MATEC Web of Conferences **1**, 06008 (2012)
DOI: 10.1051/matecconf/20120106008

Soret-driven double diffusive magneto-convection in couple stress liquid

A. K. Srivastava[1,3,a] , B. S. Bhadauria[1,2,b] , P. Mishra[1,c]

[1] Department of Mathematics, Faculty of Science
Banaras Hindu University, Varanasi−221005, India.
[2] Department of Applied Mathematics and Statistics, School for Physical Sciences,
Baba saheb Bhimrao Ambedkar University, Lucknow 226025,India
[3] Department of Mathematics, Indian Institute of Thechnology Roorkee,
Roorkee, India.

Abstract. The stability analysis of Soret driven double diffusive convection for electrically conducting couple stress liquid is investigated theoretically. The couple stress liquid is confined between two horizontal surfaces and a constant vertical magnetic field is applied across the surfaces. Linear stability analysis is used to investigate the effect of various parameters on the onset of convection. Effect of magnetic field on the onset of convection is presented by means of Chandrasekhar number. The problem is analyzed as a function of Chandrasekhar number (Q), positive and negative Soret parameter (Sr) and couple stress parameter (C), mainly. The results show that the Q, both positive and negative Sr and C delay the onset of convection. The effect of other parameters is also discussed in paper and shown by graphs.

1 Introduction

Magneto-convection arises due the interaction of electrically conducting fluid flow and the applied magnetic field. The linear and non-linear magneto-convection in an electrically conducting fluid has been extensively studied by many authors viz, Busse [1] and Chandrasekhar [2]. Since molten metals and semiconductor melts are electrically conducting, a magnetic field may be applied to control the thermally induced convective flows in these fluids. It has many applications such as crystal growth, geothermal reservoir, metallurgical applications involving continuous casting and solidification of metal alloys and others. Li [3] and Pan and Li [4] show that gravity and magnetic fields represent different mechanisms of flow reduction and that they may be combined to further suppress the convection in a modulated gravity field. Ozoe and Maruo [5] investigated magnetic and gravitational natural convection of metal silicon and performed two-dimensional numerical computations to obtain the rate of heat transfer. Siddheshwar and Pranesh [6] examined the effects of time-periodic temperature/gravity modulation on the onset of magneto-convection in electrically conducting fluids with internal angular momentum by making a linear stability analysis. Recently Siddheshwar et al. [7] investigated a weak non-linear stability problem of magneto-convection in an electrically conducting Newtonian fluid, confined between two horizontal surfaces, under a constant vertical magnetic field, and subjected to an imposed time-periodic boundary temperature or gravity modulation.

Double-diffusive convection has attracted considerable interest in the last two decades. Such systems are often termed thermohaline, referring to their most common occurrence in oceans and other large water bodies, with salt and heat playing the roles of the two components. Interesting dynamics ensues when the two components affect the density stratification in opposite senses, and convection may occur even when the total density gradient is gravitationally stable. If the gradient of two stratifying agencies such as heat and salt having different diffusivities are simultaneously present in a fluid layer many interesting convective phenomena can occur that are not possible in a single component fluid. An excellent review of the studies related to double diffusive convection has been reported by Turner ([8]-[10]), Huppert and Turner [11] and Platten and Legros [12].

Dougall [13] investigated the double diffusive convention caused by coupled molecular diffusion. Hurle and Jakeman [14] concluded from his experimental and theoretical work that in cross diffusion Dufour term is very small and may be neglected in comparison to Soret effect. Due to this fact one may leave the Dufour term while study the flow in liquids. Soret effect is a flux of salt caused by a spatial gradient of temperature. This phenomena has many applications such as in geophysics, oil reservoirs and ground water. Platten and Chavepeyer [15] was studied oscillatory motions in Benard cell due to Soret effect. According to their study, the linear theory oscillatory motions are observed in the two-component system with negative Soret coefficients and the order of magnitude of the period of oscillations is confirmed by experiments. Knobloch [16] investigated the thermal convection in a binary fluid driven by the Soret and Dufour effects. By his studied, he concluded that equations are identical to the thermosolutal problem except for a relation between the thermal and solute Rayleigh numbers. The onset of Rayleigh-Benard convection in liquid mixtures has been studied experimentally by Lee et al. [17] . They stated by his work that the

