Revue des Energies Renouvelables Vol. 11 N°2 (2008) 197 – 206

The enhanced cooling of heated blocks mounted on the wall of a plane channel filled with a porous medium

F. Benkafada[1], K. Talbi[1] and M. Afrid[2]

[1] Département de Génie Mécanique
[2] Département de Physique
Université Mohamed Mentouri
Route d'Ain El-Bey, 25000 Constantine, Algérie

(reçu le 23 Mai 2007 – accepté le 30 Juin 2008)

Abstract - *This is a two dimensional numerical simulation of the laminar air forced convection cooling of six blocks mounted on the lower wall of a plane horizontal channel filled (or not filled) with a porous medium. The blocks are equally spaced and heated by a uniform volumetric heat generation. The objective of the study is the determination of the enhanced cooling of the blocks when the channel is filled with a porous medium. The problem is modelled by the continuity, momenta and energy equations with their appropriate initial and boundary conditions. When the channel is filled with a porous medium, a Darcy-Forchheimer-Brinkman flow model is used to describe the flow field. The model equations are numerically solved by a second order accurate finite volume method. The results show that the flow field of the channel filled with a porous medium is very different from that of the channel without the porous matter. A major difference is the appearance of circulating vortices between the blocks when the porous matter is inexistent. This flow pattern difference favours a convective heat transfer enhancement of the flow in the channel filled with the porous matter. Moreover, the effective thermal conductivity of the considered porous medium is higher than that of the fluid. These two factors lead to a considerably better cooling of the blocks mounted in the channel filled with the porous matter. Thus, the use of porous media when possible is recommended because it enhances the cooling of heated blocks mounted in channels.*

Résumé - *Cette étude est une simulation numérique bidimensionnelle du refroidissement par la convection forcée de l'air de six blocs montés sur la paroi inférieure d'un canal plan horizontal rempli (ou non rempli) d'une matière poreuse. Les blocs sont équidistants et uniformément chauffés par un apport de chaleur volumétrique. Le but de l'étude est la détermination de l'amélioration du refroidissement des blocs, lorsque le canal est rempli d'une matière poreuse. Le problème est modélisé par les équations de continuité, de quantité de mouvement et d'énergie, avec leurs conditions, initiales et aux limites, appropriées. Lorsque le canal est rempli d'une matière poreuse, le modèle Darcy-Forchheimer-Brinkman est utilisé pour la modélisation de l'écoulement. Les équations modélisantes sont résolues par la méthode des volumes finis avec une précision du second ordre. Les résultats montrent que l'écoulement du canal rempli avec la matière poreuse est très différent de celui du canal qui ne contient pas la matière poreuse. Une différence majeure est l'apparence des tourbillons entre les blocs, lorsque la matière poreuse est inexistante. Cette différence des écoulements favorise l'amélioration du transfert thermique convectif de l'écoulement du canal rempli de la matière poreuse. En plus, la conductivité thermique effective de la matière poreuse considérée est supérieure à celle du fluide. Ces deux facteurs entraînent un refroidissement amélioré des blocs montés dans le canal rempli de la matière poreuse. Et donc, l'utilisation des milieux poreux lorsqu'elle est possible, est recommandée parce qu'elle améliore le refroidissement des blocs montés dans les canaux.*

Key words: Channel - Porous media - Cooling of heated blocks.

1. INTRODUCTION

The convective cooling of heated solid blocks mounted on the walls of plane channel is still an active area of research. The interest in studying this problem stems from its important applications. It simulates the case of cooling of electronic components mounted on electronic boards and the case of heat transfer from some finned heat exchange devices. A constant interest is in ways of enhancing the cooling of small heated components within which the volumetric heat generation is important. A way of enhancing the cooling of the heated solid blocks mounted on the wall of a channel is achieved by the use of porous media in the channel (if possible and practical). Some examples of studies of the cooling of heated blocks mounted on the walls of channels, involving the use of porous media, are presented next.

P.C. Huang, C.F. Yang, J.J. Huang and M.T. Chiu [1] studied numerically the enhancement of the forced convection cooling of multiple heated blocks in a channel with porous covers. They found that the recirculation caused by the porous covering enhances the heat transfer rate on the top and right faces of the second and subsequent blocks.

