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NUMERICAL STUDY OF NATURAL CONVECTION IN A RECTANGULAR POROUS MEDIUM WITH VERTICAL TEMPERATURE GRADIENT

دراسه عدديه للحمل الطبيعي فى وسط مسامى ثنائى البعد
فى شكل متعامد فى وجود انحدار حرارى راسى

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خلاصـــــه :

يحتوى هذا البحث على دراسه عدديه للحمل الحر الطبيعى المستقر فى حيز ثنائى البعد فى شكل متعامد مملوء بوسط مسامى مشبع بالمائع. تمت هذه الدراسه من خلال عمل نموذج لتحليل الانتقال الحرارى وحركه المائع داخل الوسط المسامى يستخدم معادلات الكتله وكميه الحركه والطاقه مع استخدام قانون دارسى وتقريب بوسينسك. وقد حلت هذه المعادلات عدديا وذلك باستخدام طريقه الفروق البسيطه. استخدم هذا النموذج فى حاله بها الحوائط الراسيه غير موصله للحراره والافقيه موصله للحراره ذات درجه حراره ثابته مع وجود انحدار حرارى راسى به درجه حراره الجدار الافقى السفلى اعلى من درجه حراره الجدار الافقى العلوى. وقد استخدمت نتائج هذه الحاله فى عمل مقارنه مع النتائج التى حصل عليها كلاوس اظهرت تطابقا جيدا وصحه هذا النموذج. ونتائج هذا النموذج تظهر على هيئه خطوط السريان وخطوط درجات الحراره الثابته وعدد نوسيلت الموضعى والكلى للوسط. كما تم ايضا دراسه تاثير عدد دارسى-رايلى كمتغير على انتقال الحراره وحركه المائع داخل الوسط المسامى اظهرت انهما شديدا الحساسيه لرقم دارسى-رايلى وكذلك وجود ثلاثه نظم رئيسيه لانتقال الحراره وهى التوصيل والحمل الطبيعى مع ظهور خليه واحده او خلايا متعدده.

ABSTRACT

Two dimensional steady natural convection in a rectangular cavity filled with a saturated porous medium has been studied numerically. The fluid flow is analyzed by solving numerically the mass, momentum and energy balance equations, using Darcy's law and the Boussinesq approximation. The model is used for the case when the vertical walls of the cavity are adiabatic and the horizontal walls are isothermal with vertical temperature gradient. The bottom horizontal wall is heated and the top is cold. The effect of Darcy-Rayleigh number as an external parameter on the heat transfer and fluid motion is studied. A comparison of some results is done with an experimental work of Close et al showed good agreement and validity of the model. The results are presented in terms of the streamlines and isotherms, the maximum temperature in the cavity, and the local and overall Nusselt numbers for Rayleigh-Darcy number from 1 to 1000. The motion of the fluid inside the porous material is most vigorous for

Darcy-Rayleigh number and three main convective modes are found: conduction, single and multiple cell convection and their features described in detail.

1. INTRODUCTION

Natural convection in saturated porous media has recently considerable attention and is known to be important in a wide variety of engineering applications such as geothermal reservoirs, thermal insulation by fibrous materials, packed-bed catalytic reactors, underground spreading of chemical wastes and other pollutants, and the cooling of rotating superconducting machinary [1]-[4].

To describe heat transfer in porous media, one used an equivalence between the heterogeneous porous medium, made up of a solid matrix and a saturating fluid, and a fictitious continuum for which an energy equation is defined that is similar to that used in homogeneous fluid. This is the most common practice and the one being used here.

A large cross section of the fundamental research contributed to this problem has been reviewed. Most of these studies have been theoretical, including natural convection in confined enclosures driven by horizontal temperature gradiants [5]-[13] and natural convection boundary layer [14]. A theoretical work on natural from the sides was pioneered by Weber [10]. He developed an Oseen linearized solution of the boundary layer regime in a very tall'layer. The Weber solution was modified later by Bejan [11] to account for the net heat transfer which takes place vertically through the core region of moderately tall layers. An integral-type analysis of the same boundary layer regime was reported by Simpkins and Blythe [12] and for temperature-dependent viscosity, by Blythe and Simpkins [13]. Walker and Homsy [15] developed an asymptotic solution for the flow fields inside a shallow layer using the aspect ratio as the small parameter. They showed that unlike in tall layers the core region plays an active role in the heat transfer process. An approximate integral type solution for the same geometry was proposed by Bejan and Tien [16]. Measurements of Nusselt numbers in shallow, air filled porous beds bounded by horizontal isothermal surfaces are reported by Close et al [17] . The Darcy-Rayleigh numbera covered was from 5 to 150.

The natural convection in a rectangular cavity filled with a saturated porous medium with vertical temperature gradiente and wide range of Darcy-Rayleigh number is not covered. So, the purpose of the present work is to cover this problem. The vertical walls are insulated and the horizontal walls are isothermal. The bottom horizontal wall is heated with a temperature T_w and the top horizontal wall is cooled with temperature T_c. The problem has been analysed numerically for two dimensional, steady state flow and wide ranges of Darcy-Rayleigh number. The effect of bouancy is taken into consideration and the effect of both the drag and inertia are neglected.

