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Three-dimensional modeling of a solar heat exchanger partially filled with porous media

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Abstract: This paper present numerical simulation study of the heat transfer and mixed convection flow in a three-dimensional channel filled with fluid and fitted with some porous blocks inserted intermittently in transverse of the channel which is in out thermal equilibrium with the fluid media. The frontiers are subjected to heat flux, q, on the porous blocks at the top and on the fluid compartments at the bottom, and the other walls are adiabatic. We used the Darcy-Brinkman model for the flow in porous medium. The coexistence of two regimes, the natural and forced convection, requires the optimization of the values of Rayleigh, Reynolds and Darcy numbers. Thus we are opted to determine their critical values and the neutral curves of flow stability in the aim to predict the maximum temperature and the pressure drop at the exit channel.The numerical results are reported in terms of isotherms, velocity field, streamlines, and averaged Nusselt number.

KEYWORDS: Solar energy, Three-dimensional, Mixed convection, Porous media.

INTRODUCTION

In thermal devices, improvement of convection heat transfer becomes an important factor in industries like electronic equipment and heat exchangers. Heat exchangers may be classified according to transfer process, construction, number of fluids, and heat transfer mechanisms. In industrial processes, another method for improving the convection heat transfer characteristics is using porous medium (any material which consists of solid matrix with an interconnected void is called porous media such as rocks and open cell aluminum foams). Therefore, porous media technique has been the subject of many studies and has received a considerable observation. This attention is due to the fact that this kind of structure is encountered in many engineering applications, such as filtration, building thermal insulation, ground water, oil flow and all types of heat exchangers. It has been showed that the insertion of porous matters can enhance significantly the heat transfer. P.C Huang et K. Vafai [1] obtained numerical solutions for a forced convection in an isothermal parallel plates channel partially filled with a porous media. They have showed that a significant heat transfer increase could be obtained by adding porous blocks on the bottom wall. A numerical solution was obtained by A. Hadim [2] for the problem of forced convection in fully and partially porous parallel plate channels with discrete heat sources. It was found that when the width of the heat source and the spacing between the porous inserts are of the same order of magnitude as the channel height, the heat transfer enhancement is almost the same as in the fully porous channel while the pressure drop is significantly lower. H.J. Sung et al. [3] studied numerically the effects of the height and the permeability of the porous matrix on the flow and heat transfer characteristics of forced convection in a partially porous channel. The results obtained show that there exists a critical thickness of the porous layer at which heat transfer is minimum. Moreover, the pressure drop increased as the porous block height increased and Darcy number decreased. W.S.Fu et al. [4] investigated numerically laminar forced convection through a porous block mounted on a heated wall for different porous heights, porosity (e), particle diameter and Reynolds number (Re). In addition, M.K.Akam et al. [5] used Darcy–Brinkman–Forchheimer model to investigate forced convection in parallel plate filled with porous media a high thermal conductivity. Their results showed that the maximum heat transfer (Nu) was reached for a totally porous conduit. Furthermore, they observed that the decrease in the Darcy number for high thermal conductivity had a significant effect on enhancement of heat transfer rate. H. Shokouhmand et al. [6] investigated the effect of porous thickness, Darcy number and the ratio of porous thermal to fluid conductivity on laminar flow and heat transfer characteristics between two parallel plates partially filled with a porous medium using Lattice Boltzmann Method (LBM).

O. Rahli et al. [7] present numerical study of mixed convection heat and mass transfer in horizontal rectangular channels partially filled with porous medium. The main contribution of their research is to characterize how the porous block will create a heterogeneity that will induce a change on the Poiseuille-Rayleigh-Benard (PRB) fluid circulation dynamics. A discussion of the formation and variation of recirculation is presented by S. Jaballah et al. [8] in an open channel filled with fluid and where porous blocks are intermittently inserted. Despite all the previously listed porous media modelling and the high number of Publications dealing with numerical and experimental analysis of porous media, there are still some unaddressed issues of porous metal foam applications. The modelling investigations on porous media as heat exchanger were conducted mainly for the bi-dimensional flow condition whilst published modelling studies on porous media subjected to three-dimensional flow are rather scarce. In the present work, a numerical three dimensions (3D) study of mixed convection in a channel partially filled with porous media in outside thermal equilibrium with the fluid medium. The coexistence of two regimes, the natural and forced convection, requires the optimization of the values of Rayleigh, Reynolds and Darcy numbers. Thus we are opted to determine their critical values and the curves of flow stability in the aim to predict the maximum temperature and the pressure drop at the exit channel.

