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Linear and non-linear double diffusive penetrative convection with heat and mass flux prescribed on the boundaries

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Abstract

In this paper, double diffusive penetrative convection with heat and mass fluxes prescribed on the boundaries is investigated analytically. Linear stability analysis has its own limitations. Therefore, the analysis is extended to study the behaviour of nonlinear disturbances for Rayleigh numbers near the critical value. It is of interest to observe whether finite amplitude motion can exist for Rayleigh numbers less than the critical value. By applying the modified power series technique, solvability condition and the evolution equations are derived.

1. Introduction

In recent years, the study of the phenomenon of the convective process in a horizontal fluid/porous layer has received remarkable attention owing to its very wide applications in Science, Engineering and Industrial areas. Convection can be the dominant mode of heat and mass transport in many processes that involve the freezing and melting of the storage material. Natural convection is an omnipresent transport phenomenon in saturated porous geological structures. In fact, the study of convection is of most importance in geophysical, astrophysical and heat transfer problems. For example, the extraction of energy from geothermal sources is the most promising one among the other methods and it is believed that the fluid in these reservoirs are highly permeable and consists of multi-components rather than a single component. Therefore, buoyancy driven convection in a porous medium with water as the working fluid is an important mechanism of energy transport. In fact, the key feature of a major geothermal system while on the land or beneath the sea floor is a high intrinsic heat transport. In fact, the local thermal conditions and the physical properties of media are directly of great importance on the characteristics of the heat and mass transfer in such real configurations. Moreover, the nature of the fluid flow (2D, 3D,pattern and range) is drastically dependent on the complexity of geophysical sites, i.e., the geometry, heterogeneity and anisotropy of the domains. Fluid motions induced by free convection have tangible effects in geothermal areas, on the diffusion of pollutants or on the mineral diagenesis processes.

Review

The multi-component onset of convection is important in many naturally occurring phenomena and technological processes. In double diffusive convection, heat and solute diffuse at different rates, as a result of which complex flow structures may form which have no counterpart in buoyant flows driven by a single component. Extensive literature pertaining to this phenomenon is available (Fujita and Gosting (1956); Miller (1966); Miller et al. (1967); Nield (1968); Hurle and Jakeman (197 1); Huppert and Manins (1972); Schechter et al (1972); Velarde and Schechter (1972); Vitaliano et al. (1972);Caldwell (1974); Turner (1979,1985); Griffiths (1979); Antoranz and Vegiar (1979); Leaist and Lyons (1980); Placsek and Toomre (1980); Narusawa and Suzukawa (1981); Srimani (1981); Takao, Tsuchiya and Narasuwa(1982); McTaggart (1983); Srimani (1984, 1991); Torrones and Pearistein (1989); Anamika (1990); Chen and Su (1992); Zimmermann Muller and Davis (1992); Tanny, Chen and Chen (1994); Shivakumar (1997); Skarda, Jacqmin and McCaughan (1998);).In this review, an additional effect viz., the effect of the coupled fluxes of the two properties due to irreversible thermodynamic effects is considered. This is termed as the effect of Coupled diffusion or Cross-diffusion and Sort effect is an example of this cross- diffusion where a flux of salt is caused by a spatial gradient of temperature. In fact, Dufour effect is the corresponding flux of heat caused by a spatial gradient of temperature.

Some literature (Hurle and Jakeman (1971); Skarda, Jacqmin and McCaughan (1998); Zimmermann et al (1992); Chen and Chen (1994)) in this direction are useful. McDougall (1983) has made a detailed study of Double-diffusive convection caused by coupled molecular diffusion. The results of his linear stability analysis, predicts that for a sufficiently large coupled diffusion effect, fingers can form even when the concentrations of both the components make the fluid's density gradient statically stable. The conditions for the occurrence of finger as well diffusive instabilities are predicted. The results of his finite amplitude analysis reveal that for sufficiently large cross-diffusion effect, fingers do exist.