Y. Ould-Amer, S. Chikh, K. Bouhadef and G. Lauriat [2] studied numerically the laminar forced convection cooling of heated blocks mounted on a wall of channel. They found that the insertion of a porous matrix between the heated blocks enhances the heat transfer on the vertical sides of the blocks and reduces the level of the temperature within the blocks.

S.C. Tzeng [3] studied the convective heat transfer in a rectangular channel filled with sintered bronze heads and periodically spaced heated blocks. He found a lack of recirculation in regions between the blocks where the forced convective heat transfer is low. He also found that the Nusselt number for each block decreases along the direction of the flow until it reaches its fully developed value.

S. Chikh, A. Boumediene, K. Bouhadef and G. Lauriat [4] studied numerically the forced convection in a channel with intermittent heated porous blocks. They found that for the blocks with low permeability, recirculation zones appear between the blocks and prevent the fluid from going through the next blocks. They also found that the insertion of the porous blocks leads to the wall temperature decrease up to 90 %.

A. Korichi and L. Oufer [5] studied the heat transfer in a rectangular channel with two blocks on the lower wall and one block on the upper wall. The blocks are heated by a constant heat flux. One of their results stated that the temperature difference between the blocks is reduced by the increase of the Reynolds.

In our present study, we consider a two dimensional numerical simulation of the air forced convection cooling of six blocks mounted on the lower wall of a plane horizontal channel filled (or not filled) with a porous medium. The blocks are equally spaced and heated by a uniform volumetric heat generation. The objective of the study is the determination of the enhanced cooling of the blocks when the channel is filled with a porous medium. First, we consider the cooling of the blocks in the channel that is not filled with a porous media; and this case represents a reference state. Next, we will consider the case when the channel is filled with a porous medium. Two porous media with the same porosity and thermal conductivity but with different permeability are considered. Two different Darcy numbers will be considered: one with a relatively low Darcy number (10^{-9}) and a second with a relatively high Darcy number (10^{-2}). The flow and thermal fields of all cases will be presented and compared.

2. MATHEMATICAL MODEL

We consider a plane channel having a length L equal to 20 times its height H (Fig. 1). Six similar solid blocks are mounted on the lower wall. Each block has a length l equal to H and a height h equal to $0.25\,H$. The left face of the first block is at a distance equal to $5.6\,H$ from the entrance. The distance between two consecutive blocks is H. Each block is uniformly heated by a volumetric heat generation Q. The channel is either filled with a porous matter or not. The porosity of the porous matter is assumed homogeneous and constant. At the entrance of the channel a uniform cold flow is imposed. The walls of the channel are static, impermeable and adiabatic. At the exit of the channel, it is assumed that the flow is developed and the axial diffusive heat flux is constant. The physical properties of the fluid, the porous medium and the blocks are assumed constant. The fluid is Newtonian and the flow is assumed laminar. The viscous dissipation and the thermal dispersion are assumed negligible.

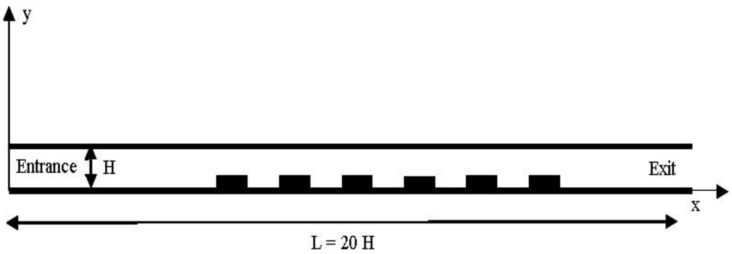

Fig. 1: A schematic view of the geometry

The flow and the conjugate heat transfer are modelled as follows:

The initial conditions

At $t = 0$, $U = 1$ (except in the solid blocks where $U = 0$), $V = 0$ et $t = 0$ (1)