[a] e-mail: atulshaswat@gmail.com
[b] e-mail: mathsbsb@yahoo.com
[c] e-mail: pankaj1mishra@gmail.com

overstable motions are possible when heated from below and only stationary motions exist when heated from above. Porta and Surko [18] has been performed experimentally the study of convective instability in a fluid mixture heated from above with negative Soret coefficient. According to their investigation, although the linear analysis predicts that the instability occurs at zero wave-number, a large wave-number pattern is observed. Bourich et al. [19] have given an excellent review of literature on the Soret effect convection either in fluid or porous media. Malashetty et al. [20] investigated double diffusive convection in a two-component couple stress liquid layer with Soret effect using both linear and non-linear stability analyses. Recently Srivastava et al. [21] investigated an electrically conducting two component Boussinesq fluid-saturated-porous medium in the presence of Soret coefficient.

Non-Newtonian fluids has lot of importance in modern technology and industries. In last few decades the theory of polar fluids has received much attention and this is due to the fact that most of the Newtonian fluids cannot precisely describe the characteristics of the fluid flow with suspended particles. These fluids have many applications that occur in industry such as the extrusion of polymer fluids, solidification of liquid crystals, cooling of metallic plate in a bath, exotic lubricants and colloidal and suspension solutions. Due to polar effect, the couple stress liquid has distinct features in non-Newtonian fluids. Stokes [22] proposed the constitutive equations for couple stress fluids. In his studied, he suggested simplest theory for the micro fluids, which allows polar effects such as the presence of couple stress, body couples and non-symmetric tensors. Siddeshwar and Pranesh [23], Sharma and Sharma [24] and Malashetty and Basavarja [25] investigated Rayleigh-Benard convection in fluids with stress non-linearly proportional to velocity gradient.

To the best of author's knowledge no study is available on magneto-convection in double-diffusive couple stress liquid under Soret effect. In view of this, the same is studied in the paper.

2 Mathematical Formulations

We consider an electrically conducting two component liquid of depth d, confined between two infinite parallel horizontal planes at $z = 0$ and $z = d$. Cartesian co-ordinates have been taken with the origin at the bottom of the layer, and the z-axis vertically upwards. The surfaces are extended infinitely in x and y directions and constant temperature gradient ΔT and salinity gradient ΔS are maintained across the layer. A constant magnetic field $H_0\hat{k}$ is applied externally in vertical upward direction (as shown in Fig. 1). Under the Boussinesq approximation, the non-dimensional governing equations for the study of magneto double-diffusive convection in an electrically conducting couple stress liquid are (followling Siddheshwar et al. [7] and Srivatava et al. [21]),

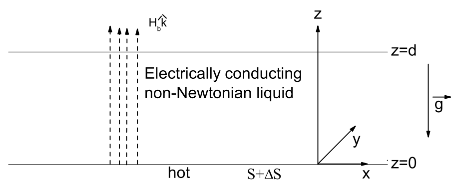

Fig.1. Schematic of physical configuration.

$$\frac{1}{\mathrm{Pr}}\frac{\partial\left(\nabla^2\psi\right)}{\partial t} = -\mathrm{R}\frac{\partial T}{\partial x} + \mathrm{R}_S\frac{\partial S}{\partial x} + \nabla^4\psi - C\nabla^6\psi + \frac{1}{\mathrm{Pr}}\frac{\partial\left(\psi,\nabla^2\psi\right)}{\partial(x,z)} + \mathrm{Q}Pm\frac{\partial}{\partial z}\left(\nabla^2\phi\right) - \mathrm{Q}Pm\frac{\partial\left(\phi,\nabla^2\phi\right)}{\partial(x,z)} \quad (1)$$

$$\frac{\partial T}{\partial t} = -\frac{\partial\psi}{\partial x} + \nabla^2 T + \frac{\partial(\psi, T)}{\partial(x,z)} \quad (2)$$

$$\frac{\partial S}{\partial t} = -\frac{\partial\psi}{\partial x} + \frac{1}{\mathrm{Le}}\nabla^2 S + Sr\frac{\mathrm{R}}{\mathrm{R}_s}\nabla^2 T + \frac{\partial(\psi, S)}{\partial(x,z)} \quad (3)$$

$$\frac{\partial\phi}{\partial t} = \frac{\partial\psi}{\partial z} + Pm\nabla^2\phi + \frac{\partial(\psi,\phi)}{\partial(x,z)} \quad (4)$$