The present investigation aims at answering the following questions that arise in the study:
i) What is the reason for using a fixed-heat/mass-flux boundary condition?
ii) How the critical conditions are affected by the concentration parameter?
iii) What is the effect of solute concentration on the zeroth-order solution?
iv) What is the region of validity for the existence of long horizontal scales?
v) Is it possible to predict when a gravitationally unstable two-component layer lies above a thinner stable layer?
vi) What is the nature of bifurcation?
vii) What is the nature of the Rayleigh number curve? Do local minima exist? If so, are there any marked differences between an ordinary penetrative convection and a double diffusive penetrative convective phenomenon?
viii) What is the nature of the density dependence on temperature and solute concentration?
ix) What is the cumulative effect of the governing parameters on the wave, temperature and concentration profiles?

x) What is the nature of the differential equation associated with the Horizontal and temporal structure of double diffusive penetrative convection?
xi) What is the nature of penetration under different physically feasible conditions?
xii)Is it possible to suppress or enhance penetrative double diffusive convection by considering a suitable choice of the parameters?

2. Formulation and solution of the problem

The physical configuration is as shown in figure 1, where a two-component fluid i.e., ice-saline water, which is of infinite horizontal extent is confined between two plates which have fixed heat and mass-flux boundary conditions defined on them. No-slip velocity boundary conditions are imposed on the two boundaries.
The idealized equation of state for the fluid will be taken to be

$$\rho = \rho_0[1 - \alpha(T - T^*)^2 + \alpha_s(C - C^*)^2]$$

where ρ_0, α and T^* are absolute constants of the fluid, in water the values $\rho_0 = 1\text{g/cm}^3$,

$\alpha = 8 \times 10^{-6} K^{-2}$ and $T^* = 3.98^0$C give a reasonably accurate prescription. Also let,

$$T = T^* + \beta(z - d) + \theta(x, y, z, t)$$

$$C = C^* + \beta^*(z - d) + S(x, y, z, t)$$

where $[T^* + \beta(z - d)]$ and $[C^* + \beta^*(z - d)]$are the static temperature and concentration distributions,$\theta$and S are the deviations from the static state due to the convective motion. Here$z = d$ corresponds to the vertical position of the static density maximum and correspondingly, for $0 < z < d$ the fluid under consideration is gravitationally unstable, while for $d < z < \square$ it is stably stratified. Using the above forms for the density dependence and the background temperature field, non-dimensionalizing quantities with respect to the reference length d, the reference time d^2/κ and the reference temperature βd and $\beta^* d$. The set of two-dimensional, dimensionless Boussinesq equations is

$$\frac{\partial\theta}{\partial t} + \frac{\partial(\psi,\theta)}{\partial(x,z)} = -\psi_x + \nabla^2\theta \quad (1)$$

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

$$Pr^{-1}\left[\nabla^2\psi_t + \frac{\partial(\psi,\nabla^2\psi)}{\partial(x,z)}\right] = R(z - 1 + \theta)\theta_x - R_s(z - 1 + S)S_x + \nabla^4\psi \quad (3)$$

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where $Pr = \frac{\nu}{\kappa}$ is the Prandtl number,

$\tau^* = \kappa_s/\kappa$ is the Diffusivity parameter,

$R = 2\alpha g \beta^2 d^5/\kappa\nu$ is the Penetration Rayleigh number,

$R_s = 2\alpha_s g {\beta^*}^2 d^5/\kappa\nu$ is the Penetration solute Rayleigh number.

The two boundaries are assumed to be rigid (no-slip) and hence the velocity, temperature and concentration boundary conditions in the dimensionless form are given by

$\psi = \psi_z = 0$ on □ = 0 and □

□$_□$ = □$_□$ = 0 on □ = 0 and □

where □ = (−□$_□$, 0, □$_□$) is utilized.

