Results on Thermal Stability Analysis for Equal Thermal Diffusivity and Solute Diffusivity of an Incompressible Viscous Fluid

Abstract

In this paper we examine the framework of linear stability analysis with the model suggested by Brinkman, the thermal instability of an incompressible viscous fluid in the presence of magnetic field confined in an anisotropic porous medium. Uniform temperature and concentration gradients are maintained along z-axis. The interesting properties associated with magnetic field have attracted a number of different results on stability by using perturbations and normal mode analysis. In present paper, the important results obtained include different conditions of stability, existence of oscillatory modes, non-oscillatory modes, discussion for stable and unstable modes, if exist in the problem. A particular case that equal thermal diffusivity and solute diffusivity considered and obtained different types of results on stability.

Introduction

Instability of compressible or incompressible flows has been studied extensively by a number of research workers in past few decades. In almost all such investigations, the Boussinesq's approximation is used to simplify the equations of motion. Many research workers examined the shear flow instability of an incompressible visco-elastic second order fluid in a porous medium in which the modified Darcy's law is replaced by the celebrated Brinkman model so that both the inertia and viscous terms are included in their usual forms. The behavior of conducting fluid depends upon different situations in the absence and in the presence of a magnetic field. The interesting properties associated with a magnetic field, have attracted a number of research workers to work in this direction.

Review of the Literature

In a porous medium the instability of fluid flows under varying assumptions has been well summarized by Scheidegger[1] and Yih[2, 3]. While investigating the flows or flow instabilities through porous medium, the liquid flow has been assumed to be governed by Darcy's law[4] by most of the research workers, which neglects the inertial forces on the flow. Brinkman[5] proposed a plausible modification to Darcy's law that takes into account the viscous forces. Instability of compressible or incompressible flows has been studied extensively by a number of research workers in past few decades. In almost all such investigations, the Boussinesq's approximation is used to simplify the equations of motion. Goel, Agrawal and Jaimala[6] examined the shear flow instability of an incompressible visco-elastic second order fluid in a porous medium in which the modified Darcy's law is replaced by the celebrated Brinkman model so that both the inertia and viscous terms are included in their usual forms. The behavior of conducting fluid is very much different in the absence and in the presence of a magnetic field.

The interesting properties associated with a magnetic field, have attracted a number of research workers to work in this direction. Bansal and Agrawal[7] have studied the thermal instability of a compressible shear flow in the presence of a weak applied magnetic field. The problem of compressible shear layer in the presence of a weak applied magnetic field through porous medium has been studied by Bansal, Bansal and Agrawal[8].

Subodh Kumar Rana
Assistant Professor,
Deptt.of Mathematics,
M.M.College,
Modinagar

The thermosolutal convection in a porous medium was studied by Nield[9], Chakrabarti and Gupta[10] and Sharma etal[11]. Khare and Sahai[12] have studied the thermosolutal convection in a heterogeneous fluid layer in a porous medium in the presence of magnetic field.

Using the model as suggested by, Banerjee and Agrawal[13] investigated the thermal instability of parallel shear flows in the presence of both adverse and non-adverse temperature gradients. In the present paper, we have examined within the framework of linear analysis, the thermosolutal instability of an incompressible viscous fluid in the presence of magnetic field confined in an anisotropic porous medium.

Though some literature has been reported in which magnetic field destabilizes a wave number range known to be state in its absence. [Kent[14] , Gilman[15] and Jain[16]] in most of the situations and magnetic field has a stabilizing effect. Kirti Prakash and Naresh Kumar[17] examined the thermosolutal instability of a Maxwellian visco-elastic fluid in porous medium in the presence of variable gravity and suspended particles. Anshu Agarwal, Jaimala and S.C.Agrawal[18] examined the shear flow instability of visco-elastic fluid in an anisotropic porous medium. In this paper an attempt has been made to examine the thermosolutal instability of an incompressible, viscous fluid in the presence of magnetic field and confined in a porous medium following Brinkman model.