where the non-dimensional parameters, Prandtl number $\mathrm{Pr} = \frac{\nu}{\kappa_T}$, thermal Rayleigh number $\mathrm{R} = \frac{\beta_T g\Delta T d^3}{\upsilon\kappa_T}$, soultal Rayleigh number $\mathrm{R}_S = \frac{\beta_S g\Delta T d^3}{\upsilon\kappa_T}$, Chandrasekhar number $\mathrm{Q} == \frac{\mu_m H_b^2 d^2}{\rho_0\upsilon\upsilon_m}$, magnetic Prandtl number $Pm = \frac{\upsilon_m}{\kappa_T}$, couple stress parameter $C = \frac{\mu_c}{\mu d^2}$, Soert parameter $Sr = \frac{D\beta_S}{\kappa_T\beta_T}$ and Lewis number $\mathrm{Le} = \frac{\kappa_T}{\kappa_S}$. In these parameters, β_T and β_S are coefficient of thermal and solutal expansions respectively, κ_T and κ_S are the thermal and solutal diffusivity respectively, D is cross diffusion due to T component, υ and υ_m are kinematic and magnetic viscosity respectively and μ_m is magnetic permeability. Now linearizing the above set of equations and combining Eqs. (1) and (4), we get

$$\left[\left(\frac{\partial}{\partial t} - Pm\nabla^2\right)\left(\frac{1}{\mathrm{Pr}}\frac{\partial}{\partial t}\nabla^2 - \nabla^4(1 - C\nabla^2)\right) - \mathrm{Q}Pm\nabla^2\frac{\partial^2}{\partial z^2}\right]\psi + \mathrm{R}\left(\frac{\partial}{\partial t} - Pm\nabla^2\right)\frac{\partial T}{\partial x} - \mathrm{R}_S\left(\frac{\partial}{\partial t} - Pm\nabla^2\right)\frac{\partial S}{\partial x} = 0 \quad (5)$$

$$\left(\frac{\partial}{\partial t} - Pm\nabla^2\right)T + \frac{\partial\psi}{\partial x} = 0 \quad (6)$$

$$\left(\frac{\partial}{\partial t} - \frac{1}{\mathrm{Le}}\nabla^2\right)S + \frac{\partial\psi}{\partial x} - Sr\frac{\mathrm{R}}{\mathrm{R}_S}\nabla^2 T = 0 \quad (7)$$

The Soret parameter Sr may take either positive or negative value. A positive Soret parameter indicates that the solute diffuse towards the cooler plates, while negative Soret parameter indicates the reverse. Eqs. (5) − (7) are solved for stress-free, isothermal, isohaline boundary conditions, as given below

$$\psi = T = S = 0 \quad \text{at} \quad z = 0, 1. \tag{8}$$

3 Stability Analysis

In this section, we predict the threshold of both marginal and oscillatory convection, using linear theory. To make this study, assume the solutions to be periodic waves of the form

$$\begin{pmatrix} \psi \\ T \\ S \end{pmatrix} = e^{\sigma t} \begin{pmatrix} \Psi \sin \pi\alpha x \\ \Theta \cos \pi\alpha x \\ \Phi \cos \pi\alpha x \end{pmatrix} \sin \pi z \tag{9}$$

where Ψ, Θ and Φ are the amplitudes of stream function, temperature and concentration field respectively. Substituting (9) in the Eqs. (5)-(7), we obtain a matrix equation

$$\begin{bmatrix} \left[\left(\frac{\sigma}{\mathrm{Pr}} + a^2\eta\right)\left(\sigma + Pma^2\right) + \mathrm{Q}Pm\pi^2\right]a^2 & R\left(\sigma + Pma^2\right)\pi\alpha & -\mathrm{R}_S\pi\alpha\left(\sigma + Pma^2\right) \\ \pi\alpha & \left(\sigma + a^2\right) & 0 \\ \pi\alpha & Sra^2\frac{\mathrm{R}}{\mathrm{R}_S} & \left(\sigma + \frac{a^2}{\mathrm{Le}}\right) \end{bmatrix} \begin{bmatrix} \Psi \\ \Theta \\ \Phi \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{10}$$