Linear stability analysis

For all values of the parameters □, □$_□$, □, □* and □□ there exists the exact solution

□ = □ = □ = 0 for all □, □, □

to the set of equations (1) to (3). This solution is the basic state solution corresponds to the linear temperature and salinity variation. The aim of section is to describe the critical values of the parameters at which the system becomes unstable to small perturbations. Therefore, we assume the solution of the linearized equations to be of the form

□ = Re{□(□)exp[□□ + □□□]}
□ = Re{□(□)exp[□□ + □□□]}
□ = Re{□□Ψ(□)exp[□□ + □□□]}

so that the disturbance has an assumed horizontal wave number '□' and is some temporal growth rate □. In general, □ may be complex(i.e., □ = □$_□$ + □□$_□$). For marginal state □$_□$ = □$_□$ = 0 and for an oscillatory mode □$_□$ = 0 and □$_□$ ≠ 0. The eigenvalue problem for □$_□$(□, □, □$_□$, □*)is thus

$$\left.\begin{array}{c}(\square^2-\square^2-\square)\square=-\square^2\Psi\\ [\square^*(\square^2-\square^2)-\square]\square=-\square^2\Psi\\ (\square^2-\square^2)\left(\square^2-\square^2-\frac{\square}{\square\square}\right)\Psi=\square(1-\square)\square\\ \square\square=\Psi=\square\Psi=0 \text{ on } \square=0 \text{ and } \square\end{array}\right\}\quad(4)$$

where $\square$ stands for the operator $\square/\square\square$. The condition for marginal stability in the case of ordinary convection without constraints is $\mathrm{Re}\{\square\}=0$ and $\mathrm{Im}\{\square\}=0$. In the case of penetrative convection, there is no available proof for concluding the validity of ‘principle of exchange of stabilities’ for the eigenvalue problem (7) to (10). For our purposes we assume (this assumption has been confirmed by a number of numerical solutions) that the principle holds. The eigenvalue problem then reduces to finding the critical Rayleigh number $\square_{\square}(\square,\square,\square_{\square},\square^*)$ which is the smallest eigenvalue of

$$\left.\begin{array}{c}(\square^2-\square^2)\square=-\square^2\Psi\\ [\square^*(\square^2-\square^2)]\square=-\square^2\Psi\\ (\square^2-\square^2)^2\,\Psi=\square_{\square}(1-\square)\square-\square_{\square}(1-\square)\square\\ \square\square=\square\square=\Psi=\square\Psi=0 \text{ on } \square=0 \text{ and } \square\end{array}\right\}\quad(5)$$

From (8), it is evident that in the case of double

$$\left.\begin{array}{c}\square_{\square}=\square_{\square 0}+\square^2\square_{\square 2}+\square^4\square_{\square 4}+\cdots\ldots\ldots\ldots\ldots\\ \square=\square_0(\square)+\square^2\square_2(\square)+\square^4\square_4(\square)+\cdots\ldots\ldots\\ \square=\square_0(\square)+\square^2\square_2(\square)+\square^4\square_4(\square)+\cdots\ldots\ldots\\ \Psi=\Psi_0(\square)+\square^2\Psi_2(\square)+\square^4\Psi_4(\square)+\cdots\ldots\ldots\end{array}\right\}$$

The zeroth-order solution is simply

$$\left.\begin{array}{c}\square_0=1\\ \square_0=1/\square^*\\ \Psi_0=(\square_{\square 0}-\square_{\square}^*)\square^2(\square-\square)^2(5-2\square-\square)/5!\end{array}\right\}$$

where $\square_{\square}^*=\square_{\square}/\square^*$

From the solvability condition $\square_{\square 0}$ is determined and is simply

$$(\square_{\square 0}-\square_{\square}^*)=\frac{6!}{\square^4\left(1-\frac{1}{2}\square\right)}$$

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Calculating quantities of the next two orders, the following formulae for $\square_{\square 2}$ is obtained

$$\square_{\square 2} = \frac{30(211\square^2 - 884\square + 884)}{1001\square^2\left(1 - \frac{\square}{2}\right)^3}$$

Weakly nonlinear analysis

Linear theory has its own limitations. Nonlinear theory is capable of unfolding many interesting results associated with the phenomenon.