2. FORMULATION AND NUMERICAL METHOD

Consider a rectangular cavity of height H and width W (Fig.1) filled with an isotropic homogeneous fluid saturated porous medium which obeys Darcy's law. The fluid and the porous medium are treated as a system with an equivalent heat conductivity and the fluid is assumed to be a normal Boussinesq fluid. All walls of the cavity (enclosure) are assumed to be impermeable. Here T_H and T_C represent the temperature of the hot and cold walls respectively, while the other two walls are adiabatic. Characteristic temperature difference are, thus, $\Delta T = T_H - T_C$.

The fluid is considered to be incompressible, with density changes occuring only as a result of changes in the temperature according to

$$\rho = \rho_c (1 - \beta (T - T_c)) \qquad (1)$$

where ρ is the density, T is the temperature, β is the coefficient of thermal expansion, and the subscripts refer to the reference conditions. The viscous drag (Brinkman model) and inertia terms in the equations of motion are neglected, which are valid assumptions for low Darcy and particle Reynolds numbers, and for high Prandtl number, respectively. Owing to the last assumption, velocity slip at the bounding surface is necessary. With these assumptions, the conservation equations for mass, momentum, and energy for steady, two dimensional flow in an isotropic, homogeneous porous medium are

Continuity

$$\partial u/\partial x + \partial v/\partial y = 0 \qquad (2)$$

Momentum (Darcy's law)

$$\partial P/\partial x + (\mu/K)\, u = 0 \qquad (3)$$

$$\partial P/\partial y + (\mu/K)\, v \quad \rho g \beta (T - T_c) \qquad (4)$$

Energy equation

$$u\, \partial T/\partial x + v\, \partial T/\partial y = \alpha\, (\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2) \qquad (5)$$

where u, v, K, μ, α, P and g are respectively the velocity components in the x and y directions, Permiability, dynamic viscosity, effective thermal diffusivity, Pressure and acceleration due to gravity

The pressure is eliminated by the cross differentiation of the components of equations (3),(4) after substituting for the density from equation (1) this gives

$$(\mu/K)(\partial u/\partial y - \partial v/dx) = -\rho g \beta\, \partial T/\partial x \qquad (6)$$

The continuity relation given by equation (2) is identically satisfied through the introduction of an appropriately defined stream function .

$$u = \partial\psi/\partial y \qquad v = -\partial\psi/\partial x \tag{7}$$

A non-dimensional form of the governing equations can be achieved by scaling all the variables by appropriate characteristic values of those variables. These are defined by:

$$X = x/W \;,\quad Y = y/H$$
$$\Psi = \psi \; H/\alpha W \;,\quad \theta = (T-T_c)/(T_H-T_c) \tag{8}$$
$$U = \partial\Psi/\partial Y \quad \text{and} \quad V = -\partial\Psi/\partial X$$

With the above assumptions, the governing equations (5)-(7) transform into stream function and temperature non-dimensional equations as:

$$\partial^2\Psi/\partial X^2 + A^2 \; \partial^2\Psi/\partial Y^2 = Ra \;\; \partial\theta/\partial X \tag{9}$$

$$U \;\; \partial\theta/\partial X + V \;\; \partial\theta/\partial Y = (1/A^2)\partial^2\theta/\partial X^2 + \partial^2\theta/\partial Y^2 \tag{10}$$

The governing parameters are the aspect ratio

$$A = W/H$$

and the Darcy-Rayleigh number Ra

$$Ra = Kg\beta(T_H-T_c)H\rho\;/\alpha\mu \tag{11}$$

The Darcy-Rayleigh number includes the parameters which express both the porous media and the fluid. It expresses the porous media through the permeability K, the conductivity α and the height H. It expresses the fluid through the fluid density ρ and viscosity μ. Darcy-Rayleigh number includes also the operating driving conditions such as the temperature difference (T_H-T_c), the coefficient of expansion β and the gravity g. So, It comes out naturally as the coefficient of the bouyancy driving force along the flow.

The non dimensional hydrodynamic and thermal boundary conditions are

$$\Psi = 0 \quad \text{on all the boundaries}$$
$$\theta = 1 \quad \text{for } Y=0 \text{ and } 0 \le X \le 1 \tag{12}$$
$$\theta = 0 \quad \text{for } Y=1 \text{ and } 0 < X < 1$$
$$\partial\theta/\partial X = 0 \quad \text{for } X=0,1. \text{ and } 0 < Y < 1$$

The non-dimensional local heat transfer coefficient is characterized by the Nusselt number defined as:

$$Nu_w = -\,\partial\theta/\partial Y \tag{13}$$

The result for the total heat transfer rate will be presented in terms of the Nusselt number defined as

$$Nu = -\int_0^1 (\partial\theta/\partial Y)\, dX \tag{14}$$

Finite difference equations are derived from equations (9) and (10) by integration over finite area elements, following the procedure developed by [18]-[19]. The successive substitution formulae, derived in this way by employing the upwind differences [20] for the convective terms in the energy equation, satisfy the convergence criterion and are quite atable for many circumstances [20]. The temperature field was first found by solving equation (10) and using transient explicit method. Once the temperature had been determined, equation (9) was solved using a point iterative method which makes use of the new values as soon as they are available [20]. The ψ values so obtained were used in equation (10) together with the recently calculated temperature field to obtain the new values for the temperature. For the present work uniform mish sizes have been used for both X and Y directions. A non-uniform grid field could not be identified for this problem because the nature of the velocity and temperature fields change substantially with Ra. Based on several trial cases, a suitable grid field was selected for the present calculations. A convergence criterion of $\sigma \le 5\times10^{-d}$ in both ψ and T at the grid points in the domain was used to test the convergence of the iterative scheme where

$$\sigma = (\phi^n - \phi^{n-1})/\phi^n$$

where n is the iteration number and ϕ stands for both ψ and T.