For non-trivial solution of Ψ, Θ and Φ, we follow the same processor applied by Srivastava et al. [21], we get

$$R = \left(\sigma + a^2\right)\frac{P1}{P2} \tag{11}$$

where $a^2 = \pi^2\alpha^2 + \pi^2$,

$$P1 = \left[\left\{\left(\frac{\sigma}{\mathrm{Pr}} + a^2\eta\right)\left(\sigma + Pma^2\right) + \mathrm{Q}Pm\pi^2\right\} a^2\left(\sigma\mathrm{Le} + a^2\right) + \mathrm{R}_S\pi^2\alpha^2\mathrm{Le}\left(\sigma + Pma^2\right)\right],$$

where $\eta = 1 + Ca^2$ and

$$P2 = \pi^2\alpha^2 \left[\left(\sigma + Pma^2\right)\left(\sigma\mathrm{Le} + a^2\right) + Sr\mathrm{Le}a^2\left(\sigma + Pma^2\right)\right]$$

For the direct bifurcation (i.e., steady onset), we have $\sigma = 0$ at the margin of stability. Then Rayleigh number at which marginally stable steady mode exists, becomes

$$\mathrm{R}^{st} = \frac{(a^4\eta + \mathrm{Q}\pi^2)a^2 + \mathrm{R}_S\pi^2\alpha^2\mathrm{Le}}{\pi^2\alpha^2(1 + Sr\mathrm{Le})} \tag{12}$$

The minimum value of Rayleigh number R^{st} at the critical wave number $\alpha = \alpha_c$, where $\alpha_c^2 = \chi$ satisfies the equation

$$\eta\chi^4 + 2\eta\chi^3 + \left(\eta - \left(\frac{1}{\xi} + \mathrm{Q}\right) + \frac{\mathrm{R}_S\mathrm{Le}(\eta - 1)}{\pi^2}\right)\chi^2 - 2\left(\frac{1}{\xi} + \mathrm{Q}\right)\chi - \left(\frac{1}{\xi} + \mathrm{Q}\right) = 0 \tag{13}$$

In the absence of magnetic field the Eq. (12) reduces to

$$\mathrm{R}^{st} = \frac{a^6\eta}{\pi^2\alpha^2(1 + Sr\mathrm{Le})} + \frac{\mathrm{R}_S\mathrm{Le}}{(1 + Sr\mathrm{Le})} \tag{14}$$

which gives the result of Malashetty et al. [20]. Further when $\mathrm{R}_S = 0$ and absence of Soret effect, Eq. (14) reduces to

$$\mathrm{R}^{st} = \frac{a^6\eta}{\pi^2\alpha^2} \tag{15}$$

which is same the result of Siddheshwar and Pranesh [23]. If $C = 0$ that is when couple stress is absent, we get the classical results of Chandrasekhar [2], that is critical Rayleigh number $\mathrm{R}_c^{st} = 657.5$ and wave-number is $\alpha_c^2 = 0.5$.

The growth rate σ is in general a complex quantity such that $\sigma = \sigma_r + i\sigma_i$. The system with $\sigma_r \leq 0$ is always stable, while for $\sigma_r \geq 0$ it will become unstable. For neutral stability state $\sigma_r = 0$. Therefore, we now set $\sigma = \sigma_i$ in Eq.(11) and clear the complex quantities from the denominator, to obtain

$$\mathrm{R} = \Lambda_1 + i\sigma_i\Lambda_2 \tag{16}$$

The expression for Λ_1 and Λ_2 is not presented for brevity.

Since R_T is a physical quantity, it must be real. Hence, from Eq. (16) it follows that either $\sigma_i = 0$ (steady onset) or $\Lambda_2 = 0$ ($\sigma_i \neq 0$, oscillatory onset). For oscillatory onset $\Lambda_2 = 0(\sigma_i \neq 0)$, gives a dispersion relation of the form (on dropping the subscript i)

$$C_0\left(\omega^2\right)^2 + C_1\left(\omega^2\right) + C_2 = 0 \tag{17}$$

where the constants $C_i's$ are as under

$$C_0 = a^2(1 + \mathrm{Le})\frac{\mathrm{Le}}{\mathrm{Pr}} - \mathrm{Le}a^2\left\{\frac{(1 + Sr\mathrm{Le})}{\mathrm{Pr}} - \eta\mathrm{Le}\right\}$$