We introduce the scale

$$\square = \square\square, \quad \square = \square^4\square$$

$$\square_0 = \square_0(\square, \square)$$

$$\left.\begin{array}{r} \square = \square_0 + \square^2\square_2 + \square^4\square_4 + \square^6\square_6 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \\ \square(\square,\square,\square) = \square^2\square_0(\square,\square,\square) + \square^4\square_2(\square,\square,\square) + \square^6\square_4(\square,\square,\square) + \cdots\ldots\ldots. \\ \square(\square,\square,\square) = \square^2\square_0(\square,\square,\square) + \square^4\square_2(\square,\square,\square) + \square^6\square_4(\square,\square,\square) + \cdots\ldots\ldots\ldots \\ \Psi(\square,\square,\square) = \square^3\Psi_0(\square,\square,\square) + \square^5\Psi_2(\square,\square,\square) + \square^7\Psi_4(\square,\square,\square) + \cdots\ldots\ldots. \end{array}\right\}$$

(6)

$$\left.\begin{array}{r} \square^2\square_\square = \Psi_{\square-2\square} - \square_{\square-2\square\square} + \square_{\square-4\square} + \sum_{\square=4}^{\square}\frac{\square(\Psi_{\square-4}, \square_{\square-\square})}{\square(\square,\square)} \\ \square\square_\square = 0 \text{ on } \square = 0 \text{ and } \square \end{array}\right\} \qquad (7)$$

$$\left.\begin{array}{r} \square^*\square^2\square_\square = \Psi_{\square-2\square} - \square^*\square_{\square-2\square\square} + \square_{\square-4\square} + \sum_{\square=4}^{\square}\frac{\square(\Psi_{\square-4}, \square_{\square-\square})}{\square(\square,\square)} \\ \square_\square = 0 \text{ on } \square = 0 \text{ and } \square \end{array}\right\} \qquad (8)$$

$$\square^4\Psi_{\square} = -\sum_{\square=0}^{\square} \square_{\square-\square}(\square - 1)\,\square_{\square\square} - \sum_{\square=2}^{\square} \square_{\square-\square}\left[\sum_{\square=2}^{\square} \square_{\square-\square}\square_{\square-2\square}\right] + \square_{\square}(\square - 1)\square_{\square\square} + \square_{\square}\sum_{\square=2}^{\square}[\square_{\square-2}\square_{\square-\square\square}] - 2\Psi_{(\square-2)\square\square\square\square} - \Psi_{(\square-4)\square\square\square\square} + \square\square^{-1}\left[\Psi_{(\square-4)\square\square\square} + \Psi_{(\square-6)\square\square\square} + \sum_{\square=4}^{4}\frac{\square(\Psi_{\square-\square},\ \Psi_{(\square-4)\square\square} + \Psi_{(\square-6)\square\square})}{\square(\square,\square)}\right]$$

$\Psi_{\square} = \square\Psi_{\square} = 0$on $\square = 0$ and $\square$

$\square\square_{\square} = \square\square_{\square} = 0$ on $\square = 0$ and $\square$

Where the quantities have the negative

$$\int_0^{\square}\left[\Psi_{\square\square} - \square_{\square\square\square} + \square_{\square-2\square} + \sum_{\square=2}^{\square}\frac{\square(\Psi_{\square-2},\ \square_{\square-\square})}{\square(\square,\ \square)}\right]\square\square = 0$$

$$\int_0^{\square}\left[\Psi_{\square\square} - \square^{*}\square_{\square\square\square} + \square_{\square-2\square} + \sum_{\square=2}^{\square}\frac{\square(\Psi_{\square-2},\ \square_{\square-\square})}{\square(\square,\ \square)}\right]\square\square = 0$$

Must be satisfied for all values of $\square$ for which $\square_{\square}$, $\square_{\square}$ and $\Psi_{\square}$ are known.