For $t > 0$,

The continuity equation

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \tag{2}$$

The horizontal momentum equation

$$\begin{aligned}\frac{1}{\phi}\frac{\partial U}{\partial t} + \frac{1}{\phi^2}\frac{\partial (UU)}{\partial x} + \frac{1}{\phi^2}\frac{\partial (VU)}{\partial y} &= -\frac{\partial P}{\partial x} - \frac{U}{\mathrm{Re\,Da}} - \frac{C_f\sqrt{U^2+V^2}\,U}{\sqrt{\mathrm{Da}}} \\ &+ \frac{1}{\mathrm{Re}\,\phi}\left[\frac{\partial}{\partial x}\left(\frac{\partial U}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\partial U}{\partial y}\right)\right]\end{aligned} \tag{3}$$

The vertical momentum equation

$$\begin{aligned}\frac{1}{\phi}\frac{\partial V}{\partial t} + \frac{1}{\phi^2}\frac{\partial (UV)}{\partial x} + \frac{1}{\phi^2}\frac{\partial (VV)}{\partial y} &= -\frac{\partial P}{\partial y} - \frac{V}{\mathrm{Re\,Da}} - \frac{C_f\sqrt{U^2+V^2}\,V}{\sqrt{\mathrm{Da}}} \\ &+ \frac{1}{\mathrm{Re}\,\phi}\left[\frac{\partial}{\partial x}\left(\frac{\partial V}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\partial V}{\partial y}\right)\right]\end{aligned} \tag{4}$$

Therefore the flow field is modelled by a Darcy-Forchheimer-Brinkman model [6].

Notice that if the channel is not filled with a porous matter the Navier-Stokes equation are obtained by eliminating the terms containing the Darcy number (Da) and setting the porosity equal to 1. The coefficient C_f in the Forchheimer terms is set equal to 0.55.

The energy equation

$$\frac{\partial [CT]}{\partial t} + \frac{\partial [UT]}{\partial x} + \frac{\partial [VT]}{\partial y} = \frac{1}{\mathrm{Re\,Pr}}\left[\frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right)\right] + S \tag{5}$$

Since there is a steady solution for all the cases in this study, the value of C does not matter because it is multiplied by the temperature time derivative which tends to zero at steady state. Thus, this constant is set equal to 1. Also, in the solid blocks, the velocity is zero at all times.

In the above equation,

$$C = \begin{cases} 1 & \text{for the fluide} \\ \dfrac{\left[\rho\, C_p\right]_m}{\left[\rho\, C_p\right]_f} & \text{for the porous medium} \\ \dfrac{\left[\rho\, C_p\right]_s}{\left[\rho\, C_p\right]_f} & \text{for the solid} \end{cases} \tag{6}$$

$$S = \begin{cases} 0 & \text{outside the blocks} \\ \dfrac{\left(K_s / K_f\right)}{\text{Re Pr}} & \text{inside the blocks} \end{cases} \tag{7}$$

$$K = \begin{cases} 1 & \text{for the fluid} \\ \left(K_m / K_f\right) = 5.77 & \text{for the porous medium} \\ \left(K_s / K_f\right) = 500 & \text{for the solid blocks} \end{cases} \tag{8}$$

The boundary conditions

$$\text{At } x = 0,\ U = 1,\ V = 0,\ T = 0 \tag{9}$$

$$\text{At } x = 20,\ \frac{\partial U}{\partial x} = \frac{\partial V}{\partial x} = \frac{\partial^2 T}{\partial x^2} = 0 \tag{10}$$

$$\text{At } y = 0,\ U = 0,\ V = 0,\ \frac{\partial T}{\partial y} = 0 \tag{11}$$

$$\text{At } y = 1,\ U = 0,\ V = 0,\ \frac{\partial T}{\partial y} = 0 \tag{12}$$

The controlling parameters in the model equations and their boundary conditions are:

If the channel is not filled with a porous medium:

The aspect ratio $= L / H = 20$;

The Reynolds number $\text{Re} = U_e^* . H / \nu = 100$;

The Prandtl number $\Pr = \dfrac{\nu}{\alpha} = 0.7$.