$$C_1 = a^6\left(1 - Pm^2\mathrm{Le}\right)\left\{\frac{(1 + Sr\mathrm{Le})}{\mathrm{Pr}} - \eta\mathrm{Le}\right\} + a^6(1 + \mathrm{Le})\eta(1 + Sr\mathrm{Le}) + a^6Pm^2(1 + \mathrm{Le})\frac{\mathrm{Le}}{\mathrm{Pr}} + \mathrm{R}_sL_e\pi^2\alpha^2\{1 + (Sr - 1)\mathrm{Le}\} + \mathrm{Le}\{Pm\mathrm{Le} + (1 + Sr\mathrm{Le})\} \mathrm{Q}Pm\pi^2a^2 - \mathrm{Q}Pm\pi^2a^2(1 + \mathrm{Le})\mathrm{Le}.$$

$$C_2 = a^{10}Pm^2\left\{\frac{(1 + Sr\mathrm{Le})}{\mathrm{Pr}} - \eta\mathrm{Le}\right\} + a^{10}Pm^2(1 + \mathrm{Le})\eta(1 + Sr\mathrm{Le}) + \mathrm{Q}Pm\pi^2a^6(1 + \mathrm{Le})(1 + Sr\mathrm{Le}) + \mathrm{R}_s\mathrm{Le}\pi^2\alpha^2\{1 + (Sr - 1)\mathrm{Le}\}a^4Pm^2 - \mathrm{Q}Pm\pi^2a^6\{Pm\mathrm{Le} + (1 + Sr\mathrm{Le})\}$$

Now Eq. (16) with $\Lambda_2 = 0$, gives

$$\mathrm{R}^{Osc} = \left[a^2D1 + \frac{\mathrm{Q}Pma^2\pi^2}{\omega^2 + Pm^2a^4}D2 + \mathrm{R}_s\mathrm{Le}\pi^2\alpha^2D3\right]D4^{-1} \tag{18}$$

$$D1 = \left(a^4 - \omega^2\mathrm{Le}\right)\left(a^4\eta(1 + Sr\mathrm{Le}) + \frac{\omega^2\mathrm{Le}}{\mathrm{Pr}}\right) - a^4(1 + \mathrm{Le})\omega^2\left(\left(\frac{1+Sr\mathrm{Le}}{\mathrm{Pr}}\right) - \eta\mathrm{Le}\right)$$

$$D2 = \left(a^4 - \omega^2\mathrm{Le}\right)\left(Pma^4(1 + Sr\mathrm{Le}) - \omega^2\mathrm{Le}\right) + a^4(1 + \mathrm{Le})\left(Pm\mathrm{Le} + (1 + Sr\mathrm{Le})\omega^2\right)$$

$$D3 = \left(a^4\left(1 + Sr\mathrm{Le} + \omega^2\mathrm{Le}\right)\right)$$

$$D4 = \left[\pi^2\alpha^2\left\{\omega^2\mathrm{Le}^2 + a^4(1 + Sr\mathrm{Le})^2\right\}\right]$$

Also for the oscillatory convection to occur, ω^2 must be positive.

4 Results and Discussion

Normal mode analysis is used to investigate the linear stability for the onset of magneto-convection in a couple stress, binary liquid with Soret effect. The stability of basic flow are governed by non-dimensional parameters: couple stress parameter (C), Chandrasekhar number (Q), Soret coefficient (Sr), Lewis number (Le), Prandtl number (Pr), Solutal Rayleigh number (R_S), and magnetic Prandtl number (Pm). The entire stability analysis is divided into (i) Stationary convection and (ii) Oscillatory convection.

The neutral stability curves in $R-\alpha$ plane, for different values of parameters are shown in Figs. 2-7. In the figures, we present the variation of R with respect to α for fixed values of the parameters $C = 1.0$, $Q = 25.0$, $Sr = -0.003$, $Le = 1.0$, $R_S = 10.0$, $Pm = 0.001$ and $Pr = 2.0$, with variation in one of the parameter. From these figures, it is clear that the neutral curves are connected in a topological sense. This connectedness allows the linear stability criteria to be expressed in terms of the critical Rayleigh number, R_c, below which the system is stable and unstable above.

The characteristic curves for different value of Chandrasekhar number Q for stationary and oscillatory modes have been presented in Fig. 2(a) and 2(b) respectively. We see that the effect of increasing Q is to increase the critical value of Rayleigh number for both stationary and oscillatory modes, implying that Q has a stabilizing effect. Similar effect is shown by couple stress parameter C, solutal Rayleigh number R_S and Lewis number Le in Fig. 3, 5 and 6 respectively. In Fig. 4(a)-4(b), we investigate the effect of positive and negative value of Soret parameter on the neutral stability for fixed values of other parameters. It can be observed that an increment in Sr decreases the minimum of Rayleigh number for stationary and oscillatory state for both positive and negative values thus destabilizing the system.

