International Journal of Thermal Sciences 41 (2002) 861–870

International Journal of Thermal Sciences

www.elsevier.com/locate/ijts

Free convection in a square porous cavity using a thermal nonequilibrium model

A. Cihat Baytas [a,*], Ioan Pop [b]

[a] *Institute for Nuclear Energy, Istanbul Technical University, 80626 Maslak, Istanbul, Turkey*
[b] *Faculty of Mathematics, University of Cluj, R-3400 Cluj, CP 253, Romania*

Received 22 May 2001; accepted 30 October 2001

Abstract

Two-dimensional steady free convection in a square cavity bounded by isothermal vertical walls at different temperatures and adiabatic horizontal walls has been studied numerically by adopting a two-temperature model of heat transfer. Such a model, which allows the fluid and solid phases not to be in local thermal equilibrium, is found to modify the flow behaviour and heat transfer rates. Knowledge of this behaviour is important for the design of thermal insulation systems and other practical applications. As far as we know, this problem has not yet been studied in the available literature. © 2002 Éditions scientifiques et médicales Elsevier SAS. All rights reserved.

Keywords: Square cavity; Free convection; Porous medium in nonequilibrium; Numerical study

1. Introduction

Free convection in porous media occurs in many systems and in nature including geophysical, environmental and technological problems. Such problems are of great interest, for example, in the utilisation of geothermal energy, high-performance building insulation, post-accident heat removal from pebble-bed nuclear reactors, multishield structures used in the insulation of nuclear reactors, pollutant dispersion in aquifers, solar power collector, etc. The state-of-the-art has been very well summarised in the recent books by Nield and Bejan [1], Ingham and Pop [2], Vafai [3] and Pop and Ingham [4].

The problem of free convection flow in differentially heated cavities, with top and bottom walls insulated, and filled with Darcian or non-Darcian fluid-saturated porous media, is of fundamental interest to many technological applications in the modern industry. Walker and Homsy [5], Bejan [6], Prasad and Kulacki [7], Gross et al. [8] Beckermann et al. [9], Lai and Kulacki [10], Manole and Lage [11], Choi et al. [12], Mamou et al. [13], Baytas and Pop [14,15] and Baytas et al. [16] have contributed with some very important theoretical results to this topic.

However, it was assumed in these studies that the convecting fluid and the porous medium are everywhere in local thermodynamic equilibrium. The inclusion of more physical realism in the Darcian fluid model is, however, important for the accurate modelling of any practical problem. Although the problems of convective heat transfer in porous cavities when the fluid and the porous medium are in the local thermodynamic equilibrium have received great attention in the literature, the analyses devoted to convective flows using a thermal nonequilibrium model are to our knowledge scarce. A literature search indicates that this model of porous medium convection has been first considered by Combarnous [17], and Combarnous and Bories [18] and very recently by Banu and Rees [19] for the Darcy–Benard convection. Also, Vafai and Sozen [20], Kuznetsov [21–23] and Kuznetsov and Vafai [24] have considered this model for the forced convection flow in a packed bad. Actually, in the studies of Kuznetsov [21–23], phase difference was suggested to occur between the propagating waves in fluid phase and solid phase due to the effects of thermal nonequilibrium model adopted. However, in the papers by Vafai and Sozen [20] and Kuznetsov and Vafai [24], effects of nonequilibrium were suggested to be more significant at higher Reynolds number and for higher porosity. High velocity and high porosity are the conditions that are often encountered in regenerators (see, [25]). Therefore, adoption of thermal

* Correspondence and reprints.
E-mail address: baytas@itu.edu.tr (A.C. Baytas).

PII: S1290-0729(02)01379-0

Nomenclature

c_p	specific heat of fluid at constant pressure	$J\cdot kg^{-1}\cdot K^{-1}$
D	height of porous cavity	m
g	acceleration due to gravity	$m\cdot s^{-2}$
h	volumetric heat transfer coefficient between solid and fluid	$W\cdot m^{-2}\cdot K^{-1}$
H	dimensionless scaled value of h	
k	thermal conductivity	$W\cdot m^{-1}\cdot K^{-1}$
K	permeability of the porous medium	m^2
Nu	average Nusselt number	
Ra	modified Rayleigh number for a porous medium	
T	temperature	K
u, v	velocity components along x and y axes	$m\cdot s^{-1}$
x, y	Cartesian coordinates	m

Greek symbols

α	thermal diffusivity	$m^2\cdot s^{-1}$
β	coefficient of thermal expansion	K^{-1}
γ	modified conductivity ratio	
ε	prescribed error	
Γ	thermal diffusivity ratio	
ν	fluid kinematic viscosity	$m^2\cdot s^{-1}$
θ	dimensionless temperature	
ϕ	porosity	
ρ	fluid density	$kg\cdot m^{-3}$
ψ	stream function	$m^2\cdot s^{-1}$

nonequilibrium model is important in the study of thermal performance of regenerators.

A recent restatement of the full equations has been presented by Nield and Bejan [1], where the equations governing the evolution of temperature in the solid and fluid phases are coupled by means of terms allowing the local transfer of heat to be proportional to the local temperature difference between the phases. The review papers by Kuznetsov [26] and Vafai and Amiri [27] give detailed information about the research on thermal nonequilibrium effects of fluid flow through a porous packed bed. The effects of adopting of this model on the free convection boundary-layer over a vertical flat plate and near the lower stagnation point of a cylindrical surface embedded in a fluid-saturated porous medium have been studied recently by Rees and Pop [28,29].