If the channel is filled with a porous medium, we add to the previous parameters:

The Darcy number $\text{Da} = \dfrac{k}{H^2}$ is equal to 10^{-9} or 10^{-2};

The porosity $\phi = 0.8$.

3. NUMERICAL METHOD

The model equations are solved by a finite volume method. The used discretization method is second order accurate in space and time. The time derivatives are discretized with the second order Euler backward approximation. The time discretization of all the convective terms and the Forchheimer terms follows the second order Adam-Bashforth scheme. However, the time discretization of the Darcy terms, the pressure terms and all the diffusive terms is totally implicit. For the spatial discretization, we used the second order accurate central difference scheme. The used mesh is uniform in both spatial directions with 202 points in the x direction and 82 points in the y direction. The sequential solution of the systems of discretization equation of the computed variables follows the Simpler Algorithm discussed by S. Patankar [7]. The systems of discretization equations are solved by the sweeping method [7]. Starting from the initial conditions, the time integration (time marching) with a time step equal to 10^{-4} is continued until the steady state solution is obtained. The steady solution is obtained when the computed variables become time invariant. Also at steady state, the mass and heat balances are satisfied.

4. RESULTS

4.1 The case when the channel is not filled with a porous medium (the reference state)

This is the case of the air convection cooling of the heated blocks. It is considered a reference state with which we will compare the cases of convection cooling of the blocks in a channel filled with porous matter. The obtained steady flow field is illustrated in Figure 2. Away from the entrance, the flow starts developing as a simple channel flow; however, its development is disturbed by the presence of the blocks. The flow becomes axially periodic in the region between the first and the last blocks, with a spatial period equal to twice the block's axial dimension. In the spaces between the blocks, which are open cavity-like, the velocity magnitude is small and the diffusive viscous effect is more important than the convective one, leading to the generation of clockwise rotating vortices. Above the blocks, the fluid streams axially. After the last block, the flow restarts developing again towards the exit. The pressure variation is mainly axial; there is a very small vertical pressure variation in the blocks region.

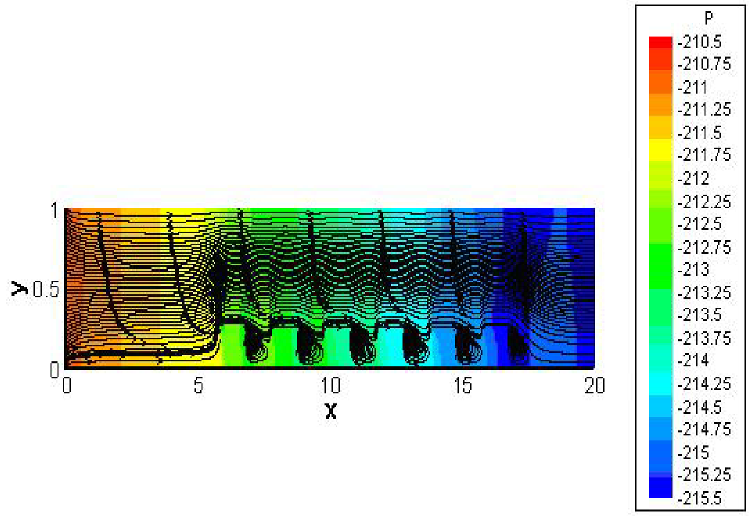

Fig. 2: Pressure field and streamlines of the air cooling when the channel is not filled with a porous medium. We notice the presence of clockwise rotating vortices between the blocks.
(In this figure and the figures 3-7, the height of the channel and the vertical size of the blocks have been magnified 5 times for a better graphical representation).

The thermal field is shown in Figure 3. The entrance cold flow is maintained until it approaches the first block. From there, it starts heating axially by the heated blocks. There is a continuous axial heating of the flow because more heat is added by each crossed block. From the first block to the channel exit, the temperature decreases vertically towards the channel upper wall. The temperature in the middle of the first block is 15.01 and that in the middle of the last block is 30.40. However, the temperature rise between two consecutive blocks gets smaller axially: the temperature difference between the middles of the second and the first blocks is about

4.99; and that between the middles of the sixth and the fifth blocks is about 1.953. In the spaces between blocks, the heat transfer within the vortices regions is mainly by diffusion which reduces the heat transfer (the cooling of the blocks). When the last block is passed, the heat is distributed mainly by the axial convection and the transverse diffusion, until the channel exit is reached.