At zeroth order the right hand side of is zero and hence

$\square_0 = \square_0(\square,\square)$

$\square_0 = \square_0(\square,\square)/\square^{*}$

$\Psi_0 = \square_{10}(\square)\square_{0\square} = \square_{0\square}(\square_0 - \square^{*}_{\square}) - \square^2(\square - \square)^2(5 - 2\square - \square)/5!$

where $\square_2 = \frac{\square_2}{(\square_{\square 0}-\square^{*}_{\square})}$,$\square(\square) = \frac{\square_{\square 2}}{(\square_{\square 0}-\square^{*}_{\square})}$ $\square(\square) = \frac{1}{(1-\frac{\square}{2})}$

BY introducing the scale

$$\square = \frac{\square}{\square_{\square 0}} - 1 = \square^2\square_2\square(\square,\square) = \square^2\square_0(\square,\square)$$

into

$$\square_{\square} + \square\square_{\square\square\square\square} + \square\square_{\square\square} - \square(\square\square_{\square})_{\square} = 0$$

Which is in terms of unscaled variables.

3. Results and discussion

The results of the study pertaining to this chapter are presented through graphs and are discussed. The following results are predicted.

i)The zeroth order solution (linear theory) is given by (). Explicitly, the solution is same as in the case of ordinary penetrative convection(Roberts 1985) but implicitly the effect of concentration is involved.

ii) The vertical structure of the fluid velocity is revealed through$\Psi_0(\square)$. Inthe case of double diffusive penetrative convection, a factor $(\square_{\square 0} - \square^*_{\square})$multiplies the polynomial in $\square$. The horizontal velocities are given by$-\Psi_0$ times a function of $\square$, while the vertical velocities are given byΨ_0 times the derivative of the same function of $\square$. Further, the polynomial in Ψ_0 is a fifth degree in $\square$.

iii) A number of interesting aspects of this leading order solution (zerothorder) exists. The critical Rayleigh number, irrespective of solute concentration, has the asymptotic form when the layer depth$\square$becomes small.

iv) In figure (2) the graph of$\square_{\square 0}$ vs$\square_{\square}$ is drawn for h$\square = 0.5$ and $\square = 1.5$, and$\square^* = 0.1$ and $\square^* = 0.316$. It is observed that as $\square$ decreases $\square_{\square 0}$ increases for allvalues of$\square_{\square}$. $\square_{\square 0}$ assumes a minimum at $\square_{\square} = 3$ in both the cases andfor sufficiently large $\square_{\square}$, i.e., for $\square_{\square} > 3.5$, increases drastically. Further, for$\square \geq 1.25$ figure (3), $\square_{\square 0}$ assumes zero value for $\square_{\square} < 3$. Also, the effect of$\square^*$ is insignificant.

v) In figure (4), the graphs of $(\square_{\square 0} - \square^*_{\square})$ vs $\square$ for$\square^* = 0.1$ and $\square^* = 0.316$ arepresented. For values of $\square > 0.5$,$(\square_{\square 0} - \square^*_{\square})$ assumes a zero value. Fromthis it is clear that, by the proper choice of$\square^*_{\square}$, $\square_{\square 0}$ can be made toassume positive values even for largevalues of $\square$, which is not possiblein ordinary penetrative convection.

vi) In figure (5), the graphs of $\Psi_0(\square)$vs $\square$ are presented for various valuesof $\square$. Since$(\square_{\square 0} - \square_{\square}^{*}) \to \infty$as $\square = 2$, and is negative for $\square > 2$, we can interpret that the singularity is due to the assumption of the preferred long horizontal scales. Further, the negative Rayleigh number for $\square > 2$ may beinterpreted as a situation where the quadratic thermal expansion coefficient if negative, in which case, the inverse situation of a gravitationally unstable fluid layer lies above a thinner stable layer. Another important result is that in the region $5 - 2\square < \square < \square$, there exists acounter cell of the stably stratified fluid figure (5).
vii) In figure (6) the graph of$\square_{\square 2}$ vs $\square$ is presented. The graph reveals that subcritical motions do exist for $\square > 1.5$ and a proper choice of $\square_{\square}^{*}$.This graph also justifies the conclusion that convection on a long horizontal scale is inhibited by setting the overlying stably stratified fluid to motion and for $\square \geq 2$ an infinitely large number is needed for the system.
viii) Finally, it is concluded that long horizontal scales are only feasible for $\square < 2$ and for larger h the convective motion will have finite horizontal periodicity.