Formulation of the problem

In this paper, we discussed the thermosolutal instability of an incompressible, viscous fluid confined in an anisotropic porous medium in the presence of magnetic field. The fluid system has been considered between two rigid boundaries talking along x-axis and situated at $z = 0,$ and $z = d$ respectively. The magnetic field has also been considered along x-axis. Uniform temperature and concentration gradients are maintained along z-axis. Equations expressing the conservation of momentum, mass, magnetic field, temperature, solute mass concentration and equation of state in Brinkman model are:

(2.1) $\dfrac{\rho}{\phi}\left[\dfrac{\partial \mathbf{v}}{\partial t} + \dfrac{1}{\phi}(v.\nabla)v\right] = -\nabla p + \rho g + \mu\left(\dfrac{1}{\phi}\nabla^2 - \dfrac{1}{k_1}\right)v$

$+ \dfrac{1}{4\pi}(\nabla \times \mathbf{H}) \times \mathbf{H},$

(2.2) $\qquad\qquad \nabla.\mathbf{v} = 0,$

(2.3) $\qquad\qquad \nabla.\mathbf{H} = 0,$

(2.4) $\qquad\qquad \dfrac{\partial \mathbf{H}}{\partial t} = \dfrac{1}{\phi}\, \nabla \times (\mathbf{v} \times \mathbf{H}),$

(2.5) $\qquad\qquad \dfrac{\partial T}{\partial t} + \dfrac{1}{\phi}\,(\mathbf{v}.\nabla)T = \kappa \nabla^2 T,$

(2.6) $\qquad\qquad \dfrac{\partial C}{\partial t} + \dfrac{1}{\phi}(\mathbf{v}.\nabla)C = \kappa'\nabla^2 C,$

(2.7) $\quad \rho = \rho_0\left[1 - \alpha(T - T_0) - \alpha'(C - C_0)\right],$

where

$\mathbf{v}$	=	fluid velocity,
$\mathbf{H}$	=	magnetic field vector,
ρ	=	density,
μ	=	viscosity coefficient,
κ	=	thermal diffusivity,
κ'	=	solute diffusivity
α	=	thermal expansion coefficient,
α'	=	solute expansion coefficient,
ϕ	=	medium porosity,
k_1	=	(k_x, k_y, k_z) medium permeability,
g	=	(0, 0,–g), the gravitational

acceleration. The suffix zero indicates the reference state. The basic state under investigation is, therefore, characterized by

(2.8) $\mathbf{v} = (0,0,0), \qquad\qquad \mathbf{H} = (H_0,0,0),$

$\qquad T = T_0 - \beta z \qquad and \qquad C = C_0 - \beta' z,$

where $\beta\left(= \dfrac{T_1 - T_2}{d}\right)$ and $\beta'\left(= \dfrac{C_1 - C_2}{d}\right)$ may be either positive or negative. Here T_1 and C_1 (T_2 and C_2) are the temperature and concentration at the lower plate (upper plate), respectively.

Perturbations and Normal Mode Analysis

The basic state (2.8) is slightly perturbed so that every physical quantity is assumed to be the sum of a mean and fluctuating component, later designated as prime quantities and assumed to be very small in comparison to their equilibrium state values. We assume that the small disturbances are the functions of space and time variables. Hence the perturbed flow may be represented as

(3.1)
$$\begin{aligned}
\mathbf{v} &= (0,0,0) + (u',v',w'), \\
H &= (H_0,0,0,) + (h'_x, h'_y, h'_z), \\
T &= T(z) + \theta', \\
C &= C(z) + \gamma', \\
\rho &= \rho_0(z) + \rho', \\
and\ p &= p_0(z) + p',
\end{aligned}$$

where $(u',v',w'), (h'_x, h'_y, h'_z), \theta', \gamma', \rho'\ and\ p'$ are respectively the perturbations in fluid velocity, magnetic field, temperature, concentration, density and pressure.