4.2 The case when the channel is filled with a porous medium

The case of $\mathrm{Da} = 10^{-9}$

This is the case of a channel filled with a porous matter with a relatively low Darcy number. The flow field is presented in Figure 4. This flow field is remarkably different from that of the reference state. A major difference is the absence of rotating vortices in the spaces between the blocks. The flow just follows the contour of the blocks as it moves axially. This is due to the negligible effect of the viscous terms in the momenta equations. The major terms in these equations are the pressure term and the Darcy term. The balance of these terms determines the flow profile at each cross section of the channel. The flow is also spatially periodic between the first and the last blocks region. The axial velocity level is highest between each block's upper horizontal face and the channel upper wall and gets reduced between the channel walls, in the space between the blocks. This is due to the axial conservation of the flow rate: when the flow area gets smaller the velocity level gets higher. The axial pressure drop across the channel is much higher than that of the reference state and this is a disadvantage if consideration is given to the power required to flow the fluid across the channel.

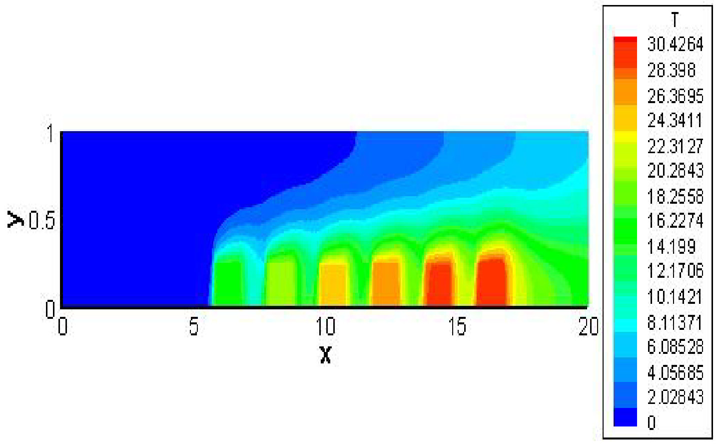

Fig. 3: The thermal field of the air cooling when the channel is not filled with a porous medium. We notice the axial blocks temperature increase downstream.

The temperature distribution in the channel is shown in Figure 5. The thermal field is quite different from that of the reference state. The enhanced axial and transverse heat transfer is apparent. The temperature level is much smaller than that of the reference state. The temperature in the middle of the first block is 4.02 and that in the middle of the last block is 13.45. Three major factors contribute to the better cooling of the blocks in the channel filled with the considered porous medium. The first one is the absence of the vortices in the spacing between the blocks; and therefore convection with an important velocity level is influential in these regions. The second factor is the fact that the viscous effects are negligible; the velocity close to the upper surfaces of the blocks is high and thus enhances the convective axial cooling of these surfaces. The last factor is that the thermal conductivity of the porous medium is 5.77 times that of air and this is leads to a better conduction heat transfer within the porous medium.

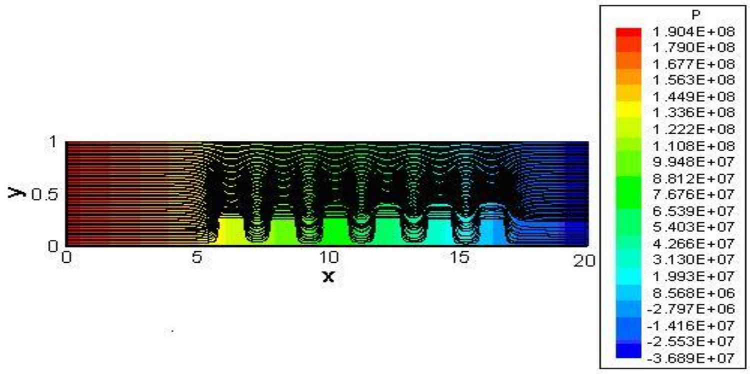

Fig. 4: The flow field of the air cooling in the channel filled with a porous medium with $\mathrm{Da} = 10^{-9}$. There are no vortices between the blocks.