4.Conclusion

The advantage of considering double diffusive penetrative convection is that by the proper choice of the solute parameter it is possible to have a good control over the penetrative convection under consideration. Once again it is stressed that the specification of heat and mass fluxes on the boundaries have the following two additional special advantages:
i) A remarkable analytical simplification is available.

ii) In geophysical applications there is no assurance that the commonly used boundary conditions of fixed temperature and concentration are appropriate. Finally, it can be concluded that the results are in excellent agreement with the available results in the limiting cases and the questions posed in the introduction are answered.

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Figures:

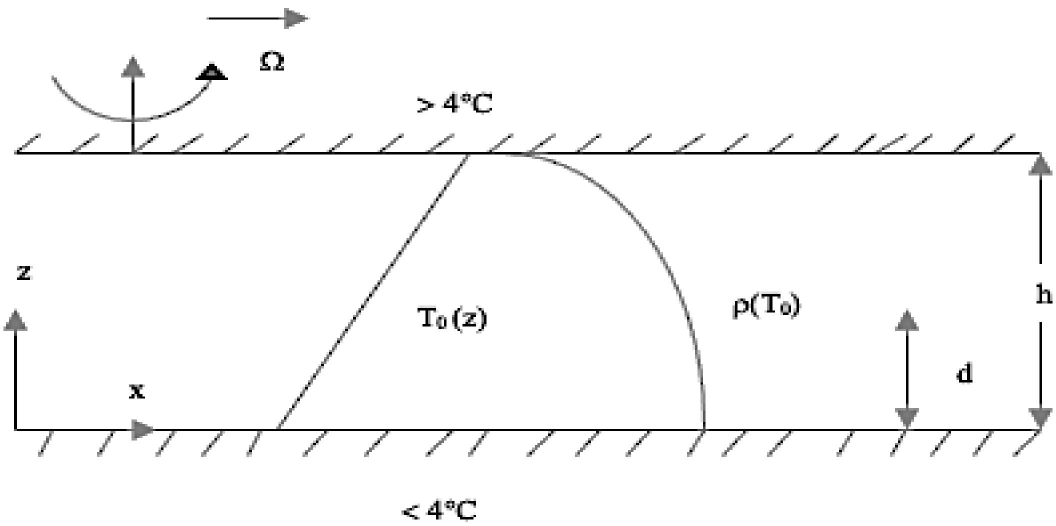

Figure 1: Conductive state in ice water convection

h=0.25	h=0.5	h=0.75	h=1.0	h=1.25	h=1.5	h=1.75	Rs
210.7	15.4	3.7	1.5	0.886	0.669	0.714	10
211.6	16.3	4.6	2.4	1.17	1.15	1.16	100
220.6	25.3	13.6	11.4	10.1	10.5	10.1	1000
310.6	115.5	103.6	101.4	100.1	100.1	100.1	10000