Problem formulation

We consider the problem of mixed convection flow in a (3D) channel of height and depth (H) and length (L); (A = L/H=7) partially filled with a porous medium heated due to solar radiation absorption. The frontiers are subjected to heat fluxes, q on the porous blocks at the top and on the fluid compartments at the bottom (see Figure 1).

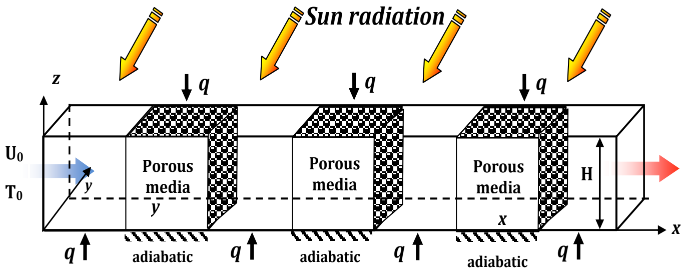

Figure1: Considered physical domain model and coordinates system

Fluid flow enters the channel at a uniform velocity, U0 and constant temperature, T0. At the channel exit an established flow is considered and zero normal gradients are imposed. This configuration permits to analyze the different modes such that the mixed, the forced and the free convection. The fluid is supposed Newtonian and incompressible, and the flow is unsteady and laminar. The thermo physical properties of the incompressible fluid are taken to be constant except for the density variation in the buoyancy terms, where the Boussinesq approximation applies as:

$$\rho = \rho_0 (1 - \beta(T - T_0)) \tag{1}$$

where, $\beta = -\frac{1}{\rho_0}\left[\frac{\partial \rho}{\partial T}\right]$

In the present study a one-domain approach has been retained, with a unique momentum conservation equation. Retaining the corresponding terms in the conservation equations leads to the full Navies-Stokes equation in the fluid or the Darcy-Brinkman model in the porous media. This implies numerical difficulties in terms of convergence and accuracy at the fluid-porous interface when the permeability contrast is high (low Darcy number in the porous layer).Also the porous medium is taken as homogeneous and isotropic, the solid matrix is supposed to be rigid, the Darcy–Brinkman formulation, including the convective inertia term is adopted in the analysis.

$$\left.\begin{array}{l}(x,y)=(x'/H',y'/H');\ t=t'/t_0\quad th\ \ t_0=H'/V_0;\\(u,v,w)=(u',v',w')/V_0;\qquad P=P'/P_0\ ;\\with\ P_0=\rho_0.V_0^2\ ;\ T=\dfrac{(T'-T_0')}{\Delta T'};\ \Delta T'=T_w-T_0\end{array}\right\}$$

To solve the conservation governing equations of continuity, momentum and energy in dimensionless form, respectively separately for each layer, the equations are combined into one set by introducing the following dual parameter.

$$a=\begin{cases}1\ porous\ media\\0\ fluid\ media\end{cases}$$

$$\nabla.\vec{V}=0 \tag{1}$$

$$\left[\frac{a}{\varepsilon}+(1-a)\right]\frac{\partial\vec{V}}{\partial t}+\left[\frac{a}{\varepsilon^2}+(1-a)\right]\left(\vec{V}.\nabla\right)\vec{V}=-\nabla P-\frac{1}{\mathrm{Re}}\left[\frac{a}{Da}.\vec{V}+\nabla^2\vec{V}+\frac{Ra}{\mathrm{Pr}.\mathrm{Re}}.T.\vec{k}\right] \tag{2}$$

$$\left[a(\sigma-1)+1\right]\frac{\partial T}{\partial t}+\left[a\left(\frac{1}{\varepsilon}-1\right)+1\right]\vec{V}.\nabla T=\nabla\left\{\left[\left(\frac{\tilde{\lambda}}{\mathrm{Pr}.\mathrm{Re}}-1\right)+1\right]\nabla T\right\} \tag{3}$$