3. RESULTS AND DISCUSSION

The primary objective of this study is to gain insight into the physical nature of the flow of the natural convection in the fluid saturated porous medium under vertical temperature gradient. Therefore,the effects of the Darcy-Rayleigh number on the free convection of two dimensional rectangular cavity filled with saturated porous media has been studied numerically. The vertical walls of the cavity are adiabatic and the bottom horizontal wall is heated and the upper one is cold isothermally, and vertical temperature gradient exists. A wide range of Darcy-Rayleigh number have been considered. The temperature and flow fields are represented. Experimental data for global heat transfer in a box with an aspect ratios from 1.82 to 4 and Darcy-Rayleigh number up to 150 were represented by Cloae et al [17]. Their experimental equipment used have been a packed bed of spheres saturated with gas contained between horizontal isothermal plates, with the assumption that the solid and adjacent fluid temperatures are equal. Although these results are for low range of Darcy-Rayleigh number, it is compared with the corresponding values obtained here by the numerical model. The experimental results for [17] are shown in Fig. 2 as a continuous line. It is clearly seen that the results are in good agreement.

Two variables are used to characterize the flow. The first of them is ψ_{max} which is defined by

$$\psi_{max} = \pm \max \mid \psi(x,y) \mid$$

where the positive and negative signs are taken for counter clockwise and clockwise circulation respectively. The second non-dimensional variable is expressed by a function of the average fluid speed over the area A of the rectangular porous material defined as:

$$U_m = \int_A (U^2 + V^2)\, dA$$

and will be named in the following as the average fluid speed.

The effect of Ra is shown by numerical experiment for aspect ratios of 1 and 3 and Ra varied from 1 to 1000. Table 1 shows the values of ψ_{max} and U_m as a function of Ra for aspect ratios 1 and 3. The stream lines and the isotherms are shown in Figures 3-6 respectively. Figures 3 - 6, as well as table 1 show that there are three main types of flow:

A - The heat is mainly transferred by conduction. By Ra under 40 the maximum stream function ψ_{max} and U_m are very small as shown in table 1 and can be neglected, that gives negligable flow velocities. Also the isothermal lines are nearly parallel to the isothermal walls.

B - By $40 \leq Ra < 200$ by the aspect ratio A=3 and $40 \leq Ra < 150$ by A=1, the isothermal lines in the enclosure begin to deviate from the parallel straight lines and increase near the right vertical wall and decrease near the left vertical wall as shown in figures 4 and 6. The stream function shows a single cell flow with a single extremum value as shown in Figure 5 for A=1 and three cells with 3 extremum values for A=3 as shown in Fig. 3 .The extremum values of the stream function and the mean velocity which are indicated by ψ_{max} and U_m and shown in table 1, show by $Ra \geq 40$ relatively recognizable jump. The values of these variables increase with the increase of Ra. This indicates another mode of flow. In which, natural convection heat transfer exists beside the conduction heat transfer and the two forms of the heat transfer are coupled together. But, the natural heat transfer exists with relatively low velocity and $\gamma = 1$ where γ is the ratio of the number of cells to the Aspect ratio i.e. single cell flow for A=1 and 3 cells for A=3.. The physical notation of a cell is associated with an identifible body of fluid rotating in the same sense. Therefore, it has to be bounded by a closed stream line within which the vorticity is of the same sign.

C - Natural convection with multiple cells circulating in alternate directions with $\gamma > 1$. By further increase of Ra until it exceeds the value of 200 by the aspect ratio A=3 and the value 150 at A=1, the colder and denser fluid at the top tends to "topple over" making two dimensional cellular patterns with 5 cells by A=3 and 2 cells by A=1 as shown in Figures 3 and 5 respectively. Figures 3 and 5 also show multiple extremum values of the stream function whose magnitude become larger as Ra increased indicating more vigorous motion. That gives the begining of third mode of flow, which can be depicted by natural convection motion with multiple cells circulating with more vigorous motion in alternate directions with ratio of number of cells to the aspect ratio γ >. As the Ra is the result of the temperature difference TH-Tc and the local component of the gravity acceleration g, it is considered the driving force for the fluid motion and heat transfer in the porous material. Therefore, the increase of the stream function and the more vigorous motion of the fluid with the increase of Ra which appears in Figs. 3 and 5 can be qualitatively discussed in the following way: choose a particular stream tube (cell) close to the boundaries with counter clockwise flow direction, the right hand side branch of which is hotter (and therefore, dense) than the average, after picking up heat at the lower boundary. Likewise, the branch on the left-hand side is cooler than the average. In the two vertical branches, the gravity vector is aligned with the stream tube and the density difference helps the circulation of the fluid inside the cavity. So, with the increase of Ra the temperature difference between the hotter and colder walls (the vertical temperature gradient) increases, the density difference increases, the resistance to the flow decreases and the fluid motion becomes more vigorious. Fig. 9 presents the stream and the isothermal lines for the same case. It shows that the ascending stream is always hotter than the descending one, providing the driving force in the respective direction of motion. These phenomena reflects itself also in the heat transfer results as will be discussed later.