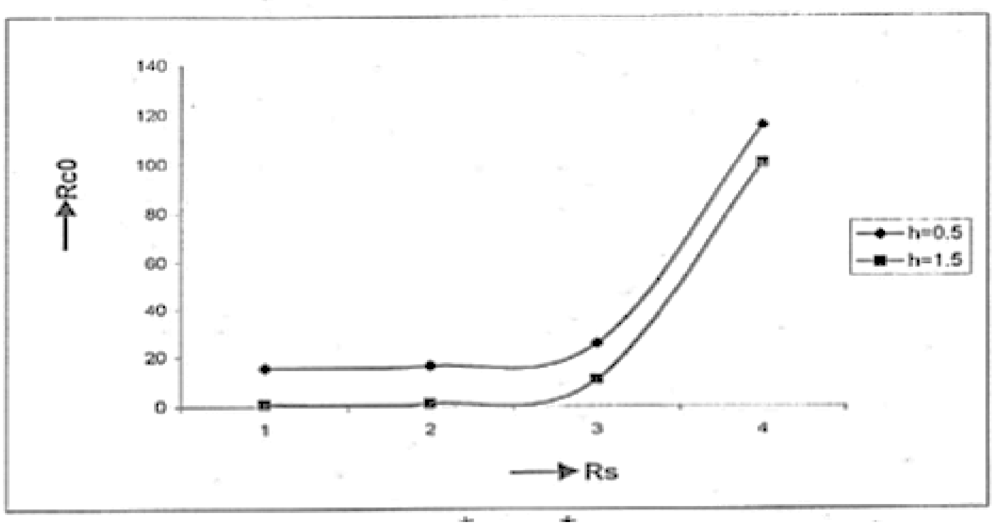

Figure 2: Rco V/S RS for Tou =0.1, Tou=0.316 and different values of z

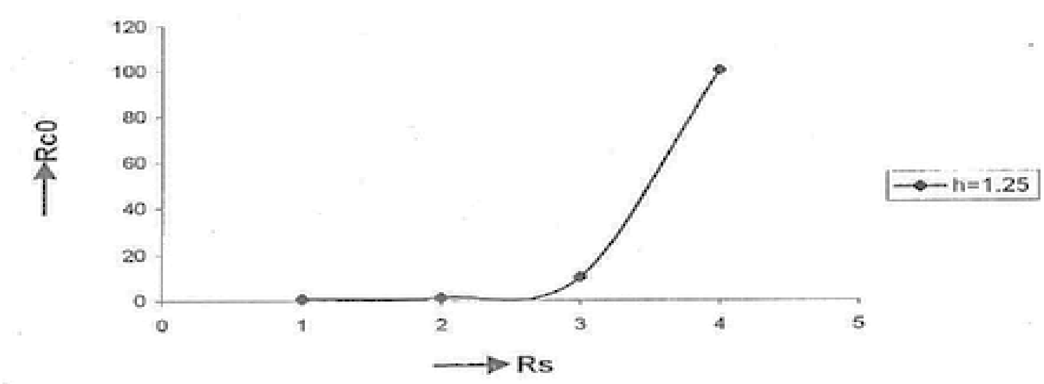

Figure 3: Rc0 V/s Rs for Tou = 0.1, Tou= 0.316

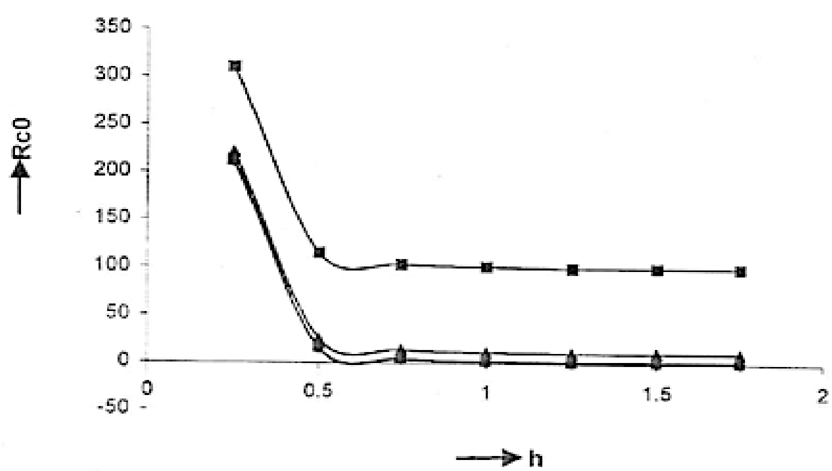