Variation of R with respect to wave number α, for different value of Pm, has been depicted in Fig. 7. From the figure, we notice that for stationary convection there is no effect of Pm, whereas for oscillatory convection value of critical Rayleigh number decreases with increasing value of Pm thus destabilizing the system. Variation of R with wave number α for different value of Pr is also shown by Table 1. It is clear that for oscillatory convection there is slight increase the value of R on increasing the value of Pr indicating that it stabilizes the system.

5 Conclusions

In the present article, linear stability analysis is performed, to study the magneto double diffusive convection in couple stress liquid in the presences of Soret coefficient. Linear stability analysis is performed using normal mode technique. The following conclusions are drawn:

1. Effect of increasing Q, C, R_S, Le is found to increase the onset of stationary, oscillatory convection, thus it delay the onset of convection.

2. On increasing the value of Sr, value of Rayleigh number corresponding to stationary and oscillatory convection decrease, thus it advances the onset of convection.

3. On increasing the value of Pm, there is no effect on stationary convection however Rayleigh number decreases with increasing value of Pm.

4. On increasing the value of Pr, Rayleigh number slightly increases with increasing value of Pr, thus stabilize the system.

ACKNOWLEDGMENT

Author AKS dedicate his work to Late Prof. M. S. Malashetty and one of my collogue Late Mr. Anoj Kumar.

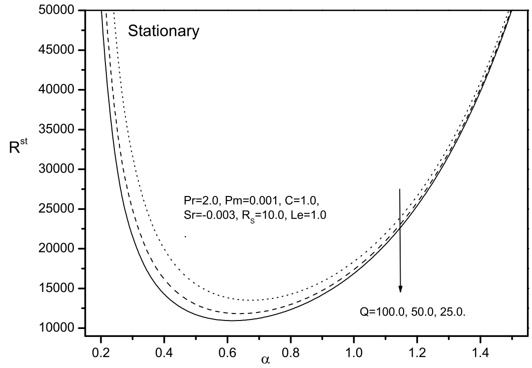

Fig. 2(a). Variation of R^{st} with α for different Chandrashekhar number.

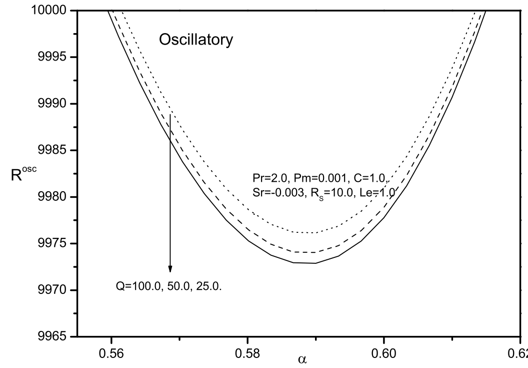

Fig. 2(b). Variation of R^{osc} with α for different Chandrashekhar number.

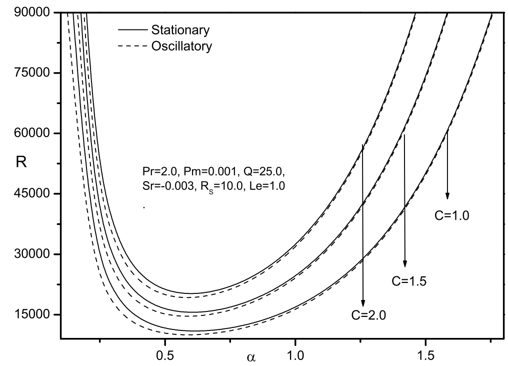

Fig. 3 Variation of R with α for different couple stress parameter.

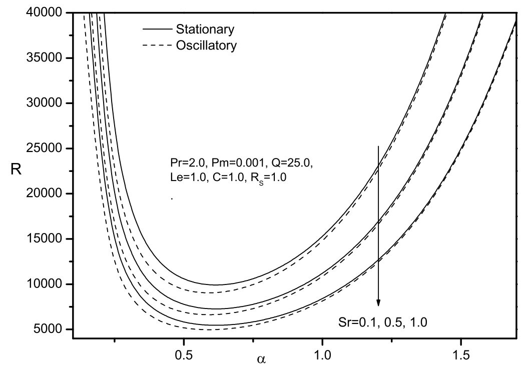

Fig. 4(a). Variation of R with α for different value of positive Soret number.