Table 1 ψ_{max} and U_m as a function of Ra for A =1 and 3

	A = 3		A = 1	
Ra	ψ_{max}	U_m	ψ_{max}	U_m
10	0.00075	.000051	0.001697	0.0000136
20	0.00171	.0000281	0.004994	0.0001346
30	0.0034	.000115	0.0137	0.0009072
40	0.0098	.0013643	0.04573	0.01024
100	1.79	83.98	5.2	144.03
150	2.56	191.58	7.4	318.7
200	2.75	456.50	9.2	520.4
250	3.34	691.01	10.676	741.6
300	3.83	952.95	11.99	978.4
350	4.34	1249.00	13.18	1228.0
400	4.88	1548.2	14.29	1490.0
600	6.53	2811.8	18.168	2634.0
800	7.58	2383.88	21.46	3914.75
1000	8.93	3828.38	20.6	5302.14

For the heat transfer The regions on the wall that participate more effectively in the heat transfer process can be identified using the local Nusselt number Nu_x. This is shown for the lower and the upper isothermal walls in figures 7 and 8 respectively for Ra = 20, 100, 200 and 600 and unit aspect ratio . It is found that for the single cell mode, which corresponds to

Ra=100 curve shown in Figures 7 and 8, most of the heat is transferred at the corners of the material. When multiple cell convection is present, as in Ra=200 and 600 curves in Fig. 5 most of the heat is transferred at several localized spots at the walls. These correspond to the boundaries between the cells where the flow is directly from the hot to the cold wall. Flow in the opposite direction leads to a minimum point in the Nu_x curve at the lower hotter wall and maximum point at the higher colder one.

The heat transfer process in the porous media can now be discussed by considering the flow pattern as being composed of a number of variable area closed stream tubes as shown in Fig. 3. A diagramatic sketch for this is shown in Fig. 10. Heat is transferred in from the hotter side and out of these tubes to the colder side crossing their imaginary walls by conduction. Also, heat is transferred through the tube itself in the direction of flow (carried by the flow) mainly by convection as shown in Fig.7 due to the driving force discussed before. Near the hotter wall, more heat enters the tube through the walls than leaves it, i.e. the heat balance in the tube is positive. The net heat energy gained is transferred towards the colder wall where a net amount of heat is withdrawn from the tube through its walls, complating in this manner the heat transfer process. Therefore, The heat transfer through the porous material depends mainly on two effects. The first of them is the heat conducted through the imaginary walls of the tubes and the second is the convection of the fluid moving within it. These two effects are mainly coupled together. From this point of view it can be said that the presence of multiple cells has the overall effect in increasing the heat transfer.

4. CONCLUSIONS

The phenomenon of natural convection in a two-dimensional enclosures filled with porous medium saturated with fluid subjected to vertical temperature gradient was studied by means of numerical method. The mass, momentum and energy equations, using Darcy's law and the Boussinesq approximation are used in a model solved by the finite difference technique. The effect of the Darcy-Rayleigh number of the fluid motion and heat transfer is discussed.

A comparison of some results of the numerical model is made with experimental results showed good agreement and the validity of the model, which can be safely used in extended works in this field.

The Darcy-Rayleigh number includes the parameters which express both the porous media and the fluid. So, it is the coefficient of the buoyancy driving force for the fluid motion and heat transfer in the porous media. and the porous material is most vigorous to it.

With the increase of Darcy-Rayleigh number, three main modes of the flow and heat transfer appears:

- Heat is mainly transferred by conduction with parallel isothermal lines to the isothermal walls.
- Besides the conduction heat transfer exists the natural convection heat transfer with low velocity flow and ratio of number of cells to the aspect ratio $\gamma = 1$
- Besides the conduction heat transfer exists the natural convection motion with multiple cells with $\gamma > 1$ and are circulating with more vigorous motion in alternate directions.

The density difference dut to the temperature gradient helpe the circulation of the fluid inside the cavity and the ascending stream is always hotter that the descending one.

The heat transfer depends on the heat conducted through the imaginary walls of the cells and the convection of the fluid moving within it, and the two effects are coupled together. The presence of multiple cells has the overall effect in increasing the heat transfer.

5. NOMENCLATURE

A	Aspect ratio = W/H
g	acceleration due to gravity. m^2/s
H	height of the porous material, m
K	permiability of the porous medium, m^2
Nu	global Nusselt number
Nu_x	local Nusselt number
P	pressure, Pa
Ra	Darcy-Rayleigh number $= g\,\beta\,K(T_H-T_C)/\alpha\nu$
T	temperature K
T_H, T_C	temperature of hot and cold isothermal boundaries respectively, K
u	field velocity in x direction, m/s
v	field velocity in y direction, m/s
x,y	spatial coordinates
X,Y	dimensionless distances on x and y axes respectively
W	width of the porous material, m
α	thermal diffusivity of porous medium, m^2/s
β	coefficient of volumetric expansion, K^{-1}
γ	ratio of the number of cells to the aspect ratio
μ	dynamic viscosity of the saturated fluid,
ν	kinematic viscosity of the saturated fluid, m^2/s
ρ	fluid density
φ	stream function
ψ	dimensionless stream function
ψ_{max}	maximum extremum value of the stream function
σ	convergence criterion
ϕ	stands for the stream function and the temperature
θ	non-dimensional temperature = $(T-T_C)/(T_H-T_C)$

