Natural Flow Convection in a Vertically Multilayered Porous Media with Varying Permiabilities (Part 1: Temperature and Flow Fields).

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Natural Flow Convection in a vertically multilayered
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سريان الحمل الطبيعى فى وسط مسامى رأسى
متعدد الطبقات ذو درجات نفاذيه مختلفه
(الجزء الاول: درجات الحراره وخطوط السريان)

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خلاصــــــــــه:

يحتوى هذا البحث على دراسه عدديه للحمل الطبيعى الحر فى حيز ثنائى البعد فى شكل متعامد مملوء بوسط مسامى متعدد الطبقات الرأسيه ومعرض لفرق فى درجات الحراره بين الجداريين الرأسيين. وقد اهتم هذا الجزء بدراسه تأثير عدم تساوى درجات النفاذيه للطبقات الرأسيه ونسبة البعد للطبقه الوسطى لوسط ثلاثى الطبقات الرأسيه على سلوك كل من درجات الحراره وسرعات وخطوط سريان المائع. الطبقه الاولى والثالثه لهما نفس العرض ودرجه النفاذيه، بينما يتراوح مدى التغير فى نسبه درجة النفاذيه للطبقه الوسطى الى الطبقات الاخرى K_r من 0,1 الى 10 ونسبه بعدها الى العرض الكلى W_r من 0 الى1. وقد حلت كل من معادلات الاستمرار وكميه الحركه والطاقه عدديا وذلك بأستخدام طريقه الفروق البسيطه. كما أجريت مقارنات مع النتائج التى حصل عليها لورياث وبراساد [13] أظهرت تطابقا جيدا وأثبتت صحه هذا النموذج. وقد لظهرت النتائج شده حساسيه شكل السريان والسرعه ودرجات الحراره داخل الوسط المسامى للتغير فى درجه النفاذيه.

ABSTRACT

Convective heat transfer through a vertical multilayered porous media is examined numerically. The examination is focused upon the effect of the nonuniform permeabilities of the sublayers, with vertical isothermal walls at different temperatures and horizontal perfect insulated walls. The study was done for a 3 layered porous medium in which the first and third layers have equal thicknesses and permeabilities, for a range of the permeability ratio K_r of the core region from 0.1 to 10 and a range of the width ratio of the inner sub-layer to the total width (W_r) varies form 0.0 to 1.0. This part is concerned with the effect of the variable permeabilty on the temperature and flow fields and the second part of this work [14], is concerned with the effect of the variable permeability

porous layers on the heat transfer. The governing equations have been written in terms of nondimensional variables and were solved using the finite difference method. A comparison is made with the results obtained by Lauriat and Prasad [13]. The comparison shows a very good agreement for the present results and hence proves the validity of the model. The results give a very good idea about the effect of the inhomogenity of the porous medium on the flow structure and temperatures.

1. INTRODUCTION

The heat transfer by natural convection across a porous medium heated from one side is a topic of fundamental importance in diverse fields such as thermal insulation engineering, geothermal reservoir dynamics and grain storage. The basic model used so far in the study of porous media heated from the sides consists of a 2-dimensional layer with vertical isothermal walls at different temperatures and with adiabatic top and bottom walls. This model has been investigated extensively during the past 20 years. The first study of the problem, an experimental one, was reported by Schneider [1]. He investigated the natural convection heat transfer through granular material under the condition of fixed height and width. The first extensive theoretical work on this problem was performed by Chan et al. [2]. Later on, these studies were followed by a series of investigations, out of which the notable theoretical solutions by Weber [3], Burns et al. [4] walker and Homsy [5], Bejan and Tien [6], Bejan [7], Simpkins and Blythe [8], Blythe et al. [9]. Weber [3] reports an Oseen-linearized analysis of the boundary layer regime in a tall layer; Weber's analysis was improved by Bejan [7] to account for the heat transfer vertically through the core and, in this way, to predict correctly the heat transfer rates revealed by experiments and by numerical simulations. Simpkins and Blythe [8] reported an alternative theory for the boundary layer regime based on an original closed form solution, and for temperature dependent viscosity [9]. The corresponding flow in the shallow layer heated from the sides was documented by Walker and Homsy [5]. They developed an asymptotic solution for the flow and temperature fields inside a shallow layer using the aspect ratio as the small parameter. They showed that unlike the in the tall layers the core region plays an active role in the heat transfer processes. An approximate integral type solution for the same geometry was reported by Bejan and Tien [6]. Tong and Subramanian [10] have presented a boundary layer analysis for a Brinkman model, and have reporeted significant contributions of the diffusion term at high Rayleigh and Darcy numbers. Furthermore, Poulikakos and Bejan [11] and Prasad and Tuntomo [12] have considered the Forchheimer-extended Darcy model to study the inertia effects on free convection in a vertical cavity. Lauriat and Prasad [13] considered the

Brinkman-extended Darcy equation of motion together with the transport term and examined the significance of each term.   Elkady [15] clarified numerically the effect of the dimensions of the   rectangular cavity on the heat transfer through the inclined cavity with variable inclination angles from 0 to 180.

The survied literature presented above have been concerned with natural convection in layers only filled with homogeneous porous medium, which may not be a good approximation for the porous layers in the real life. The purpose of this study is to analyse and understand the effect of the inhomogenity of the porous medium on the flow structure and the convective heat transfer in a vertical layered porous media with vertical isothermal walls at different temperatures. This part is concerned with the temperature and flow fields, and the effect of the variable permeability porous layers on the heat transfer is considered in the second part of this work [14].