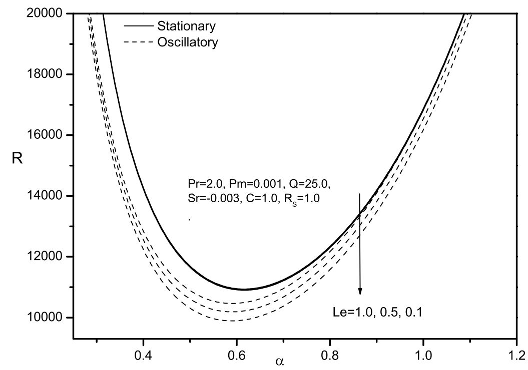

Fig. 6. Variation of R with α for different value of Lewis number.

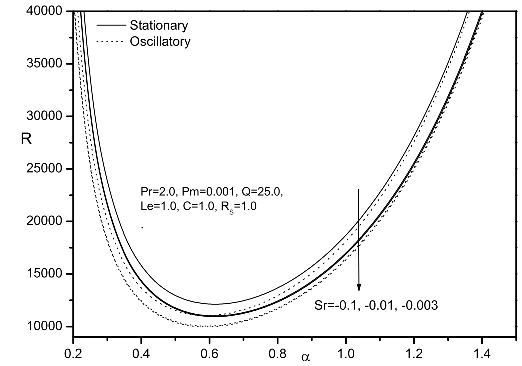

Fig. 4(b). Variation of R with α for different value of negative Soret number.

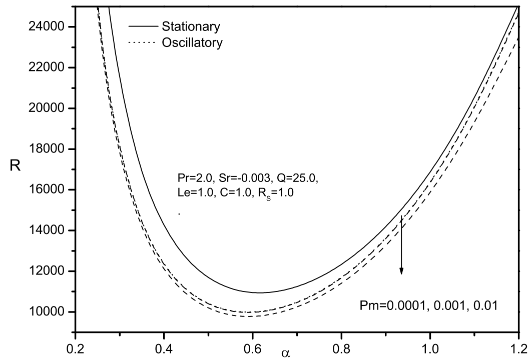

Fig. 7. Variation of R with α for different value of magnetic Prandtl number.

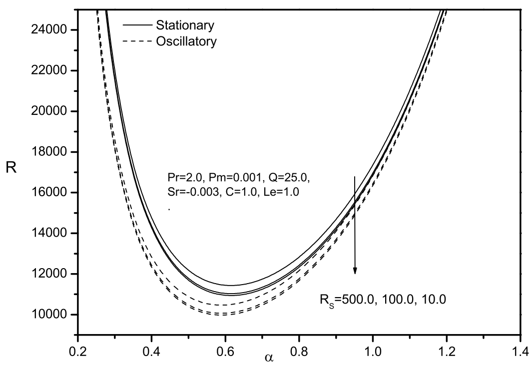

Fig. 5. Variation of R with α for different value of solutal Rayleigh number.

Table 1. Variation of R^{osc} with α for different value of Pr.

α	R		
	Pr=2.0	Pr=6.0	Pr=10.0
0.1	110219.75	110219.75	110222.46
0.2	30902.7	30902.7	30903.47
0.3	16509.16	16509.16	16509.58
0.4	11853	11853	11853.3
0.5	10170.54	10170.54	10170.79
0.6	9836.86	9836.86	9837.1
0.7	10348.64	10348.64	10348.88
0.8	11559.47	11559.47	11559.72
0.9	13474.95	13474.95	13475.23
1	16186.75	16186.75	16187.06
1.1	19850.25	19850.25	19850.6
1.2	24678.65	24678.65	24679.06
1.3	30944.1	30944.1	30944.58
1.4	38982.4	38982.4	38982.97
1.5	49199.7	49199.7	49200.39
1.6	62080.43	62080.43	62081.26
1.7	78195.78	78195.78	78196.82
1.8	98212.09	98212.09	98213.41
1.9	122896.94	122896.94	122898.67
2	153116.02	153116.02	153118.45