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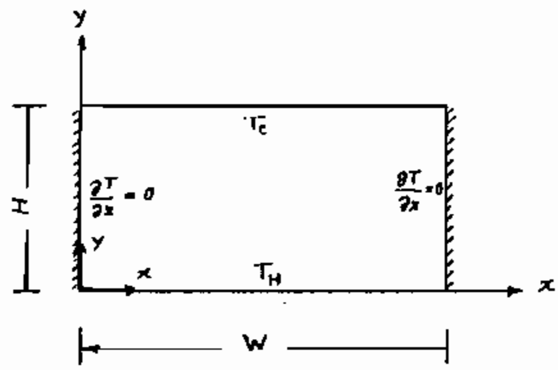

Fig. 1
Schematic diagram of the rectangular porous cavity, coordinate system and the thermal boundaries

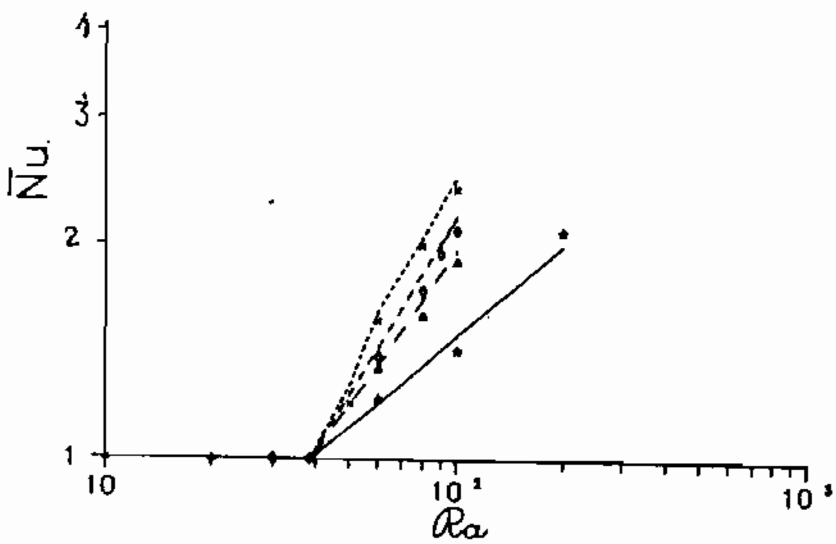

Fig. 2
Nu as a function of Ra compared with the data of Close et al (17)
—— A = 4, – – – A = 2.85, ---- A = 2.2, ---- A = 1.82