Motivated by the recent papers by Rees and Pop [28,29], the aim of the present paper is to study the steady state free convection in a square porous cavity using a nonequilibrium model of microscopic heat transfer between the fluid and the solid phase of the porous medium. To our best knowledge, such an investigation has not been reported to date. The results reported here have been obtained numerically by solving the evolutionary model using a cell-centered finite volume scheme and the Alternating Direction Implicit (ADI) method for a range values of parameters like the solid/fluid-scaled heat transfer coefficient (H) and the porosity-scaled conductivity ratio (γ) for a value of the Rayleigh number $Ra = 10^3$. Results are presented in terms of isotherms, streamlines and average Nusselt numbers for the fluid and solid phases at the heated vertical wall. It is shown that the effects of the parameters H and γ on the flow patterns and heat transfer rates exhibit a distinct difference from those of a classical square cavity filled with a fluid-saturated porous medium in a local thermodynamic equilibrium. It is also found that the variation of the average Nusselt numbers for the fluid and solid phases is qualitatively similar to that observed in the case of vertical free convection boundary-layer flow embedded in a porous medium when the nonequilibrium model is considered.

2. Basic equations

Consider a fluid-saturated porous medium enclosed in a square cavity of height D. It is assumed that the vertical walls are at the isothermal temperatures T_H and T_C, where $T_H > T_C$, and the two horizontal walls are adiabatic. The geometry of this cavity together with the coordinate system is illustrated in Fig. 1. In the porous medium, Darcy's law is assumed to hold, the fluid is assumed to be a normal Boussinesq fluid, and the viscous drag and inertia terms of the momentum equations are negligible. Further, we assume that the convecting fluid and the porous medium are not in local thermodynamic equilibrium and, therefore, a two-temperature model of microscopic heat

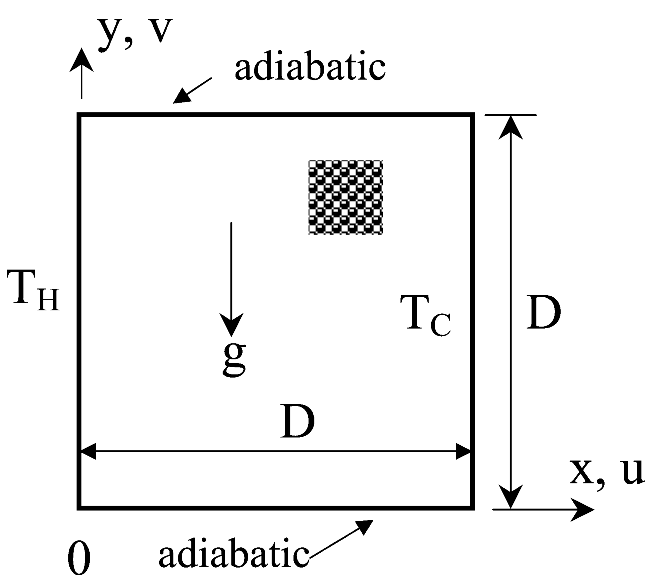

Fig. 1. Physical model and coordinate system.

transfer applies. Under these assumptions, the conservation equations for mass, momentum and energy for the unsteady two-dimensional flow in the porous cavity are, see Rees and Pop [29],

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

$$\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x} = -\frac{gK\beta}{\nu}\frac{\partial T_f}{\partial x} \tag{2}$$

$$\varphi(\rho c_p)_f \frac{\partial T_f}{\partial t} + (\rho c_p)_f\left(u\frac{\partial T_f}{\partial x} + v\frac{\partial T_f}{\partial y}\right) = \varphi k_f\left(\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial y^2}\right) + h(T_s - T_f) \tag{3}$$

$$(1-\varphi)(\rho c_p)_s \frac{\partial T_s}{\partial t} = (1-\varphi)k_s\left(\frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial y^2}\right) + h(T_f - T_s) \tag{4}$$

where u and v are the velocity components along x- and y-axes, t is the time, g is the acceleration due to gravity and T is the temperature, where the f and s subscripts denote the fluid and solid phases, respectively. The following are the other fluid and porous medium properties: K is the permeability of the porous medium, ϕ is the porosity, ν is the fluid kinematic viscosity, ρ is the density, c_p is the specific heat at constant pressure, k is the thermal conductivity and h is a volumetric heat transfer coefficient that is used to model the microscopic transfer of heat between the fluid and solid phases.

We introduce now the following non-dimensional variables

$$\tau = \frac{k_f}{(\rho c_p)_f D^2}t$$
$$(X, Y) = \frac{(x, y)}{D}, \qquad (U, V) = \frac{(u, v)D}{\alpha_f} \tag{5}$$
$$\theta_f = \frac{T_f - T_0}{T_H - T_C}, \qquad \theta_s = \frac{T_s - T_0}{T_H - T_C}$$

where $T_0 = (T_H + T_C)/2$. Using these variables along with the non-dimensional stream function ψ defined in the usual way as $U = \partial\psi/\partial X$ and $V = -\partial\psi/\partial Y$, Eqs. (1)–(4) can be written as

$$\frac{\partial^2 \psi}{\partial X^2} + \frac{\partial^2 \psi}{\partial Y^2} = -Ra\frac{\partial \theta_f}{\partial X} \tag{6}$$

$$\frac{\partial \theta_f}{\partial \tau} + \frac{\partial \psi}{\partial Y}\frac{\partial \theta_f}{\partial X} - \frac{\partial \psi}{\partial X}\frac{\partial \theta_f}{\partial Y} = \frac{\partial^2 \theta_f}{\partial X^2} + \frac{\partial^2 \theta_f}{\partial Y^2} + H(\theta_s - \theta_f) \tag{7}$$

$$\Gamma\frac{\partial \theta_s}{\partial \tau} = \frac{\partial^2 \theta_s}{\partial X^2} + \frac{\partial^2 \theta_s}{\partial Y^2} + \gamma H(\theta_f - \theta_s) \tag{8}$$