Figure 4:Rc0 V/s h for Tou = 0.1, Tou = 0.316 Rc0= Rc0- Rs*

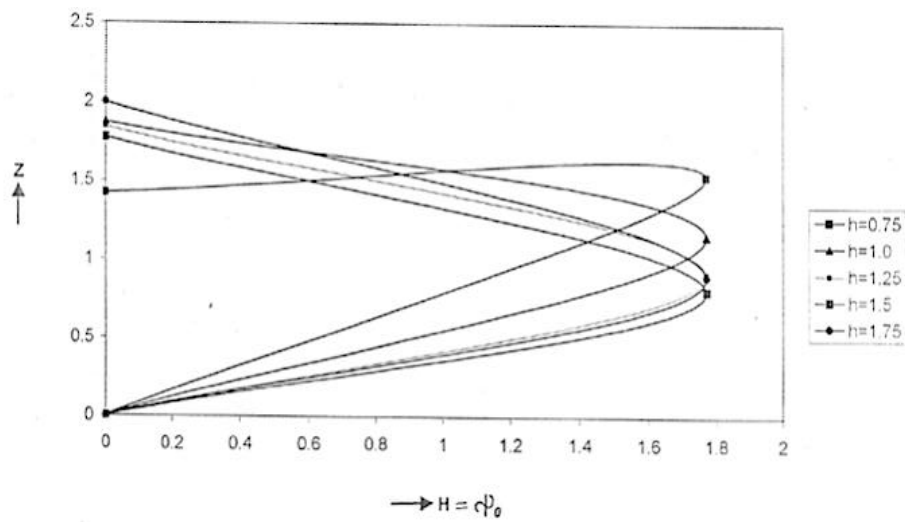

Figure 5: Z V/s H for Tou =0.1 and Tou =0.316

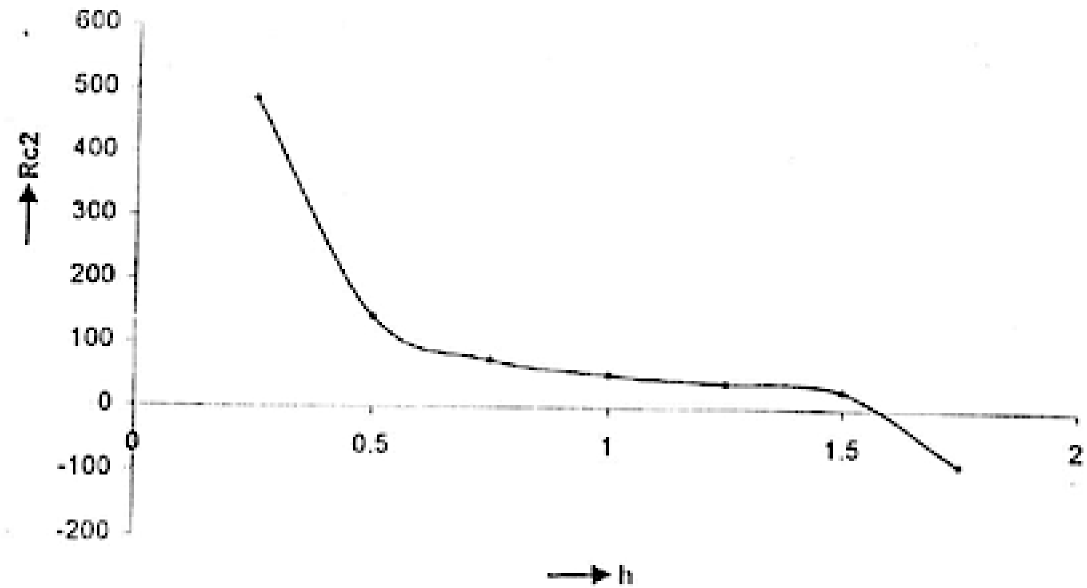

Figure 6: Rc2 V/s H