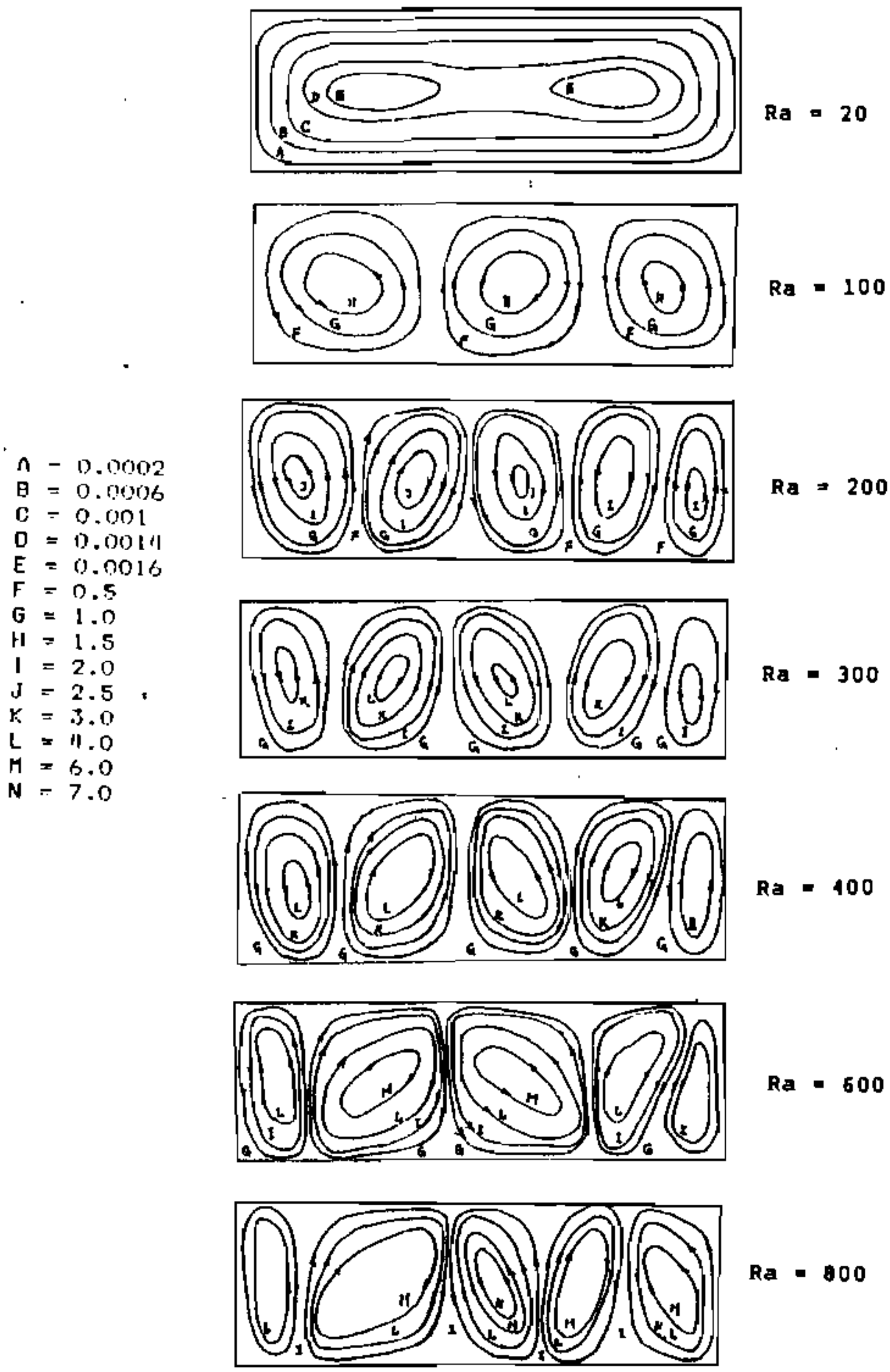

Fig. 3 Streamlines for aspect ratio A= 3

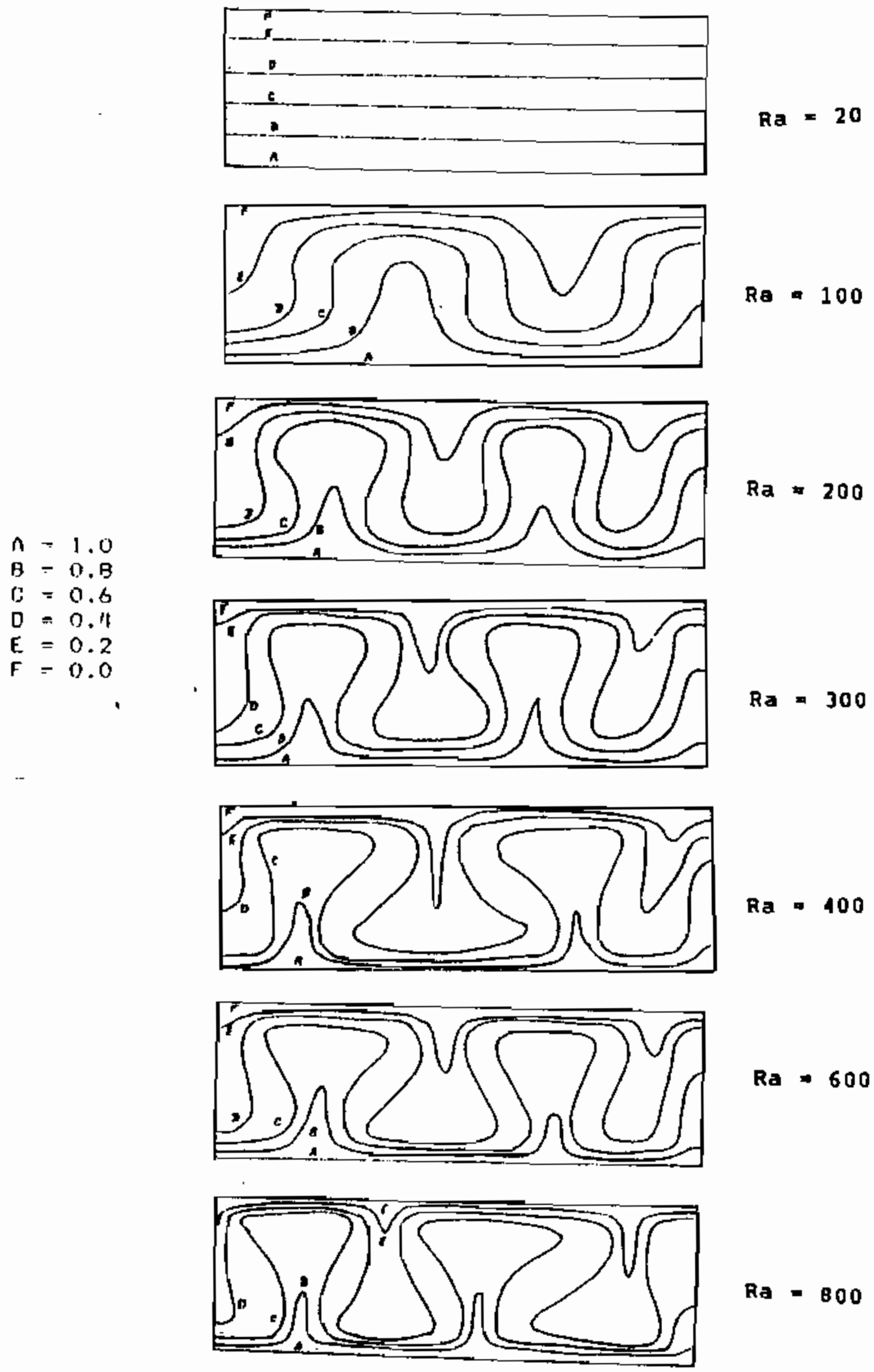

Fig. 4 Isotherms for aspect ratio A=3

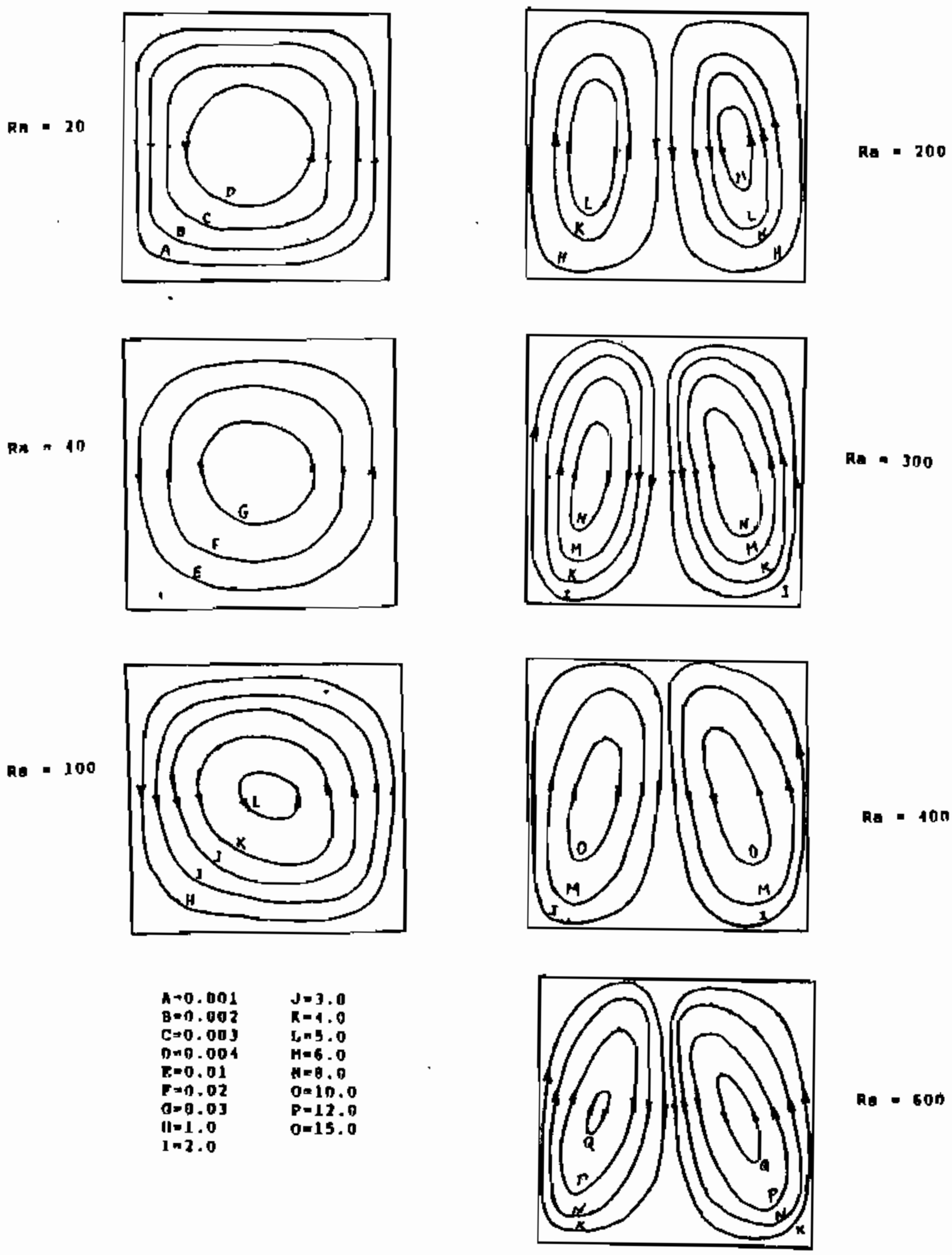

Fig. 5 streamlines for unit aspect ratio

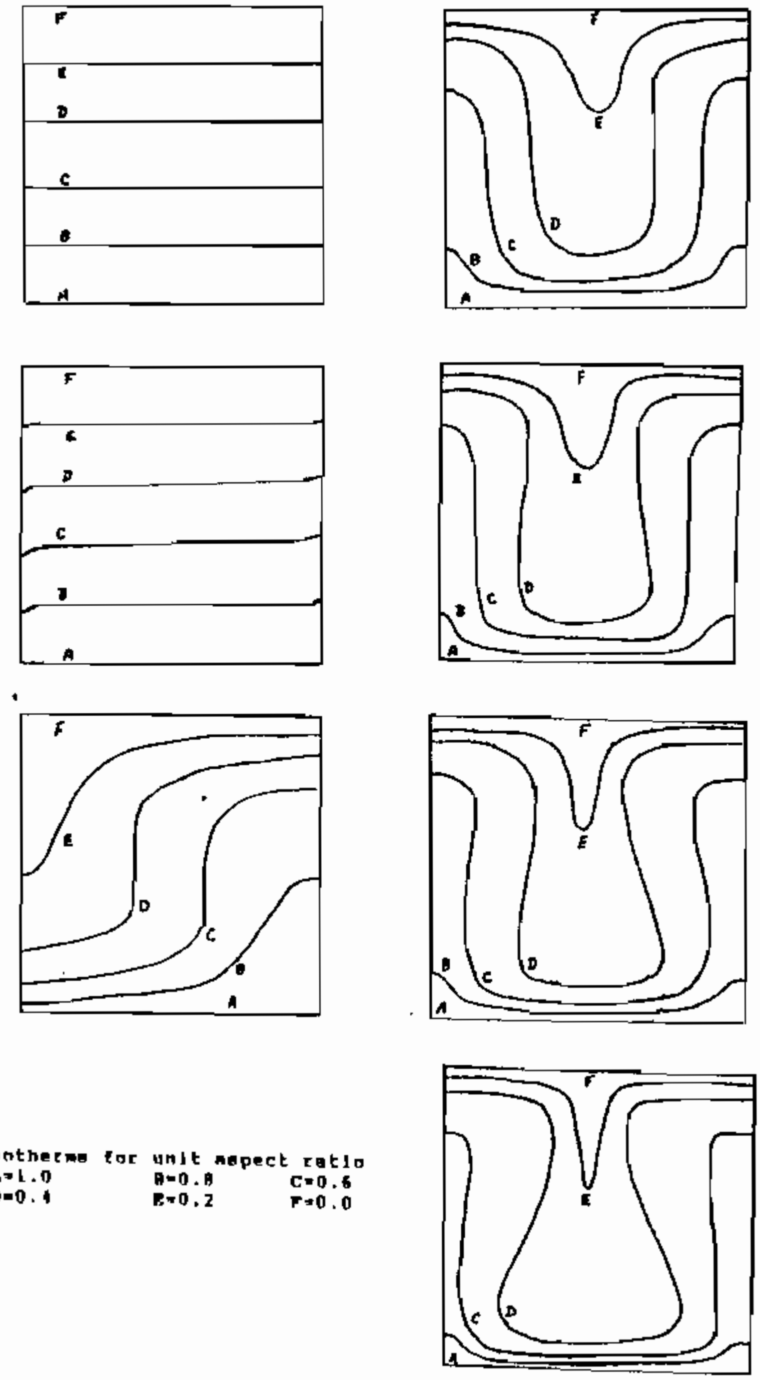