where the non-dimensional parameters H, γ and Γ are defined as

$$H = \frac{hD^2}{\varphi k_f}, \qquad \gamma = \frac{\varphi k_f}{(1-\varphi)k_s}, \qquad \Gamma = \frac{\alpha_f}{\alpha_s} \tag{9}$$

with α_f and α_s being the thermal diffusivities of the fluid and solid phases, respectively. Further, Ra is the modified Rayleigh number, which is defined as

$$Ra = \frac{gK\beta(T_H - T_C)D}{\varphi\alpha_f\nu} \tag{10}$$

The initial and boundary conditions of Eqs. (6)–(8) are

$$\begin{aligned} &\tau = 0: \psi = \theta_f = \theta_s = 0 && \text{at } X = 0, 1 \text{ and } Y = 0, 1\\ &\tau > 0: \psi = 0, \quad \theta_f = \frac{1}{2}, \quad \theta_s = \frac{1}{2} && \text{on } X = 0\\ &\qquad \psi = 0, \quad \theta_f = -\frac{1}{2}, \quad \theta_s = -\frac{1}{2} && \text{on } X = 1\\ &\qquad \psi = 0, \quad \frac{\partial \theta_f}{\partial Y} = \frac{\partial \theta_s}{\partial Y} = 0 && \text{on } Y = 0, 1 \end{aligned} \tag{11}$$

The physical quantities of most interest are the fluid and solid phases average Nusselt numbers at the vertical walls, which are given by

$$\overline{Nu_f} = \int_0^1 \left(-\frac{\partial \theta_f}{\partial X}\right)_{X=0,1} \mathrm{d}Y$$
$$\overline{Nu_s} = \int_0^1 \left(-\frac{\partial \theta_s}{\partial X}\right)_{X=0,1} \mathrm{d}Y \tag{12}$$

3. Results and discussion

The results presented here are based on the steady state results obtained from the transient solutions of Eqs. (6)–(8) subject to the boundary conditions (11). A cell-centered finite volume scheme is applied to solve the flow equation and the energy equations for the solid and fluid phases. The Alternating Direction Implicit (ADI) scheme as developed by Douglas and Paceman [30] has been used. A non-uniform grid of (42×42) sizes in (X, Y) directions were found to be suitable and the time step is $\Delta\tau = 10^{-4}$. The iteration process is terminated when the following criterion is satisfied

$$\sum_{i,j}\left|\chi_{i,j}^{n+1} - \chi_{i,j}^{n}\right| \Big/ \sum_{i,j}\left|\chi_{i,j}^{n+1}\right| \leqslant \varepsilon \tag{13}$$

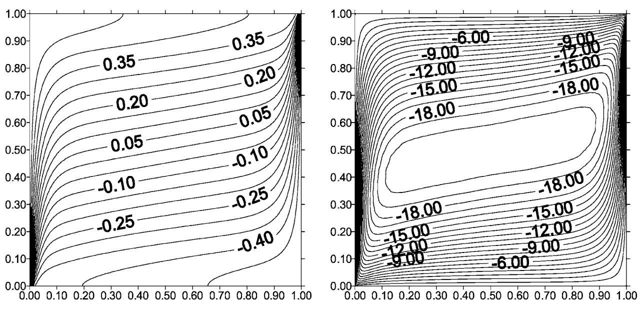

Fig. 2. Isotherms and streamlines for the case of equlibrium model.