We substitute (3.1) into the governing equations (2.1) to (2.7) and linearize them. Analysing the disturbances into normal modes, we assume that any perturbation quantity $f'(x,y,z,t)$ is of the form

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$(3.2) \qquad f'(x,y,z,t)= f(z)\exp\left[\sigma t+i(ax+by+cz)\right],$

where the real parts of the expressions denote the corresponding physical quantities a, b and c are the real wave numbers along the x, y and z directions respectively and σ, a time constant, is complex in general.

For the considered form of the perturbations in equation (3.2), linearized equations become

$(3.3) \qquad \dfrac{\rho_0}{\phi}\sigma u =-iap-\mu\left(\dfrac{l^2}{\phi}+\dfrac{1}{k_x}\right)u,$

$(3.4) \quad \dfrac{\rho_0}{\varphi}\sigma v = -ibp - \mu\left(\dfrac{l^2}{\varphi} + \dfrac{1}{k_y}\right)v + \dfrac{H_0}{4\pi}\left(iah_y - ibh_x\right),$

$(3.5) \quad \dfrac{\rho_0}{\phi}\sigma w = -icp - g\rho - \mu\left(\dfrac{l^2}{\phi}+\dfrac{1}{k_z}\right)w + \dfrac{H_0}{4\pi}\left(iah_z - ich_x\right),$

$(3.6) \qquad au+bv+cw=0,$

$(3.7) \qquad ah_x+bh_y+ch_z=0,$

$(3.8) \qquad \sigma h_x = \dfrac{-H_0}{\phi}(ibv+icw),$

$(3.9) \qquad \sigma h_y = \dfrac{H_0 iav}{\phi},$

$(3.10) \qquad \sigma h_z = \dfrac{H_0 iaw}{\phi},$

$(3.11) \qquad \left(\sigma+\kappa l^2\right)\theta=\dfrac{\beta w}{\phi},$

$(3.12) \qquad \left(\sigma+\kappa' l^2\right)\gamma=\dfrac{\beta' w}{\phi}$

$(3.13) \qquad \rho=-\rho_0\left(\alpha\theta+\alpha'\gamma\right).$

and
$(3.14) \qquad l^2 = a^2 + b^2 + c^2 .$

Equations (3.11) to (3.13) yield

$(3.15) \qquad \rho=-\dfrac{\rho_0}{\phi}\left\{\dfrac{\alpha\beta\left(\sigma+\kappa' l^2\right)+\alpha'\beta'\left(\sigma+\kappa l^2\right)}{\left(\sigma+\kappa l^2\right)\left(\sigma+\kappa' l^2\right)}\right\}w.$

After eliminating various physical quantities from these equations, we obtain the final stability equation as

(3.16)

$$\dfrac{\rho_0}{\phi}\sigma l^2 =-\mu\left(r'm^2+rc^2\right)-\dfrac{a^2 H_0^2 l^2}{4\pi\phi\sigma}$$

$$+\dfrac{g\rho_0}{\phi}m^2\left\{\dfrac{\alpha\beta}{\sigma+\kappa l^2}+\dfrac{\alpha'\beta'}{\sigma+\kappa' l^2}\right\},$$

where $\qquad m^2 = a^2+b^2 ,$

with $\qquad r=\dfrac{l^2}{\phi}+\dfrac{1}{k}$

and $\qquad r'=r$ at $k = k_z$

On simplifying equation (3.16), after multiplying by $\sigma*$ (complex conjugate of σ) in numerator and denominator and substituting $\sigma=\sigma_r+i\sigma_i$, we get

(3.17)

$$\dfrac{\rho_0 l^2}{\phi}(\sigma_r+i\sigma_i) = -\mu\left(m^2 r'+c^2 r\right)-\dfrac{a^2 H_0^2 l^2}{4\pi\phi|\sigma|^2}(\sigma_r-i\sigma_i)$$

$$+\dfrac{g\rho_0 m^2}{\phi}\left[\dfrac{\alpha\beta}{\left|\sigma+\kappa l^2\right|^2}\left\{\left(\sigma_r+\kappa l^2\right)-i\sigma_i\right\}\right.$$

$$\left.+\dfrac{\alpha'\beta'}{\left|\sigma+\kappa' l^2\right|^2}\left\{\left(\sigma_r+\kappa' l^2\right)-i\sigma_i\right\}\right].$$

Analytical Discussion

In this section, we shall prove some important results with the help of equation (3.17).