2. MATHEMATICAL MODEL AND SOLUTION PROCEDURE

Consider a two-dimensional rectangular vertical cavity (shown in Fig.1) of width W and height H, filled with mtilayered porous medium. Each layer is homogenuous, isotropioc and has constant permeability K. The porous medium is saturated with a single phase fluid of density ρ and viscosity μ . In Fig.1 T_H and T_C represent the hot and cold vertical walls of the cavity respectively while the horizontal top and bottom   walls   are insulated. The effect of both the drag and inertia are neglected, and the flow will obey Darcy's law .

The fluid properties are assumed to be constant except for the density change with temperature which gives rise to the buoyancy force, this is treated by invoking the Boussinesq approximation. While the permeability values K of the porous layers are different, the values of the thermal diffusivity in the layers are the same.   This assumption is done to study the effects of the change of the permeability alone.   With these assumptions, the conservation equations for the mass, momentum and energy for each layer become:

Continuity

$$\partial u/\partial x + \partial v/\partial y \ = 0 \tag{1}$$

Momentum (Darcy's law)

$$\partial p/\partial x + (\mu/K) u \ = 0 \tag{2}$$

$$\partial p/\partial y + (\mu/K) v \ = \ \rho \, g \, \beta \, (T - T_C) \tag{3}$$

Energy

$$u \ \partial T/\partial x + v \ \partial T/\partial y \ = \ \alpha \, (\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2 \,) \tag{4}$$

where u, v, p, α, β, g, μ and K are the velocity components in the x and y directions, pressure, thermal diffusivity, coefficient of thermal expansion, acceleration due to gravity, Kinematic viscosity and Permeability of the porous media, respectively.

Eliminating the pressure terms from equations (2) and (3), introducing the stream function φ as $u = d\varphi/dy$ and $v = -d\varphi/dx$, and scalling all the variables by appropriate characteristic values of those variables defined by:

$$X = x/W, \quad Y = y/H, \quad \Psi = \varphi H/\alpha W, \quad and \quad \theta = (T-T_C)/(T_H-T_C)$$

the governing equations (1)-(4) can be transformed into a non-dimensional stream function and a temperature equations

$$\partial^2\Psi/\partial X^2 + (1/A^2)\, \partial^2\Psi/\partial Y^2 = -Ra\,(\partial\theta/\partial X) \tag{5}$$

$$U\,\partial\theta/\partial X + V\,\partial\theta/\partial Y = A^2 . \partial^2\theta/\partial X^2 + \partial^2\theta/\partial Y^2 \tag{6}$$

where A is the aspect ratio of the cavity = H/W and Ra is the Darcy-Rayliegh number based on the height of the cavity H, and is given by :

$$Ra = Kg\,\beta\,(T_H-T_C)\,H/\alpha\,\upsilon$$

Because the vertical layers have different permeiabilities K, the Darcy-Rayleigh number Ra will be different for each layer. Taking the permeability ratio for each layer as $K_r = K/K_H$, the Darcy-Rayleigh number for each layer will be: $Ra = K_r . Ra_H$
where K_H, Ra_H are taken as the permiability value and the Darcy-Rayleigh number in the layer in contact with the hot wall.

On the solution, the boundary conditions for the nondimensional stream function and temperature are:
$\Psi = 0$ on all walls, $\partial\theta/\partial Y = 0$ for Y=0,1 and 0<X<1,
$\theta = 1$ for X=0 and 0<Y<1, $\theta = 0$ for X=1 and 0<Y<1

The solution of the governing differential equations (5) and (6) has been obtained numerically by using the finite difference scheme presented by Patankar [18]. The solution consists of the stream function and the temperature fields as well as the velocities in the x and y directions. More detailed information about the numerical procedure can be found in [16].

3. RESULTS AND DISCUSSION

The two dimensional natural convection in a multilayered with different permeabilities fluid saturated porous medium has been analyzed for vertical isothermal walls at different temperatures and with adiabatic top and bottom walls.   The study is made for 3 layered porous medium in which the first and third layers have equal thicknesses and permeabilities. A wide range of the effective parameters are considered. The permeability Darcy Rayleigh number Ra up to 6000. The effect of these parameters on the temperature, streamlines and the velocity of the saturated fluid flow inside the porous medium are studied.

3.1 The validity of the model

In the following study in sections 3.2 and 3.3, the cases of $W_r = 0.0$ and 1.0, correspond to those cases of a uniformly filled cavity, and the results obtained here for these cases are in good agreement with those obtained by the author in previous study [15]. Another comparison is done with the results obtained by Lauriat and Prasad [13] for a case of a single layer porous media with $W_r=0$, A=5 and Ra= 250, 1000 and 2500.   The values of the vertical velocity V/Ra and the temperature θ at the midheight section where Y=0.5 and the horizontal velocity U/Ra at X=0.5 are translated into the corresponding notations and expressions by this work and compared with it. The comparison which is shown in Figs 2-3 shows a very good agreement and proves the validity of the model.

3.2. Effect of sublayers width

Figs. 4-10 show the effect of the width ratio of the inner sublayer W_r on the streamlines and isothermal lines. The width ratio W_r takes the values 0.0, 0.2, 0.4, 0.6, 0.8, 1.0.

Figs 4-7 show the case where the permeability of the inner layer is five times greater than the outer layers $K_r = 5$, the aspect ratio A=3 and Ra=150. In this case of $W_r= 0$, where the whole cavity is filled with low permeability porous media,   the streamlines shown in Fig.4, tend to be in the outer region of the sublayers with less flow in the core. With the appearance of the higher permeability inner sublayer, an attraction appears for the flow towards the core, and the tendency for more flow to be initiated in this attractive layer exists. With the increase of W_r the attraction for the flow towards the core increases, and higher values of streamfunction exists also, carrying more convective heat

from the hotter side to the colder one. The flow rate increases with the increase of W_r, and the slope of the axis of the cells changes significantly. For example at $W_r = 0$, the axis is close to the vertical middle plane, but with the increase of W_r, the axis moves towards the diagonal of the cavity. Therefore, the maximum velocities (horizontal and vertical components) drift from the vertical and horizontal middle planes to the corners (left bottom and right top corners).