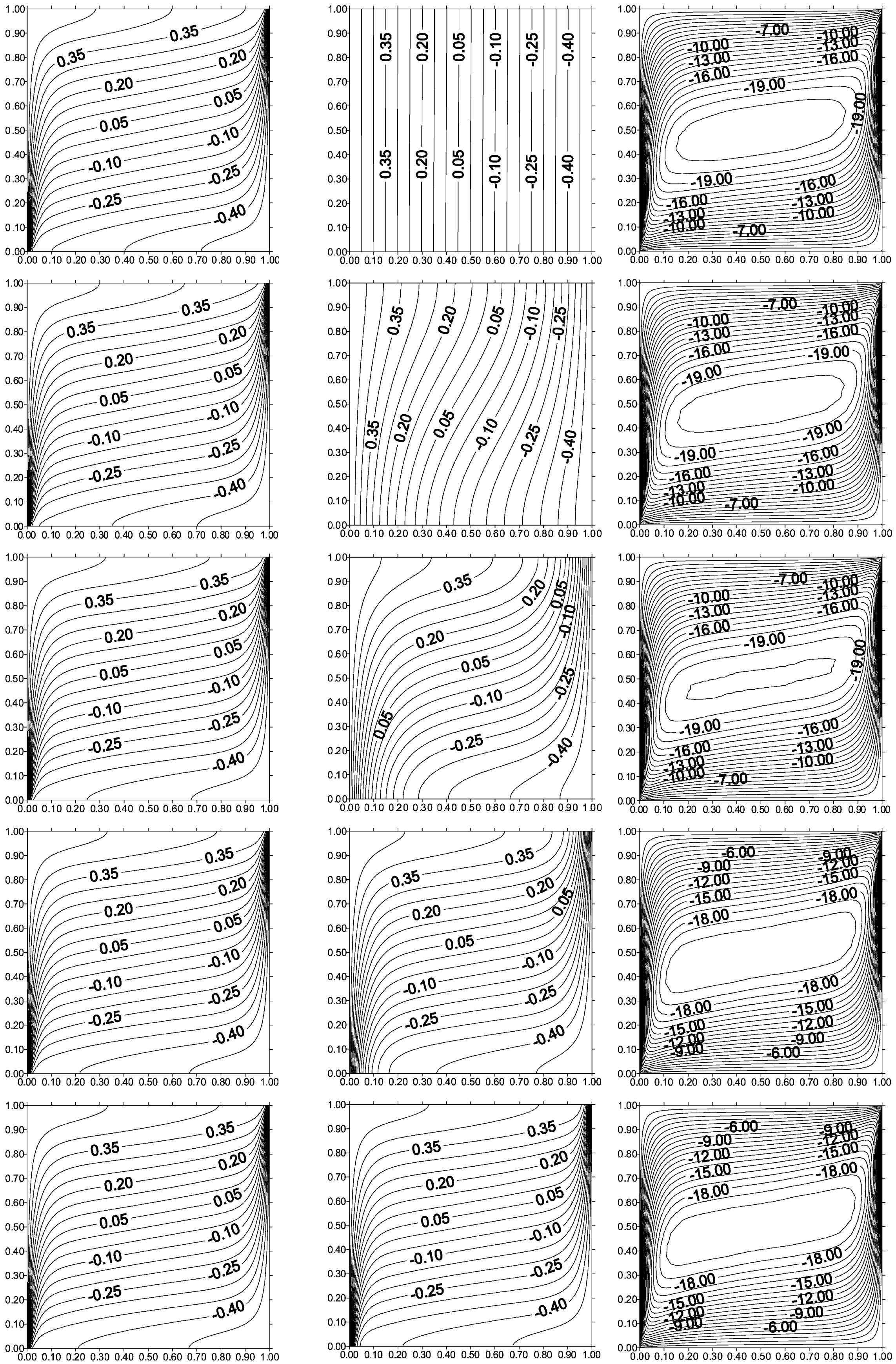

Fig. 3. Isotherms for fluid and solid and streamlines for the case of nonequlibrium model for $\gamma = 0.01$, 1.0, 10, 50, 1000 and $H = 10$.

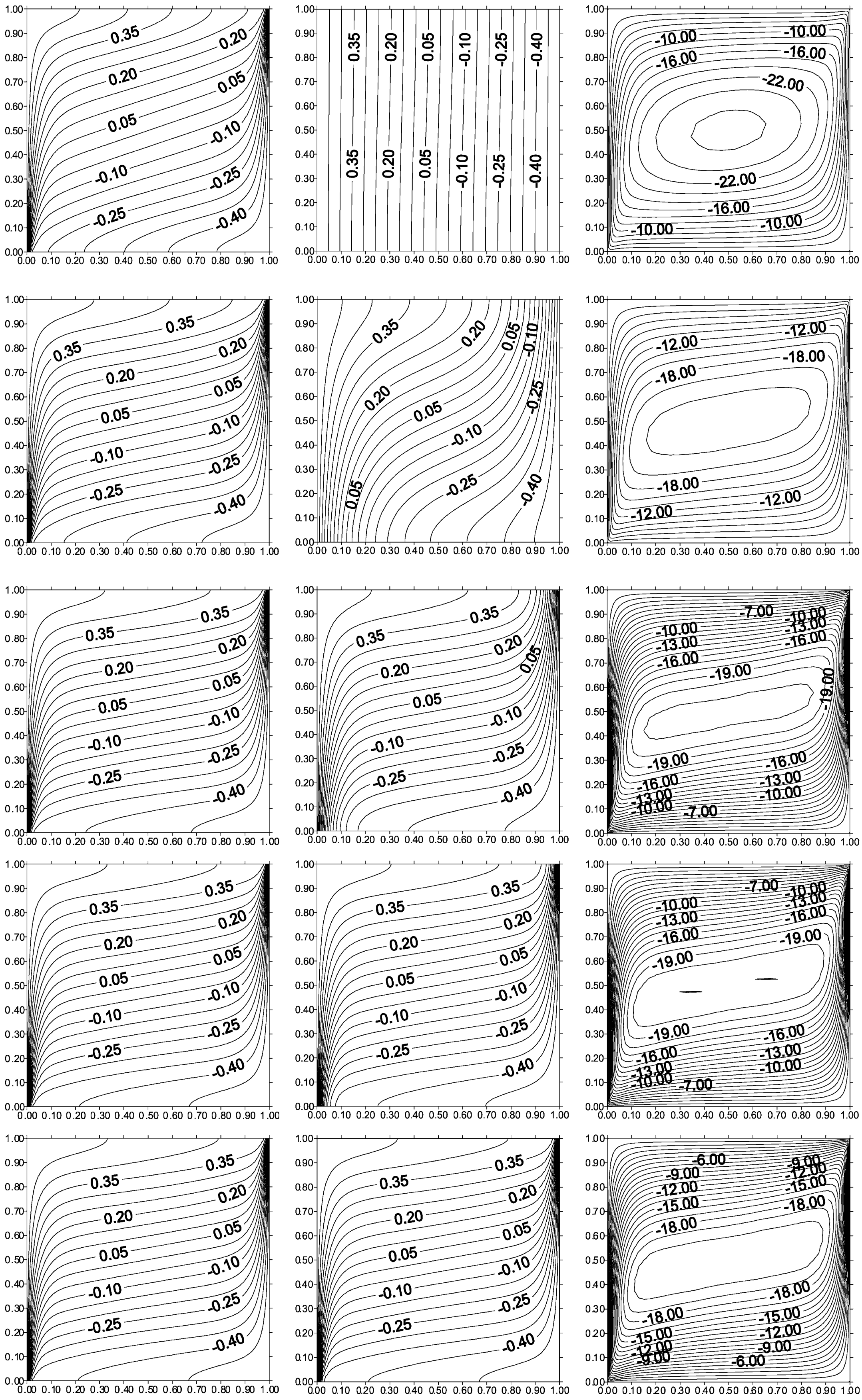

Fig. 4. Isotherms for fluid and solid and streamlines for the case of nonequlibrium model for $\gamma = 0.01$, 1.0, 10, 50, 1000 and $H = 50$.