The dimensionless parameters that characterize the problem are: the aspect ratio of the cavity $A=L/H$, the ratio thermal conductivity $\tilde{\lambda}=\lambda_{eq}/\lambda_f$ with $\lambda_{eq}=(1-\varepsilon)\lambda_s+\varepsilon\lambda_f$ and $\sigma=\left(\rho c_p\right)_{eq}/\left(\rho c_p\right)_f$ and c_p is the heat capacity. The dimensionless boundary conditions can be mathematically expressed as follow.

$$\left.\begin{array}{l}T=0,\ U=1,\ at\ x=0;0\le y\le H,0\le z\le H\\\dfrac{\partial T}{\partial x}=\dfrac{\partial U}{\partial x}=\dfrac{\partial V}{\partial x}=\dfrac{\partial W}{\partial x}=0\ at\ \ x=L,0\le y\le H\ ,0\le z\le H\\\dfrac{\partial T}{\partial y}=V=0\ at\ ,y=0;H,0\le x\le L\ ,0\le z\le H\\\dfrac{\partial T}{\partial z}=0;1,W=0\ at\ a=1;0\ ,z=0\ ,0\le x\le L\ ,0\le y\le H\\\dfrac{\partial T}{\partial z}=1;0,W=0\ at\ a=1;0\ ,z=H\ ,0\le x\le L\ ,0\le y\le H\end{array}\right\}$$

The numerical simulation of the governing equations (2)–(4) subject to boundary conditions is solved by adapting a finite volume approach. The SIMPLE algorithm as suggested by Patankar [11] is used to couple momentum and continuity equations. The governing equations are transformed into a system of algebraic equations through integration over each control volume, leading to a balance equation for the fluxes at the interfaces. The latter are solved iteratively using a tri-diagonal matrix inversion algorithm. We used the technical multi grid of $(202\times42\times42)$ nodes to obtain more precise results.

RESULTS AND DISCUSSION

Interestingly initially to examine the intervals of the governing dimensionless parameters Rayleigh number (Ra), Darcy number (Da), Renolds number (Re), Prandtl number (Pr) and thermal conductivity ratio ($\tilde{\lambda}$) used in the works. We Note that, in all the work the Prandtl number is held constant, (Pr = 0.71) .It needs relatively extensive analysis to cover the effects of each parameter. The resulting flow is established starting from a given lengthening, corresponding to a aspect ratio value (A = 7) proved to be sufficient. The aim of this study is to determine the optical values of some parameters permitting to improve the efficiency of such system. In these conditions, we studied the effects of the thermal Rayleigh number, Ra, the Reynolds number, Re, on the flow structures and on the heat transfer and finally the effect of the Darcy number, Da, on the pressure losses. Detailed comparisons of streamlines, isotherms, profiles of the temperature, velocity and pressure across the channel are carried.

The obtained Isotherms, velocity field and Streamlines in the vertical plane (xz) for (oy) = 0.5, Da = 10^{-4}, Re=10, $\tilde{\lambda} = 1$ and for different values of the Rayleigh number (Ra) are represented on Figure 2. The competition between the principal flow in the horizontal direction imposed by the forced convection, and the buoyancy force introduced by the natural convection of Rayleigh-Bénard type, this is a clear indication that the flow is complex. However for some critical value of Rayleigh number, Ra, cells appear and modify significantly the fluid flow. The critical value is obtained when the first cell in the clear fluid domain is detected; this cell corresponds to a transition between a diffusive process and a convective one. The fluid circulation more encouraging in the fluid layer and the flow penetration in the porous media block is nearly negligible.for lower values of Ra, the flow is

mainly in forced convection FC with development of dynamical boundary layers in the fluid zone and a rehomogeneisation of the flow in the porous domain while velocity takes the identical value of that input one, as shown in Figure 3. The isotherms are parallel to the vertical walls of the cavity, indicating that the heat transfer tend to a diffusive situation. The increase of Ra, the fluid circulation more encouraging in the fluid layer but a significant flow obstruction in the porous media block and the flow is mainly diffusion.