Theorem 1

The non- oscillatory modes are stable under the condition

$$\alpha\beta + \alpha'\beta' < 0$$

Proof

The real part of equation (3.17) yields

$(4.1) \qquad \sigma_r\left[\dfrac{\rho_0 l^2}{\phi}+\dfrac{a^2 H_0^2 l^2}{4\pi\phi|\sigma|^2}-\dfrac{g\rho_0 m^2}{\phi|\sigma+\kappa l^2|^2}(\alpha\beta+\alpha'\beta')\right]$

$$= -\mu(m^2 r' + c^2 r)$$
$$+\dfrac{g\rho_0 m^2 \kappa l^2}{\phi|\sigma+\kappa l^2|^2}(\alpha\beta+\alpha'\beta')$$

For non-oscillatory modes, the above equation reduces to

$$\sigma_r\left[\dfrac{\rho_0 l^2}{\phi}+\dfrac{a^2 H_0^2 l^2}{4\pi\phi|\sigma|^2}+\dfrac{g\rho_0 m^2}{\phi|\sigma+\kappa l^2|^2}|\alpha\beta+\alpha'\beta'|\right]$$
$$= -\mu(m^2 r' + c^2 r)$$
$$-\dfrac{g\rho_0 m^2 \kappa l^2}{\phi|\sigma+\kappa l^2|^2}|\alpha\beta+\alpha'\beta'|$$

In L.H.S. in big bracket the expression is positive definite and in R.H.S. the expression is negative definite so σ_r is negative and hence the modes are stable.

Theorem 2

If non-oscillatory modes exist under the condition $\alpha\beta + \alpha'\beta' < 0$, then for stable modes, we must necessarily have

$$|\sigma|^2 > \dfrac{gm^2}{l^2}(\alpha\beta+\alpha'\beta') - \dfrac{a^2 H_0^2}{4\pi\rho_0}$$

Proof

If non-oscillatory modes exist under the

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condition $\alpha\beta + \alpha'\beta' < 0$, then equation (4.1) becomes

(4.2)
$$\sigma_r\left[\frac{\rho_0 l^2}{\phi} + \frac{a^2 H_0^2 l^2}{4\pi\phi|\sigma|^2}\right.$$
$$\left. - \frac{g\rho_0 m^2}{\phi|\sigma+\kappa l^2|^2}(\alpha\beta + \alpha'\beta')\right]$$
$$= -\mu(m^2 r' + c^2 r)$$
$$- \frac{g\rho_0 m^2 \kappa l^2}{\phi|\sigma+\kappa l^2|^2}|\alpha\beta + \alpha'\beta'|$$

For non-oscillatory stable modes, the above equation (4.2) becomes

$$\frac{\rho_0 l^2}{\phi} + \frac{a^2 H_0^2 l^2}{4\pi\phi|\sigma|^2} - \frac{g\rho_0 m^2}{\phi|\sigma+\kappa l^2|^2}(\alpha\beta + \alpha'\beta') > 0$$

or

$$\frac{g\rho_0 m^2}{\phi|\sigma+\kappa l^2|^2}(\alpha\beta + \alpha'\beta') < \frac{\rho_0 l^2}{\phi} + \frac{a^2 H_0^2 l^2}{4\pi\phi|\sigma|^2}$$

or

$$\frac{g\rho_0 m^2}{\phi|\sigma|^2}(\alpha\beta + \alpha'\beta') < \frac{\rho_0 l^2}{\phi} + \frac{a^2 H_0^2 l^2}{4\pi\phi|\sigma|^2}$$