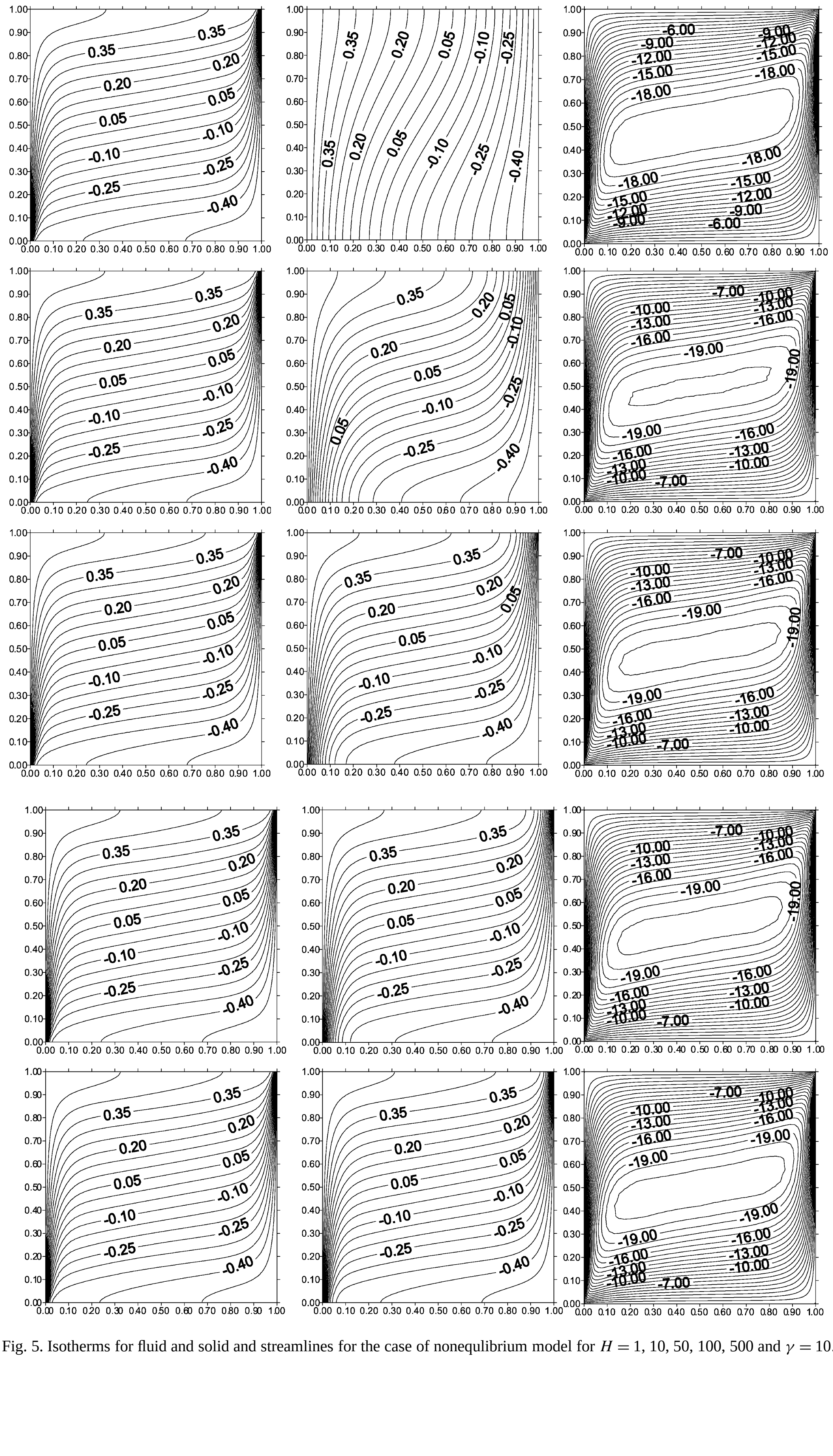

Fig. 5. Isotherms for fluid and solid and streamlines for the case of nonequlibrium model for $H = 1$, 10, 50, 100, 500 and $\gamma = 10$.