References

1. F. H. Busse, Non-linear interaction of magnetic field and convection, J. Fluid Mech., **71**, (1975), 193-215.
2. S. Chandrasekhar, *Hydrodynamic and Hydromagnetic Stability*, Dover, Inc, New York, (1981).
3. B. Q. Li, G-Jitter induced free convection in a transverse magnetic field, Int. J. Heat Mass Transfer, **39**, (1996), 2853-2860.
4. B. Pan, B. Q. Li, Effect of magnetic fields on oscillating mixed convection, Int. J. Heat Mass Transfer, **41**, (1998), 2705-2710.
5. H. Ozoe, M. Maruo, Magnetic and gravitational natural convection of melted silicon-two dimensional numerical computations for the rate of heat transfer, JSME, **30**, (1987), 774-784.
6. P. G. Siddheshwar, S. Pranesh, Effect of temperature/gravity modulation on the onset of magneto-convection in electrically conducting fluids with internal angular momentum, J. Magnetism and Magnetic Materials, **219**, (2000), L153-L162.
7. P. G. Siddheshwar, B. S. Bhadauria, P. Mishra, A. K. Srivastava, Study of heat transport by stationary magneto-convection in a Newtonian liquid under temperature or gravity modulation using Ginzburg-Landau model, Int. J. Non-Linear Mech., Article in press, (2011).
8. J. S. Turner, *Buoyancy Effects in Fluids*, Cambridge University Press, London, (1973).
9. J. S. Turner, Double diffusive phenomena, Annu. Rev. Fluid Mech., **6**, (1974), 37-56.
10. J. S. Turner, Multicomponent convection, Annu. Rev. Fluid. Mech., **17**, (1985), 11-44.
11. H. E. Huppert, J. S. Turner, Double diffusive convection, J. Fluid Mech., **106**, (1981), 299-329.
12. K. Platten, J. C. Legros, *Convection in Liquids*, Springer, Berlin, (1984).
13. T. J. M. Dougall, Double diffusive convection caused by coupled molecular diffusion, J. Fluid Mech., **126**, (1982), 379-397.
14. D. T. Hurle, E. Jakeman, Soret-driven thermosolutal convection, J. Fluid Mech., **47**, (1971), 667-687.
15. J. K. Platten, G. Chavepeyer, Oscillatory motion in Benard cell due to the Soret effect, J. Fluid Mech., **60**, (1973), 305-319.
16. E. Knobloch, Convection in binary fluids, Phys. Fluids, **23(9)**, (1920), 1918-1920.
17. G. W. T. Lee, P. Lugas, A. Tyler, Onset of Rayleigh-Benard convection in binary liquid mixtures of 3He in 4He, J. Fluid Mech., **135**, (1983), 235-259.
18. A. La Porta, C. M. Surko, Convective instability in a fluid mixture heated from above, Phys. Rev. Lett., **80(17)**, (1998), 3759-3762.
19. M. Bourich, M. Hasnaoui, M. Mamou, A. Amahmid, Soret effect inducing subcritical and Hopf-bifurcation in a shallow enclosure filled with a clear binary fluid or a saturated porous medium: A comparative study, Phys. Fluids, **16(3)**, (2004), 551-568.
20. M. S. Malashetty, S. N. Gaikwad, M. Swamy, An analytical study of linear and non-linear double diffusive convection with Soret effect in couple stress liquids, Int. J. Thermal Sciences, **45**, (2006), 897-907.
21. A. K. Srivastava, B. S. Bhadauria, V. Gupta, Magneto-convection in an anisotropic porous layer with Soret effect, Int. J. Non-Linear Mech., Article in press, (2011).
22. V. K. Stokes, Couple stresses in fluids, Phys. Fluids, **9**, (1966), 1709-1716.
23. P.G. Siddheshwar, S. Pranesh, An analytical study of linear and nonlinear convection in Boussinesq-Stokes suspensions, Int. J. Non-Linear Mech., **39**, (2004), 165-172.
24. R. C. Sharma, M. Sharma, Effect of suspended particles on couple-stress fluid heated from below in the presence of rotation and magnetic field, Indian J. Pure Appl. Math., **35(8)**, (2004), 973-989.
25. M. S. Malashetty, D. Basavaraja, Effect of thermal/gravity modulation on the onset of Rayleigh-Benard convection in a couple stress fluid, I. J. Trans. Phenomena, **7**, (2005), 31-44.