fluid", Int. J. Heat Mass Transfer, 37, 2901-2908, 1994.

[20] Mubeen Taj, S. Maruthamanikandan and Syeda Khudeja Akbar, "Effect of Chemical Reaction on Convective Instability in a Horizontal Porous Layer Saturated with a Couple-Stress Fluid", International Journal of Engineering Research and Applications (IJERA) Vol. 3, Issue 2, pp.1742-1748, 2013