An indication for the transport of energy by convection between the two isothermal vertical walls is the rate of flow inside the cavity, which can be expressed by the maximum value of the streamfunction and the mean velocity of the flow. To express these two functions two variables are used in [15-17], and are defined as:

$$\Psi_{max} = \pm \max | \Psi(x,y) | \quad and \quad U_m = {}_A\!\int (U^2 + V^2)\, dA$$

where Ψ_{max} is the maximum value of the non-dimensional streamfunction, $\pm$ are taken for counter clockwise and clockwise circulation respectively and U_m is expressed as a function of the average fluid speed over the area A.

Fig. 5 shows the behavior of those both functions expressed by U_m / U_{m0} and Ψ_{max} / Ψ_{max0} with the increase of W_r. Where U_{m0} and Ψ_{max0} are the functions of the mean velocity and maximum streamfunction in the case of $W_r = 0$. The two figures show a significant increase of both the two functions with the increase of W_r indicating the increase of the transport energy by convection part in the whole layers.

The behavior of the isothermal lines for different inner sublayer width ratios W_r is shown in Fig. 6. It is noteced that the interior temperature distribution is close to a straight line in the central part of the inner sublayer. The slope of these isothermal lines shows that the heat is transfered by both the conduction and convection. With the increase of the width of the attrractive inner sublayer, the above modification in velocity field with the W_r changes the isotherm patterns accordingly. The isothermal lines deviate in the inner sublayer towards the horizontal direction (normal to the walls of the heat flow) indicating the increase of the transport of energy by convection part in the core region. The temperature gradients near the bottom left and the right top corners are greatly modified to a sharp temperature gradients. Thus the transport of energy due to cross flow near the horizontal walls has, thus, increased also.

Fig. 7 shows the effect of the inner sublayer width ratio W_r on both the temperature and velocity distributions at the middle height of the porous media

Y=0.5 in the half of the width adjacent to the hotter side. For the case of W_r=0.0, where the whole cavity is filled with low permeability porous media, both the temperature and velocity distribution curves are nearly straight lines. With the increase of W_r both the temperature and velocity curves deviate from the straight line condition in the inner sublayer and remain taking the nearly straight line shape in the lower permeability outer layer near the hotter side, with a significant increase in the velocity field and decreasing temperatures. The step variation in the permeability across the interface of the two sublayers induces step changes in the slopes of both velocities and temperatures. The break points in both fields are shown by the symbol (o).

Figs. 8-10 show another case, where the permeability of the inner layer is five times less than that in the outer layers, i.e. K_r for the inner sublayer = 0.2, the aspect ratio A=3 and Ra=400. The behavior of the streamlines for different values of W_r is shown in Fig.8. For the case of uniform porous media where W_r=0.0, i.e. high permeability layer, the temperature difference across the two vertical walls causes a relatively high velocity flow all over the layer. As the less permeability inner sublayer appears, a new resistance appears for the flow in the core of the inner sublayer. With the increase of W_r, the damping for the existing flow in the core increaseses. The slope of the axis of the cells changes significantly. At W_r=0 the axis is close to the diagonal of the cavity, but with the increase of W_r, the axis moves towards the vertical middle plane indicating that the aximum velocities (horizontal and vertical components) drift from the corners (left bottom and right top corners) to the vertical and horizontal middle planes. Therefore, the flow is attracted to be vertically in the outer layers, where the higher permeability exists, and is forced to be exchanged between the outer sublayers carrying the convective heat energy part through the upper and lower ends of the inner layer, and less flow of convective energy transfer through the core region.

Fig. 9 shows the behavior of the functions expressed by U_m/U_{m0} and Ψ_{max}/Ψ_{max0} with the increase of W_r where U_{m0} and Ψ_{max0} are the functions of the mean velocity and maximum streamfunction in the case of W_r=0.0. The two figures show a significant decrease of both the two functions which indicates the decrease of both the mean velocity of the flow and the rate of flow inside the cavity, which in turns indicates the decrease of the transport energy by convection part in the whole layers.

Fig. 10 shows the behavior of the isothermal lines for different values of W_r. In the core of the inner sublayer, where, less flow exists, the above

modification in the velocity field with the increase of W_r changes the isotherm pattern accordingly. The isothermal lines deviate towards the vertical direction (parallel to the isothermal walls) indicating the decrease of convection heat flow through the core region. The sharp temperature gradients near the bottom left and the right top corners are greatly modified, and the transport of energy due to the cross flow near the horizontal walls has, thus, decreased.

3.3 Effect of permeability ratios

Figs. 11-13 show the streamlines and the isothermal lines behavior for three layers porous media with equal widths, Ra=250, Aspect ratio A=3 and different permeability ratios for the inner to the outer sublayers K_r from 10 to 0.1.