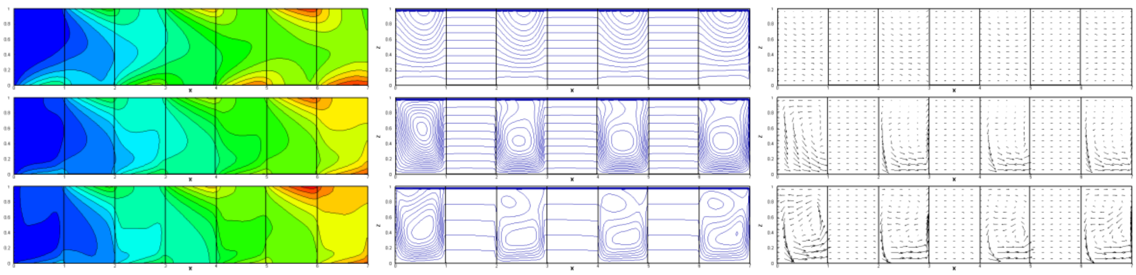

Figure 2: Isotherms, Streamlines and velocity field in the vertical plan (xz) for y=0.5, Da=10-4, $\tilde{\lambda} = 1$, Re=10 and Ra=10^4, Ra=10^5 Ra=10^6

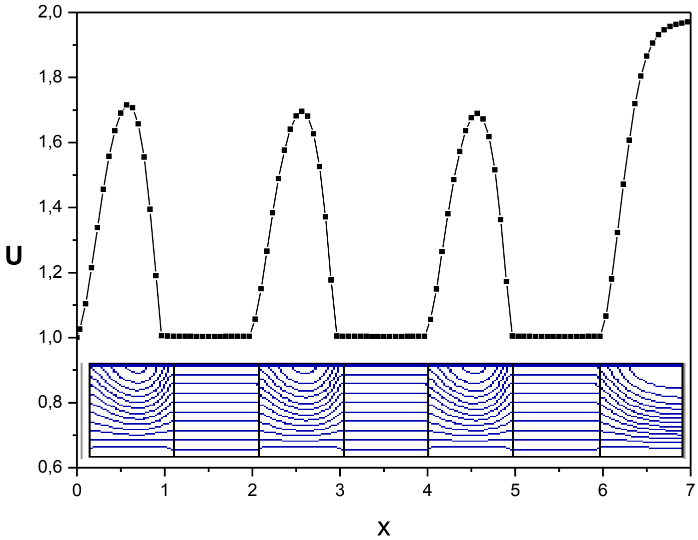

Figure 3: Velocity profiles in the horizontal mid-plan y=0.5 for, Re = 10, Ra = 104, Da = 10^{-4} and $\tilde{\lambda} = 1$

To analyze the neutral stability curve, we introduce the maximum value of the stream function in the channel: $\Psi = \int_0^1 u\,dz$. Figure 4 shows the evolution of the relative maximum flow, Ψ_{max} , versus to the Rayleigh number, Ra, for different values of the Reynolds number, Re. We note that the appearance of the first cell generates an increase of Ψ_{max} and that critical value Rac increases with the Reynolds number Re. In effect, when the Reynolds number, Re, increases the fluid particles will be exposed less time to the heating inside the cavity, and they will not be able to acquire energy necessary to generate a convective movement.

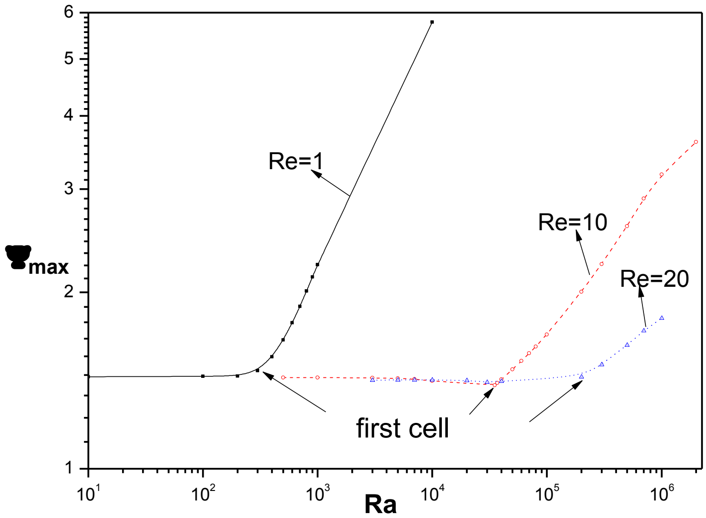

Figure4: Neutral curve stability according to Ra for Da = 10^{-4}, $\tilde{\lambda} = 1$ and different Re