Fig. 6 Isotherms for unit aspect ratio
A=1.0 B=0.8 C=0.6
D=0.4 E=0.2 F=0.0

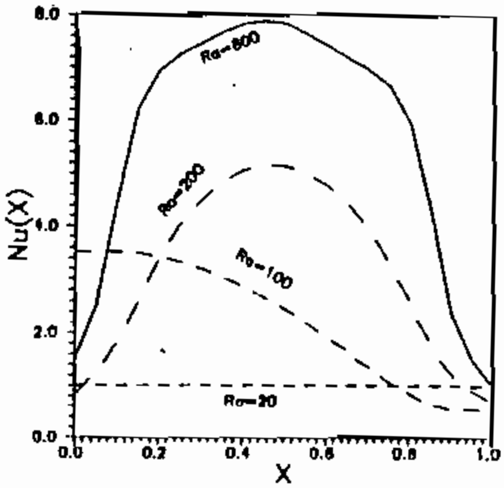

Fig.7
Spatial variation of the local Nusselt number for the lower isothermal wall for A = 1

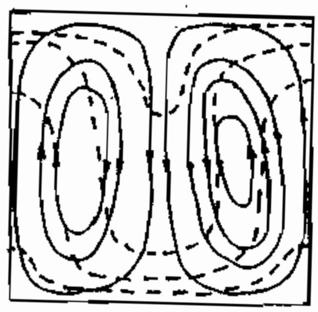

Fig. 9