The behavior of the streamlines for different values of K_r is shown in Fig.11. For the case of uniform porous media where $K_r=1$, i.e. high permeability one layer, the temperature difference across the two vertical walls causes a relatively high velocity flow all over the layer. For the case of $K_r>1$, with the increase of K_r, the attraction for the outer streamlines to change its direction gradually towards the core of the inner sublayer increases, besides the increase of the chance for the fluid rate of flow in the core to increase, carrying more convective heat from the hotter side to the colder one. For the case of $K_r<1$, with the decrease of the permeability ratio K_r the streamlines find an increased resistance to flow in the core of the inner sublayer, and is forced to change its direction gradually and compressed in the outer sublayers, tending to be parallel to the outer vertical walls. The flow is then forced to be exchanged between the outer sublayers through the upper and lower ends of the inner sublayer.

This phenomenon reflects itself on the maximum value of the streamfunction and the mean velocity of the flow in the cavity. Fig. 12 shows the increase of both U_m/U_{m1} and Ψ_{max}/Ψ_{max1} with the increase of the permeability ratio of the inner sublayer. where U_{m1} and Ψ_{max1} are the functions of the mean velocity and maximum streamfunction in the case of $K_r=1$.

Fig. 13 shows the behavior of the isothermal lines for different values of K_r. With the decrease of the inner sublayer permeability ratio K_r the above modification in the velocity field changes the isotherm pattern accordingly. The isothermal lines deviate towards the vertical direction (parallel to the isothermal walls) indicating the decrease of convection heat flow through the core region. The sharp temperature gradients near the bottom left and the right top corners are greatly modified, and the transport of energy due to the cross flow near the horizontal walls has, thus, decreased also.

4. CONCLUSIONS

This paper outlined a numerical solution for the phenomenon of the fluid flow by natural convection in a two dimensional vertical multilayered porous medium with different permeabilites and heated from the side. The study is focused on the effect of the non uniform permeability of the sublayers on the behavior of the tempreture and streamlines fields. The results indicate the following:

With the increase of K_r or the increase of W_r for $K_r>1$ or the decrease of W_r for $K_r<1$,

- the slope of the axis of the streamlines cells moves from the vertical middle plane towards the diagonal of the cavity.
- the maximum velocities (horizontal and   vertical components) drift from the vertical and horizontal middle planes to the corners (left bottom and right top corners).
- the attraction for the flow towards the core increases, the flow rate and the mean velocity in the cavity increase and higher values of streamfunction exist, carrying more convective heat from the hotter side to the colder one.
- the interior temperature distribution is close to a straight line in the central part of the inner sublayer. The isothermal lines deviate from the vertical direction (parallel to the isothermal walls) towards the horizontal direction (normal to the isothermal walls) indicating the increase of the transport of energy by convection part in the core region.
- the temperature gradients near the bottom left and the right top corners are greatly modified to a sharp temperature gradients, indicating the increase of the transport of energy due to cross flow near the horizontal walls.

With the decrease of K_r or the increase of W_r for $K_r <1$ or the decrease of W_r for $K_r >1$, a damping for the existing flow in the core increases, and the flow is attracted to be vertical in the outer layers, where the higher permeability exists, and is forced to be exchanged between the outer sublayers carrying the convective heat energy part through the upper and lower ends of the inner layer.

5. NOMENCLATURE

A	Aspect ratio $= H/W$
g	Acceleration due to gravity, m ^{2}/s
H	Height of the porous material, m
K	Permeability of the porous layer, m^2
K_H	Permeability of the porous layer adjacent to the hot wall, m^2

K_r	Ratio of the permeability of the porous layer to the permeability of the porous layer adjacent to the hot wall $= K/K_H$
p	Pressure, Pa
Ra	Darcy-Rayleigh number $= g \ \beta \ K \ H \ (T_H - T_C)/ \ \alpha \ \upsilon$
Ra_H	Darcy-Rayleigh number for the layer adjacent to the hot wall
T	Temperature, K
T_H, T_C	Temperature of the hot and cold isothermal surfaces, K
u,v	Field velocities in the x and y directions, m/s
U,V	Non-dimensional field velocities in the X and Y directions respectively
U_m	Fluid non-dimensional average velocity
x,y	Spatial coordinates
X,Y	Dimensionless distances in the x and y axis respectively
W	Width of the porous material, m
W_r	Width ratio
α	Thermal diffusivity of the porous layers, m^2/s
β	Coefficient of volumetric thermal expansion, 1/K
μ	Dynamic viscosity of the fluid
υ	Kinematic viscoisity of the fluid, m^2/s
ρ	Fluid density
φ	Stream function
Ψ	Dimensionless stream function
Ψ_{max}	Maximum extreamum value of the stream function
θ	Non-dimensional temperature $= (T-T_C)/(T_H - T_C)$

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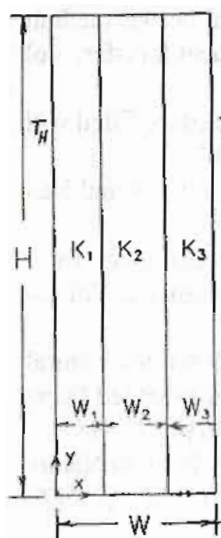
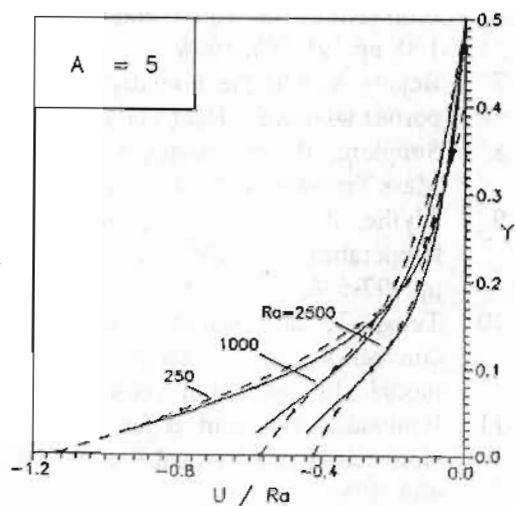Fig. 1   Schematic diagram of the
rectangular multilayered porous cavity