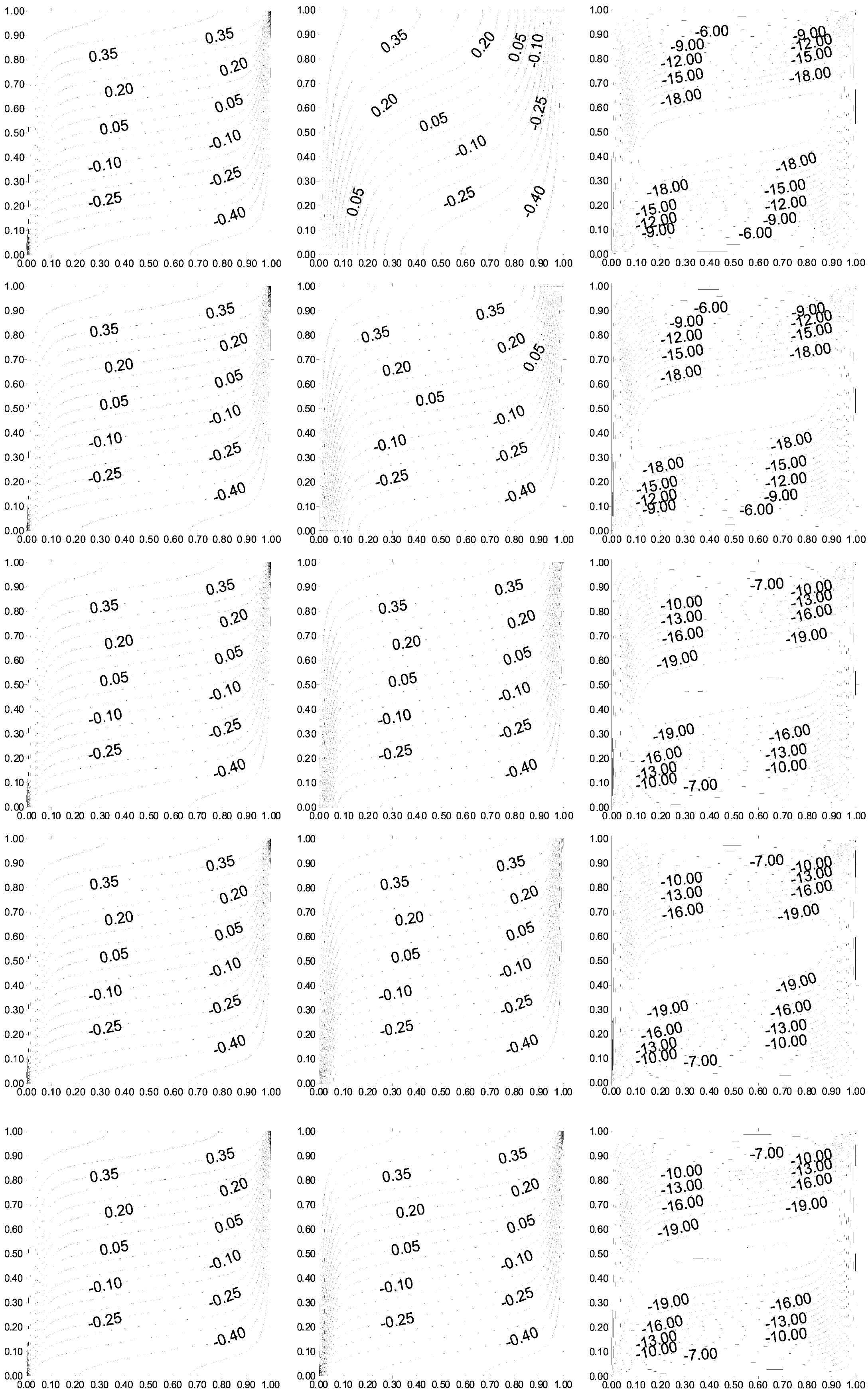

Fig. 6. Isotherms for fluid and solid and streamlines for the case of nonequlibrium model for $H = 1$, 10, 50, 100, 500 and $\gamma = 50$.

Table 1
Values of the average Nusselt numbers $\overline{Nu}_f$ and $\overline{Nu}_s$ for $Ra = 10^3$

H	$\gamma = 1$		$\gamma = 10$		$\gamma = 50$		γ	$H = 0.5$		$H = 1$	
	$\overline{Nu}_f$	$\overline{Nu}_s$	$\overline{Nu}_f$	$\overline{Nu}_s$	$\overline{Nu}_f$	$\overline{Nu}_s$		$\overline{Nu}_f$	$\overline{Nu}_s$	$\overline{Nu}_f$	$\overline{Nu}_s$
1	14.61	1.077	14.63	1.488	14.66	2.599	0.001	14.65	1.048	14.61	1.035
5	14.36	1.260	14.44	2.591	14.64	4.633	0.005	14.65	1.048	14.61	1.035
10	14.14	1.476	14.51	3.350	14.63	5.758	0.01	14.65	1.049	14.61	1.035
50	13.43	2.505	14.40	5.697	14.60	8.687	0.05	14.65	1.049	14.61	1.037
100	13.10	3.182	14.34	6.892	14.58	9.945	0.1	14.65	1.051	14.61	1.039
500	12.24	5.108	14.16	9.711	14.54	12.42	1.0	14.65	1.071	14.61	1.077
1000	11.79	5.984	14.08	10.80	14.53	13.18	1.5	14.65	1.082	14.61	1.100
3000	11.01	7.248	13.96	12.19	14.51	13.95	2.0	14.65	1.093	14.61	1.124
5000	10.66	7.741	13.92	12.68	14.51	14.15	2.5	14.65	1.105	14.61	1.148

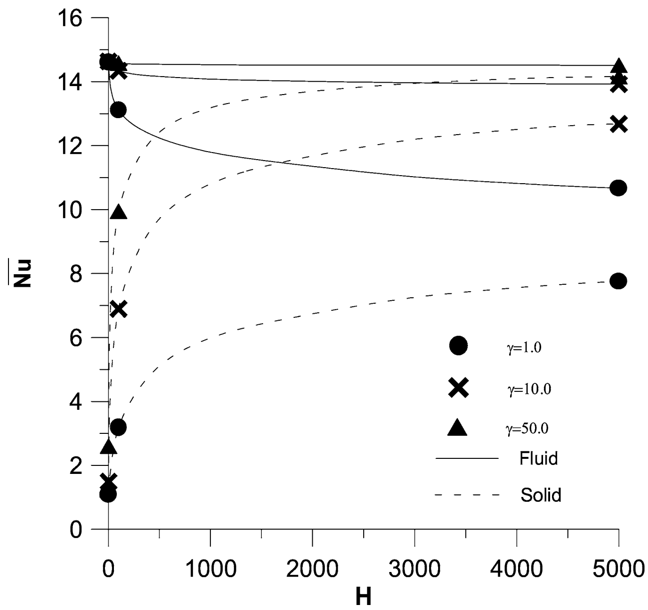

Fig. 7. Variation of the average Nusselt numbers with H for different values of γ.