Streamlines and isotherms for A=1 and Ra=400

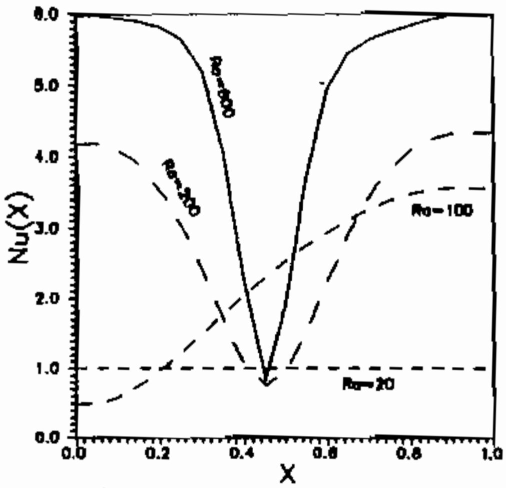

Fig. 8
Spatial variation of the local Nusselt number for the upper isothermal wall for A = 1

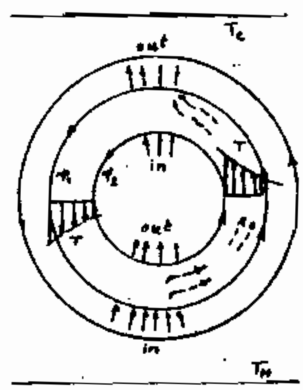

Fig. 10
Heat transfer process in the porous media
- - - convection
—— conduction