Fig. 3 The horizontal velocity U/Ra
at the middle vertical plane X = 0.5
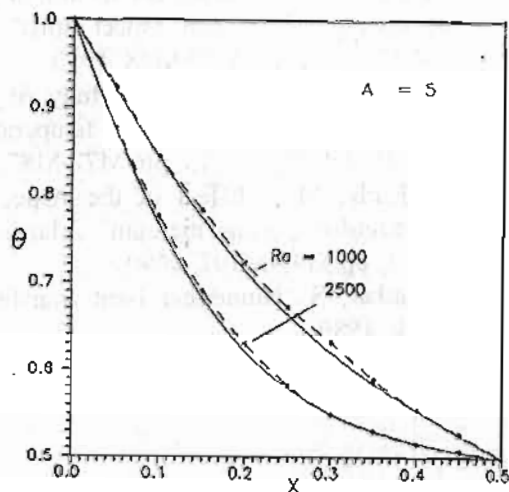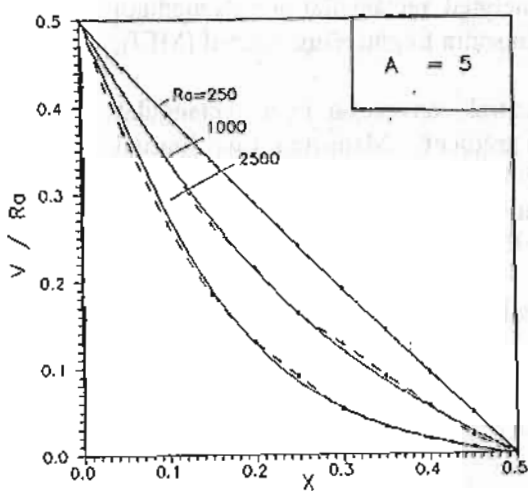- - - - -   Lauriat and Prasad [13],
————   Present work

Fig. 2 The Vertical velocity V/Ra and the non-dimensional
temperature θ at the midheight section where Y = 0.5
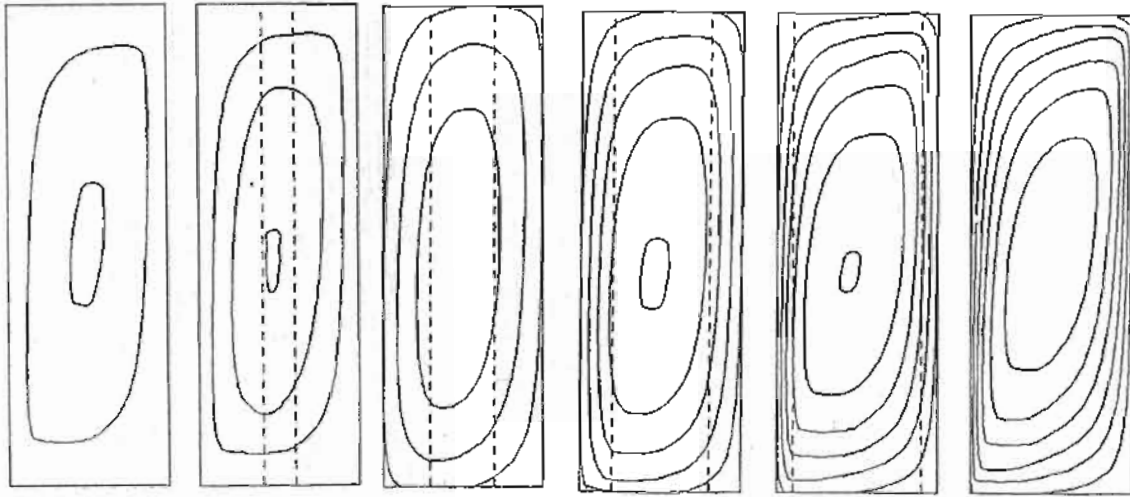- - - - -   Lauriat and Prasad [13],   ————   Present work