In Figure 5, we present the temperature profiles on different z positions (z=0.1,0.5 and 0.9) near the top wall, at for different Re number (Re = 5, 10 and 20) for Ra=10^4 and Da=10^{-4}. We note, that for $\text{Re} \neq 1$ and at z=0.5, the temperature profiles are linear relatively to the position x. For z=0.1 or 0.9, the temperature profiles are fully in opposite phases and the variation sense is inversed from fluid zone to porous one. In fact, when the Re number increases the fluid particles will not have the sufficiently time to collect the heat from heating surface or solid particles. For Re =1, we note that at the three positions, the temperature profiles are almost identical. This is due to the dominated convective phenomenon that permits the homogenisation of temperature in the channel.

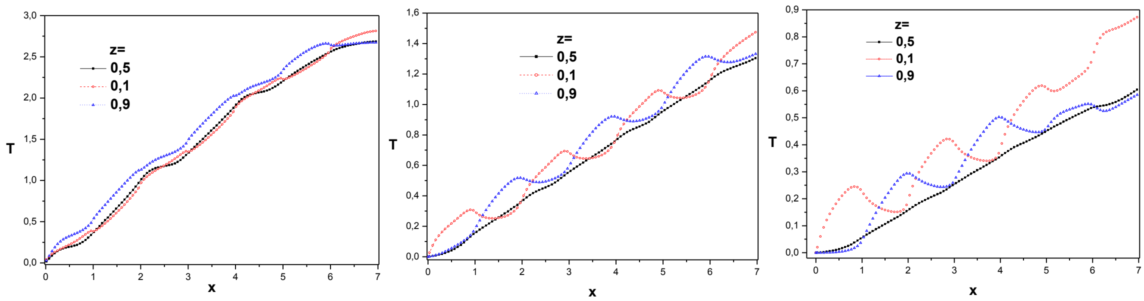

Figure 5: Temperature profiles for different z planes for Ra = 10^4, Da = 10^{-4}, $\tilde{\lambda} = 1$ Re = 5, 1 and 20

Conclusion

The current investigation is a numerical study which conducted to investigate the steady, three-dimensional heat transfer and fluid flow characteristics in an open channel filled of fluid and where porous blocks are intermittently inserted. . Comprehensive investigations are realized to optimize the values of some characteristic parameters in the aim to improve the efficiency of such system.A discussion of the formation and variation of recirculation is presented and some conditions are judged necessary to the appearance of recirculation cells in the fluid zones and to the increase of out temperature and to the cooling of top zone channel.

Nomenclature

A	Aspect ratio ; L/H	β_T	Volumetric thermal expansion; $\left(K^{-1}\right)$
c_p	Heat capacity	ρ	Fluid density; $\left(Kgm^{-3}\right)$
Da	Darcy number ; K/H	ε	Porosity
g	Gravitational acceleration; $\left(m/s^{-2}\right)$	υ	Kinematics viscosity ; $\left(m^2/s^{-1}\right)$
Ra	Rayleigh number ; $\left(g\beta_T H^3 \Delta T'/\upsilon\alpha\right)$	λ	Thermal conductivity; $\left(Wm/K^{-1}\right)$
H, L	Height and width of the channel; (m)	$\tilde{\lambda}$	Thermal conductivity ratio; $\left(\lambda_{eq}/\lambda_f\right)$
K	Permeability of the porous medium; $\left(m^{-2}\right)$	Ψ	Stream function, $\left(m^2 s^{-1}\right)$
P	Dimensionless pressure	**Subscripts**	
Pr	Prandtl number; (ν/α)	eq	Equivalent
Re	Reynolds number ; $(u_0 H/\nu)$	f	Fluid
T_0	Dimensional input temperature of fluid	0	Refers to a reference state
T	Dimensionless temperature; $(T'-T_0)/\Delta T$	s	Solid
Greek symbols		ΔT	qH/k_f
α	Fluid thermal diffusivity; $\left(m^2/s^{-1}\right)$		

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