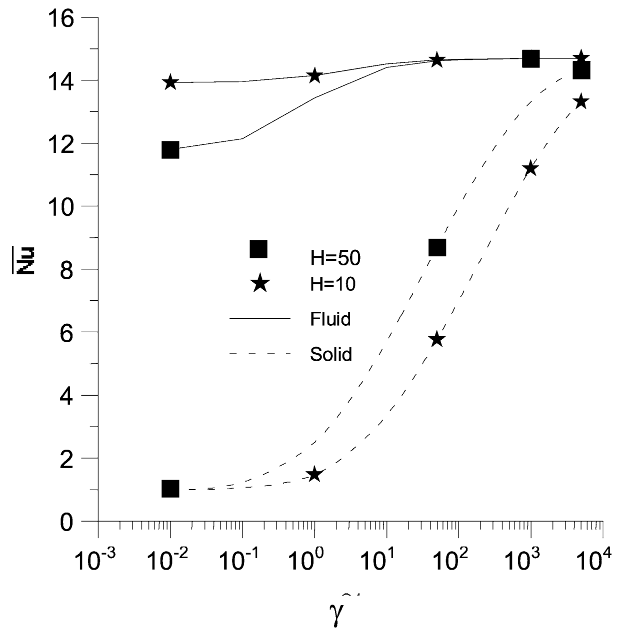

Fig. 8. Variation of the average Nusselt numbers with γ for different values of H.

where χ stands for ψ or θ_f and θ_s; n denotes the iteration order and ε is a prescribed error, where $\varepsilon = 10^{-4}$ for the temperature and $\varepsilon = 10^{-5}$ for the stream function, respectively. This method has been very successfully used recently by Baytas and Pop [14,15] and Baytas et al. [16] and it is therefore unnecessary to describe it here.

The results were obtained for some values of the parameters H (the solid/fluid-scaled heat transfer coefficient) and γ (the porosity-scaled conductivity ratio) varying in the range $0 \leqslant H \leqslant 5000$ and $0 \leqslant \gamma \leqslant 5000$, respectively, and a value of the Rayleigh number $Ra = 10^3$. Isotherms and streamlines are presented in Figs. 2–6, while the average Nusselt numbers are illustrated in Figs. 7 and 8. Fig. 2 shows the isotherms and streamlines for the case of the classical square porous cavity filled with a fluid-saturated porous medium, which is in thermodynamical equilibrium (see, [14]). However, for the case of nonequilibrium model, Figs. 3 to 5 show that the parameter γ does not considerably affect the isotherms and streamlines for the fluid phase when H is not to high, whilst the isotherms of the solid phase are substantially affected. Thus, it is clear from the isotherms plots that a state of local thermal equilibrium, indicated by the isotherms for the two phases being virtually coincident, is reached for large values of γ. A large value of γ corresponds to the fluid having a high thermal conductivity relative to the solid, thereby allowing the fluid properties to dominate the development of the flow. However, we notice that for the range values of the parameters used, there has not been observed a wave which forms due to the temperature difference between the fluid and solid phases as in the problem of forced convection in a porous packed bad studied by Kuznetsov [21, 23].

Further, Table 1 shows some values of the average Nusselt numbers $\overline{Nu}_f$ and $\overline{Nu}_s$ for the fluid and solid phases for $Ra = 10^3$. It is worth mentioning that for the case of equilibrium model the value of $\overline{Nu}_f$ obtained here is $\overline{Nu}_f = 14.06$ which is in very good agreement with the value reported, for example, by Gross et al. [8], $\overline{Nu}_f = 13.448$ and Manole and Lage [11], $\overline{Nu}_f = 13.637$. On the other hand, Table 1 and Figs. 7 and 8 show that the values of $\overline{Nu}_s$ are smaller than those of $\overline{Nu}_f$. However, these values tend asymptotically to the same value as both γ and H increase. This is in agreement with the results reported by Rees and Pop [28,29] for the case of boundary layer flow over a vertical surface or near the lower stagnation point of a cylindrical surface placed in a porous medium. It is also seen from Table 1 and Fig. 7 that when H is small there is a very substantial difference between the heat transfer rates of the fluid and solid phases, indicating that nonequilibrium effects are stronger when H is small, which is not surprising since H is a measure of the ease with which heat is transferred between the phases. Therefore, the nonequilibrium effects are very strong when H is small. As H increases the heat transfer between the phases occurs more readily and this is reflected by the increasing similarity between the heat transfer rates of the phase. For very large values of H we have almost recovered the thermal equilibrium case where the fluid and solid temperature fields are identical. Variations of $\overline{Nu}_f$ and $\overline{Nu}_s$ with γ are shown in Fig. 8 for $H = 10$ and 50. This figure shows that the same qualitative effects are obtained as variations in H. Thus, large values of γ reduce the nonequilibrium effects. However, the values of $\overline{Nu}_s$ are much lower than those of $\overline{Nu}_f$. This can also be seen from Table 1.

4. Conclusions

Steady-state flow and heat transfer characteristics have been investigated for the free convection flow in a square cavity filled with a porous medium assuming a nonequilibrium model of thermal energy transport. It is found that such a model modifies substantially the behaviour of the flow characteristics, particularly those of the local heat transfer coefficients. Although, we have considered a square porous cavity, there are no previous theoretical and experimental results against which our results can be compared. However, the results for the local heat transfer rates are found to be in excellent agreement with some published data for the case of vertical free convection boundary-layer flow in a porous medium when the convecting fluid and the porous medium are not in thermodynamic equilibrium. Further research will be done by adopting this two-temperature model for other geometrical configurations, as well.

Acknowledgements

Professor I. Pop wishes to express his deep gratitude to Institute for Nuclear Energy, Istanbul Technical University for offering him the chance to visit this University and to complete the present paper.