$$\frac{g\rho_0 m^2}{|\sigma|^2}(\alpha\beta + \alpha'\beta') < \rho_0 l^2 + \frac{a^2 H_0^2 l^2}{4\pi|\sigma|^2}$$

or

$$g\rho_0 m^2(\alpha\beta + \alpha'\beta') < \rho_0 l^2|\sigma|^2 + \frac{a^2 H_0^2 l^2}{4\pi}$$

or

$$|\sigma|^2 > \frac{gm^2}{l^2}(\alpha\beta + \alpha'\beta') - \frac{a^2 H_0^2}{4\pi\rho_0}$$

which proves the theorem.

Theorem3

If the non-oscillatory modes exist under the condition $\alpha\beta + \alpha'\beta' > 0$, then for unstable modes we must necessarily have

$$|\sigma|^2 < \frac{g\rho_0 m^2 \kappa l^2}{\phi\mu(m^2 r' + c^2 r)}|\alpha\beta + \alpha'\beta'|$$

Proof

If we impose the condition $\alpha\beta + \alpha'\beta' > 0$ in the equation (4.1) then we get

$$\sigma_r\left[\frac{\rho_0 l^2}{\phi} + \frac{a^2 H_0^2 l^2}{4\pi\phi|\sigma|^2} - \frac{g\rho_0 m^2}{\phi|\sigma+\kappa l^2|^2}|\alpha\beta + \alpha'\beta'|\right]$$
$$= -\mu(m^2 r' + c^2 r)$$
$$+ \frac{g\rho_0 m^2 \kappa l^2}{\phi|\sigma+\kappa l^2|^2}|\alpha\beta + \alpha'\beta'|$$

Now for non-oscillatory unstable modes, we must necessarily have

$$\frac{g\rho_0 m^2 \kappa l^2}{\phi|\sigma+\kappa l^2|^2}|\alpha\beta + \alpha'\beta'| > \mu(m^2 r' + c^2 r)$$

or

$$\frac{g\rho_0 m^2 \kappa l^2}{\phi\mu(m^2 r' + c^2 r)}|\alpha\beta + \alpha'\beta'| > |\sigma+\kappa l^2|^2$$

or

$$|\sigma|^2 < \frac{g\rho_0 m^2 \kappa l^2}{\phi\mu(m^2 r' + c^2 r)}|\alpha\beta + \alpha'\beta'|$$

which proves the theorem.

Remark

Also for unstable modes the consistency of the above equation we must necessarily have

$$|\sigma|^2 > \frac{gm^2}{l^2}|\alpha\beta + \alpha'\beta'| - \frac{a^2 H_0^2}{4\pi\rho_0}$$

As for unstable modes the validity of the above equation is

$$\frac{\rho_0 l^2}{\phi} + \frac{a^2 H_0^2 l^2}{4\pi\phi|\sigma|^2} > \frac{g\rho_0 m^2}{\phi|\sigma+\kappa l^2|^2}|\alpha\beta + \alpha'\beta'|$$

or

$$|\sigma|^2\rho_0 + \frac{a^2 H_0^2}{4\pi} > \frac{g\rho_0 m^2}{l^2}|\alpha\beta + \alpha'\beta'|$$

or

$$|\sigma|^2 > \frac{gm^2}{l^2}|\alpha\beta + \alpha'\beta'| - \frac{a^2 H_0^2}{4\pi\rho_0}$$

Theorem 4

Let the system be stable $(\sigma_r < 0)$ under the condition $\alpha\beta + \alpha'\beta' < 0$. Then σ_r and σ_i for stable modes $(\sigma_r < 0)$ satisfy the condition

$$\left[\sigma_r - \left(\frac{|B|}{2A} - \kappa l^2\right)\right]^2 + \sigma_i^2 > \frac{|B|^2}{4A^2},$$

where
$$A = \mu(m^2 r' + c^2 r) > 0$$

and
$$B = \frac{g\rho_0 m^2}{\phi}(\alpha\beta + \alpha'\beta') < 0 \cdot$$

Proof

The real part of equation (3.17) yields

(4.3)
$$\frac{\rho_0 l^2}{\phi}\sigma_r = -\mu(m^2 r' + c^2 r) - \frac{a^2 H_0^2 l^2}{4\pi\phi|\sigma|^2}\sigma_r$$
$$+ \frac{g\rho_0 m^2}{\phi}\frac{(\sigma_r + \kappa l^2)}{|\sigma+\kappa l^2|^2}(\alpha\beta + \alpha'\beta')$$