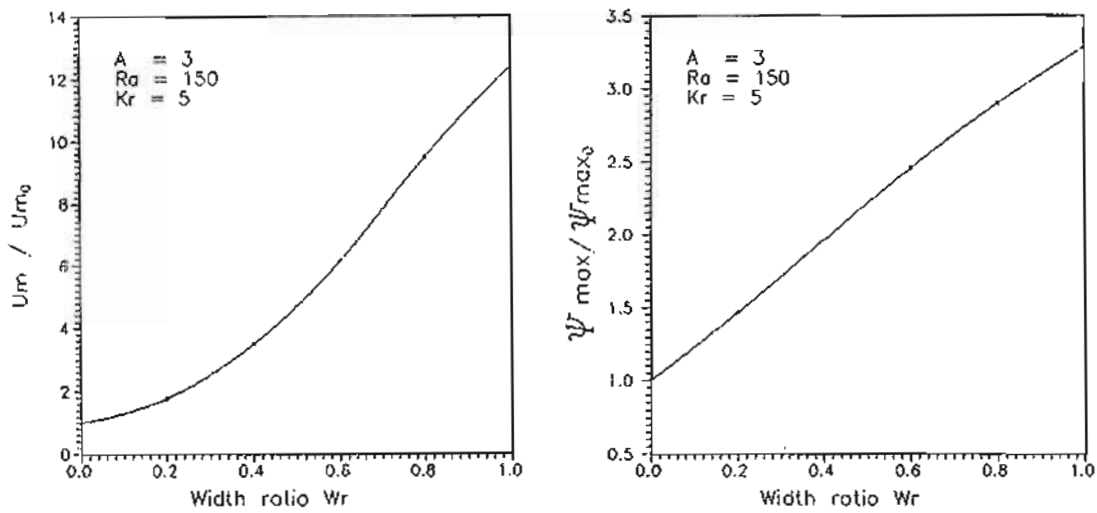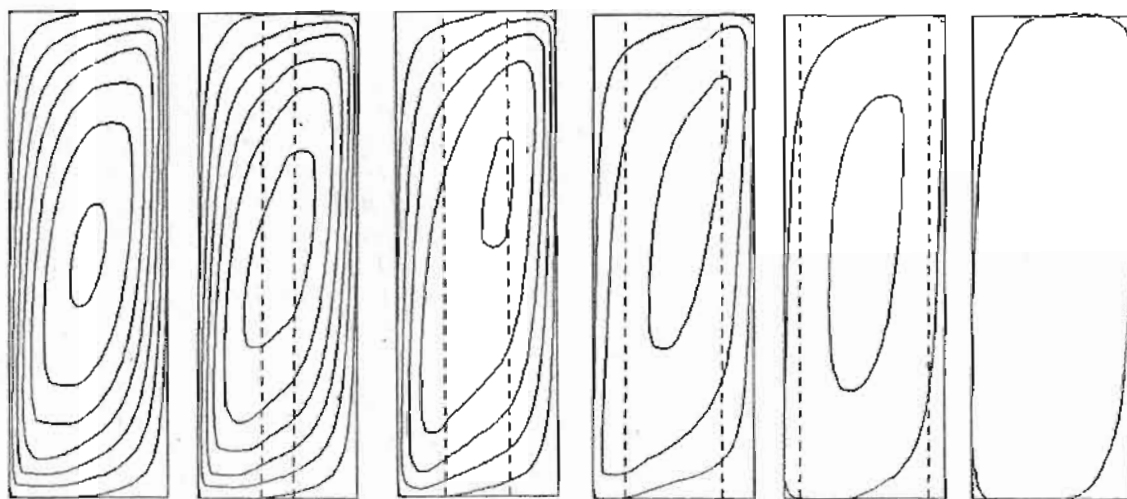Fig. 4 Streamlines for A = 3, K_f = 5 and Ra = 150
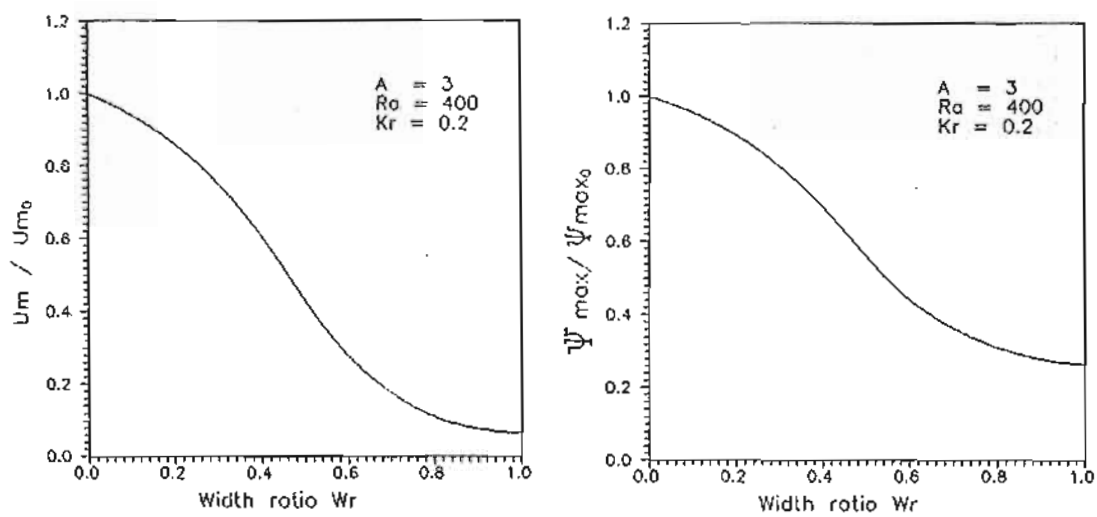(Ψ_1 = 8, $\Delta\Psi$ = 8)