References

[1] D.A. Nield, A. Bejan, Convection in Porous Media, 2nd edn., Springer-Verlag, New York, 1999.
[2] D.B. Ingham, I. Pop (Eds.), Transport Phenomena in Porous Media, Pergamon, Oxford, 1998.
[3] K. Vafai (Ed.), Handbook of Porous Media, Marcel Dekker, New York, 2000.
[4] I. Pop, D.B. Ingham, Convective Heat Transfer: Mathematical and Computational Modelling of Viscous Fluids and Porous Media, Pergamon, Oxford, 2001.
[5] K.L. Walker, G.M. Homsy, Convection in a porous cavity, J. Fluid Mech. 97 (1978) 449–474.
[6] A. Bejan, On the bounday layer regime in a vertical enclosure filled with a porous medium, Lett. Heat Mass Transfer 6 (1979) 93–102.
[7] V. Prasad, F.A. Kulacki, Convective heat transfer in a rectangular porous cavity—effect of aspect ratio on flow structure and heat transfer, Trans. ASME J. Heat Transfer 106 (1984) 158–165.
[8] R.J. Gross, M.R. Bear, C.E. Hickox, The application of flux-corrected transport (FCT) to high Rayleigh number natural convection in a porous medium, in: Proc. 8th Internat. Heat Transfer Conference, San Francisco, CA, 1986.
[9] C. Beckermann, R. Viskanta, S. Ramadhyani, A numerical study of non-Darcian natural convection in a vertical enclosure filled with a porous medium, Numer. Heat Transfer 10 (1986) 557–570.
[10] F.C. Lai, F.A. Kulacki, Natural convection across a vertical layered porous cavity, Internat. J. Heat Mass Transfer 31 (1988) 1247–1260.
[11] D.M. Manole, J.L. Lage, Numerical benchmark results for natural convection in a porous medium cavity, in: Heat and Mass Transfer in Porous Media, ASME Conference, HTD, Vol. 216, 1992, pp. 55–60.
[12] E. Choi, A. Chakma, K. Nandakumar, A bifurcation study of natural convection in porous media with internal heat sources: The non-Darcy effects, Internat. J. Heat Mass Transfer 41 (1998) 383–392.
[13] M. Mamou, P. Vasseur, E. Bilgen, Double-diffusive convection instability in a vertical porous enclosure, J. Fluid Mech. 368 (1998) 263–289.
[14] A.C. Baytas, I. Pop, Free convection in oblique enclosures filled with a porous medium, Internat. J. Heat Mass Transfer 42 (1999) 1047–1057.
[15] A.C. Baytas, I. Pop, Natural convection in a trapezoidal enclosure filled with a porous medium, Internat. J. Engng. Sci. 39 (2001) 125–134.
[16] A.C. Baytas, A. Liaqat, T. Grosan, I. Pop, Natural convection in a square cavity with heat diffusive walls and filled with a porous medium, Heat Mass Transfer 37 (2001) 467–473.
[17] M. Combarnous, Description du transfer de chaleur par convection naturelle dans une couche porouse horizontale a l'aide d'un coefficient de transfer solide-fluide, C. R. Acad. Sci. Paris A 275 (1972) 1375–1378.
[18] M. Combarnous, S. Bories, Modelisation de la convection naturelle au sein d'une couche porouse horizontal a l'aide d'un coefficient de transfer solide-fluide, Internat. J. Heat Mass Transfer 17 (1974) 505–515.
[19] N. Banu, D.A.S. Rees, The onset of Darcy–Benard convection using a thermal nonequilibrium model, Internat. J. Heat Mass Transfer (2000), submitted.
[20] K. Vafai, M. Sozen, Analysis of energy and momentum transport for fluid flow through a porous bed, ASME J. Heat Transfer 112 (1990) 690–699.
[21] A.V. Kuznetsov, An investigation of a wave of temperature difference between solid and fluid phases in a porous packed bad, Internat. J. Heat Mass Transfer 37 (1994) 3030–3033.
[22] A.V. Kuznetsov, A perturbation solution for a nonthermal equilibrium fluid flow through a three dimensional sensible storage packed bed, Trans. ASME J. Heat Transfer 118 (1996) 508–510.
[23] A.V. Kuznetsov, A perturbation solution for heating a rectangular sensible heat storage packed bed with a constant temperature at the walls, Internat. J. Heat Mass Transfer 40 (1997) 1001–1006.
[24] A.V. Kuznetsov, K. Vafai, Analytical comparison and criteria for heat and mass transfer models in metal hydride packed beds, Internat. J. Heat Mass Transfer 38 (1995) 2873–2884.

[25] K. Muralidhar, K. Suzuki, Analysis of flow and heat transfer in a regenerator mesh using a non-Darcy thermally non-equilibrium model, Internat. J. Heat Mass Transfer 44 (2001) 2493–2504.

[26] A.V. Kuznetsov, Thermal nonequilibrium forced convection in porous media, in: D.B. Ingham, I. Pop (Eds.), Transport Phenomena in Porous Media, Pergamon, Oxford, 1998, pp. 103–129.

[27] K. Vafai, A. Amiri, Non-Darcian effects in combined forced convective flows, in: D.B. Ingham, I. Pop (Eds.), Transport Phenomena in Porous Media, Pergamon, Oxford, 1998, pp. 313–329.

[28] D.A.S. Rees, I. Pop, Free convective stagnation-point flow in a porous medium using a thermal nonequilibrium model, Internat. Comm. Heat Mass Transfer 26 (1999) 945–954.

[29] D.A.S. Rees, I. Pop, Vertical free convective boundary-layer flow in a porous medium using a thermal nonequilibrium model, J. Porous Media 3 (2000) 31–44.

[30] J. Douglas Jr, D.W. Peaceman, Numerical solution of two-dimensional heat flow problems, AIChE J. 1 (1955) 502–512.