Now, if we impose the condition $\alpha\beta + \alpha'\beta' < 0$, then the equation (4.3) reduces to

(4.5)
$$\frac{\rho_0 l^2}{\phi}\sigma_r = -A - \frac{a^2 H_0^2 l^2}{4\pi\phi|\sigma|^2}\sigma_r + B.\frac{\sigma_r + \kappa l^2}{|\sigma+\kappa l^2|^2},$$

where
$$A = \mu(m^2 r' + c^2 r) > 0$$

and
$$B = \frac{g\rho_0 m^2}{\phi}(\alpha\beta + \alpha'\beta') < 0,$$

Now equation (4.5) can be written as

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$$\left[\frac{\rho_0 \, l^2}{\phi} + \frac{a^2 \, H_0^2 \, l^2}{4\pi\phi|\sigma|^2}\right]\sigma_r = -A + B.\frac{\left(\sigma_r + \kappa l^2\right)}{\left|\sigma + \kappa l^2\right|^2}$$

or

$$\left[\frac{\rho_0 \, l^2}{\phi} + \frac{a^2 \, H_0^2 \, l^2}{4\pi\phi|\sigma|^2}\right]\sigma_r = -A\left[\frac{\left(\sigma_r + \kappa l^2\right)^2 + \sigma_i^2 + \frac{|B|}{A}\left(\sigma_r + \kappa l^2\right)}{\left|\sigma + \kappa l^2\right|^2}\right]$$

or

$$\left[\frac{\rho_0 \, l^2}{\phi} + \frac{a^2 \, H_0^2 \, l^2}{4\pi\phi|\sigma|^2}\right]\sigma_r = -A\left[\frac{\left\{\left(\sigma_r + \kappa l^2\right) - \frac{|B|}{2A}\right\}^2 + \sigma_i^2 - \frac{|B|^2}{4A^2}}{\left|\sigma + \kappa l^2\right|^2}\right]$$

The term in brackets on L.H.S. is positive definite. Thus, for stable modes, we must necessarily have

$$\left[\sigma_r - \left(\frac{|B|}{2A} - \kappa l^2\right)\right]^2 + \sigma_i^2 > \frac{|B|^2}{4A^2},$$

which is the required condition.

Aim of the Study

Much work has been reported in last two decade on the stability of flows through porous media, under different physical situations When a fluid permeates a porous material the gross effect is represented by Darcy's law. We wish to examine the stability of flows through isotropic/anisotropic porous media. An effort will be made to use Forehheimer extended equation which includes the inertia effect not included in Darcy's model. Brinkman's modification of Darcy's law that takes into account the viscous force and the suggestions of Jaimala and Agrawal to replace Darcy's law, whenever required. We shall be interested in considering the Newtonian and non-Newtonian fluids depending upon the physical situation under consideration.

Conclusion

In this paper we observe the different types of the results when we consider thermal diffusivity and solute diffusivity both are equal. The stability depends on either $\alpha\beta + \alpha'\beta' > 0 \; or \; \alpha\beta + \alpha'\beta' < 0$. Uniform temperature and concentration gradients are maintathined along z-axis. The interesting properties associated with magnetic field have attracted a number of different results on stability by using perturbations and normal mode analysis. In present paper, the important results obtained include different conditions of stability, existence of oscillatory modes, non-oscillatory modes, discussion for stable and unstable modes, if exist in the problem. A particular case that equal thermal diffusivity and solute diffusivity considered and obtained different types of results on stability.

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