Fig. 5 Variation of the nondimensional average velocity and Streamfunction
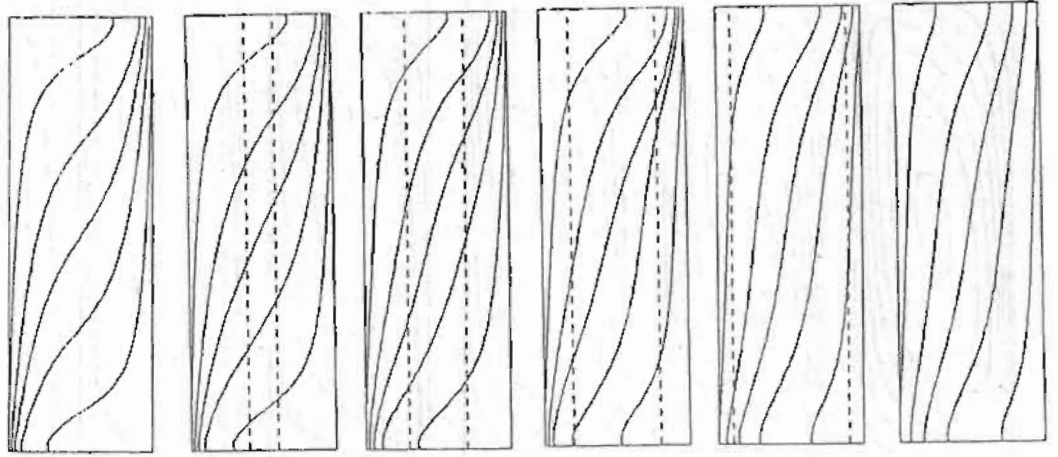with the width ratio of the inner sublayer for A = 3, K_r = 5 and Ra = 150
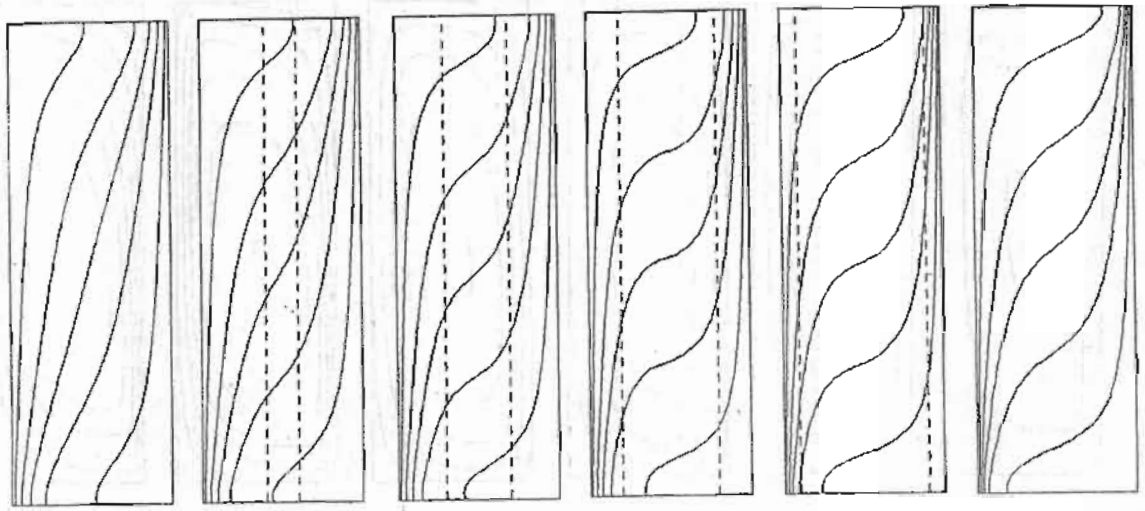
Fig. 6 isotherms for A=3, $K_r = 5$ and Ra = 150

($\theta_1 = 0.1$, $\Delta \theta = 0.2$)
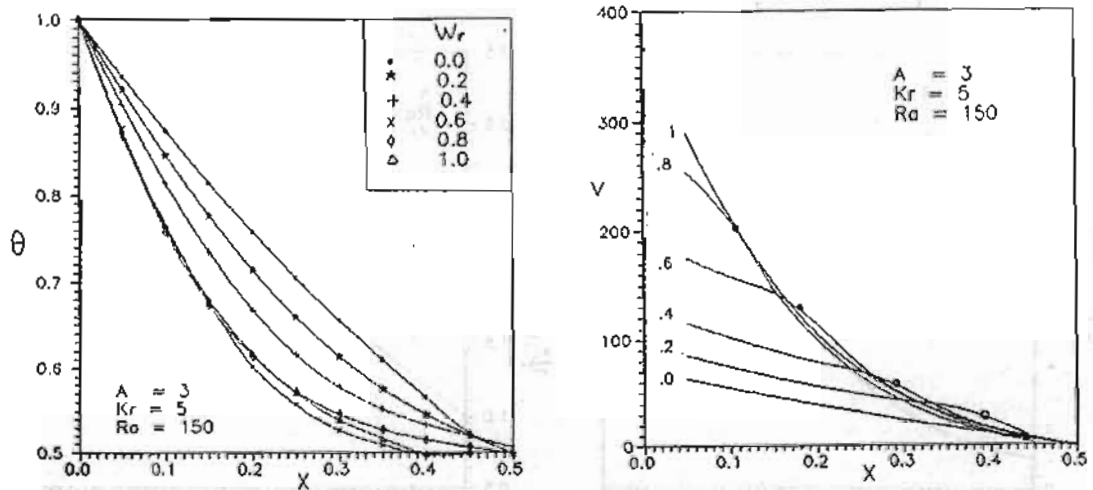
Fig. 7   The effect of the inner sublayer width ratio W_r on the temperature and velocity
distributions at the midheight section where Y= 0,5 for A = 3, K_r = 5 and Ra =150.

Fig. 8 Streamlines for A = 3, K_r = 0.2 and Ra= 400
(Ψ_1 = 5 , $\Delta\Psi$ = 5)

Fig. 9   Variation of the nondimensional average velocity and Streamfunction
with the width ratio of the inner sublayer for A = 3, K_r = 0.2 and Ra = 400

Fig. 10 isotherms for $A = 3$, $K_r = 0.2$ and $Ra = 400$
($\theta_1 = 0.1$, $\Delta\theta = 0.2$)
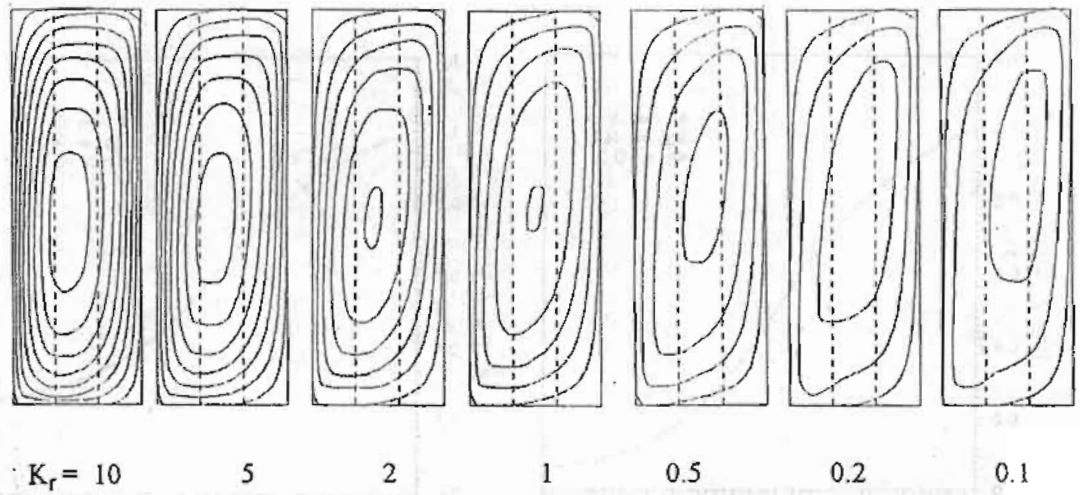

| $K_r = 10$ | 5 | 2 | 1 | 0.5 | 0.2 | 0.1 |

Fig. 11 Streamlines for $A = 3$, $W_r = 0.333$ and $Ra = 250$
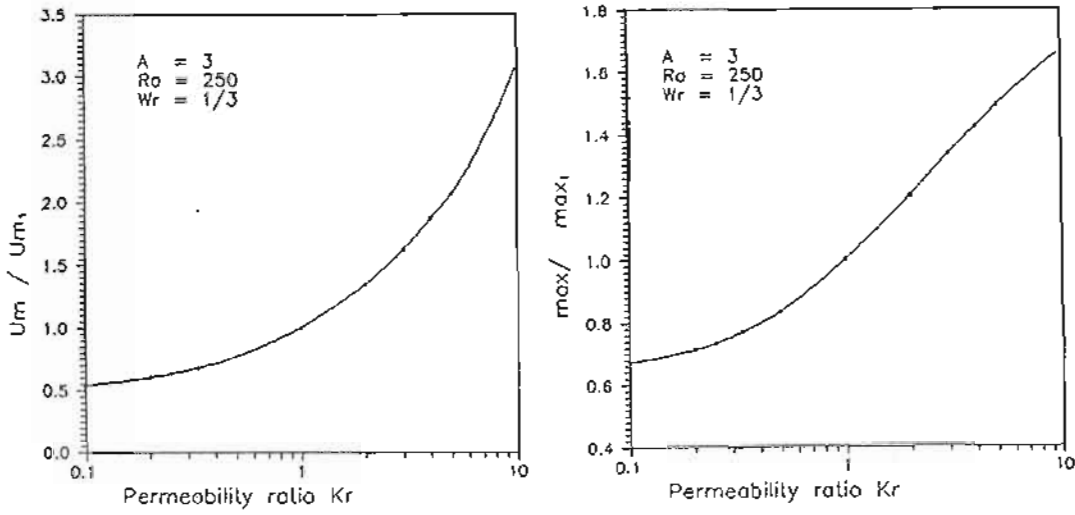($\Psi_1 = 5$, $\Delta\Psi = 5$)

Fig. 12 Variation of the nondimensional average velocity and Streamfunction with the permeability ratio of the inner sublayer for $A = 3$, $W_r = 1/3$ and $Ra = 250$

$K_r = 10$ 5   2   1   0.5   0.2   0.1
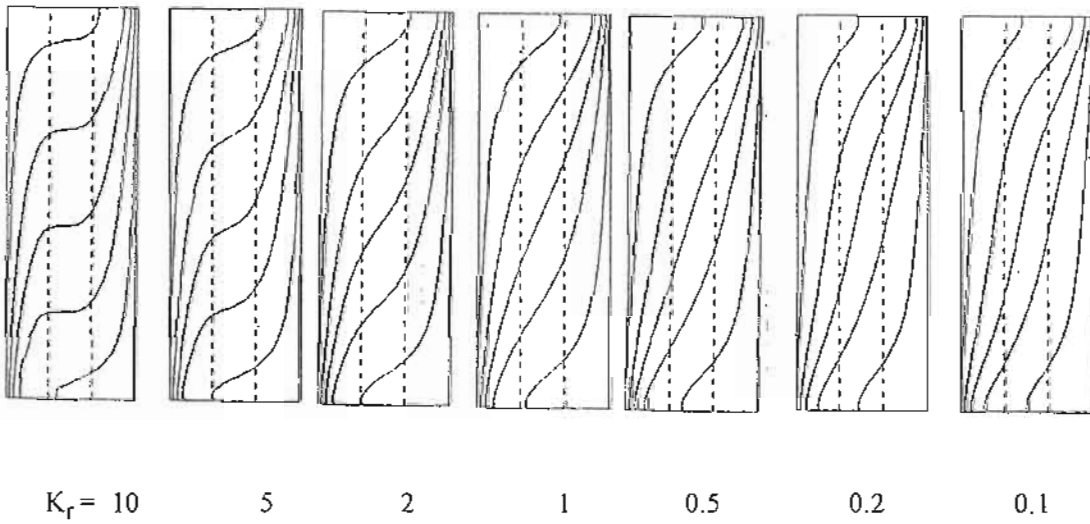
Fig. 13 Isotherms for $A = 3$, $W_r = 0.333$ and $Ra = 250$
($\theta_1 = 0.1$, $\Delta\theta = 0.2$)