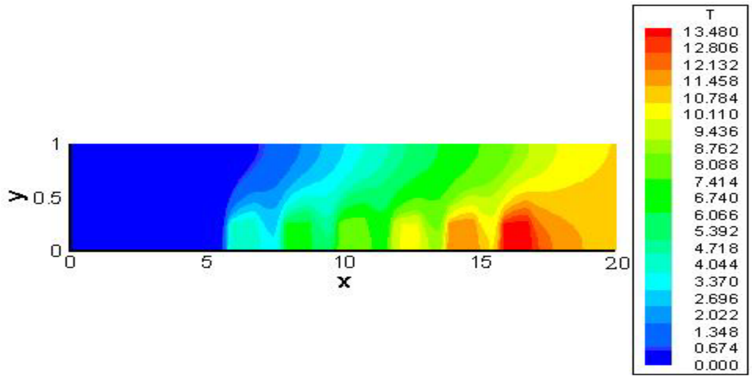

Fig. 5: The thermal field of the air cooling in the channel filled with a porous medium with $\mathrm{Da} = 10^{-9}$. We notice the reduction of the temperature level and the increase of the transversal thermal mixing compared to those of the reference state.

4.3 The case of $\mathrm{Da} = 10^{-2}$

When the number of Darcy is increased to $\mathrm{Da} = 10^{-2}$, we obtain a flow field (shown in Figure 6) that is overall quite similar to that of $\mathrm{Da} = 10^{-9}$. With the higher Darcy number, the axial velocity profile is determined from the balance of the pressure term, the Darcy term, the inertial nonlinear Forchheimer term and the viscous Brinkman term, in the momentum equation. All these terms are significant. The effect of the viscous Brinkman term is the velocity variation in the direction outward from the walls: the velocity is zero at the wall; however, its variation (increased magnitude) away from the wall is limited to a short distance. Along this short distance the Brinkman term is not negligible. The effect of the Forchheimer term is the flattening of the axial velocity profile away from the channel walls. Without this term the velocity would continue varying away from the walls without flattening. It is noticed that with the higher Darcy number, there are no vortices in the space between the blocks, like in the case with the smaller Darcy number. The reason of the absence of the vortices is that although the viscous Brinkmann term is not totally negligible; it is not strong enough to induce the vortices generation: the combined effect of the pressure, the Darcy and the Forchheimer terms inhibit the vortices formation leading to a flow pattern that contours the blocks just as in the case of the low Darcy number. It is found that the velocity level near the upper horizontal faces of the blocks is significantly high as in the case of the low Darcy number. The axial pressure drop with the higher Darcy number is much smaller than that with the smaller Darcy number; but is greater than that of the reference state.

The temperature distribution of the higher Darcy number case is illustrated in Figure 7. It is qualitatively and quantitatively very close to that of the lower Darcy case. The axial temperature profile at a channel vertical distance ($y = 0.10625$) passing through the blocks is graphed for the two Darcy numbers in Figure 8; and graphed with the profile of the reference state in Figure 9. From Figure 8, we conclude that the temperature profiles of the two Darcy numbers are very close. In Figure 9, it is clear that the temperature profiles of the two Darcy numbers are quantitatively much smaller than that of the reference state. The closeness of the temperature fields of the two Darcy numbers is explained next. First, the porous media of the two cases have the same porosity and thermal conductivity. Second, as the flow contour the blocks, the flows' velocity levels are similar closer to the blocks' vertical walls.

Third, close to the blocks' upper surfaces, the velocity level of the high Darcy number is a little smaller and this explains the fact that the temperature obtained with this case is a little higher than that obtained with the lower Darcy number. Thus, it is advantageous to use, if possible, a porous medium to enhance the cooling of the heated blocks. However, if consideration is given to the fan power required to flow the fluid, a porous media with a high Darcy number and a relatively high thermal conductivity is recommended.

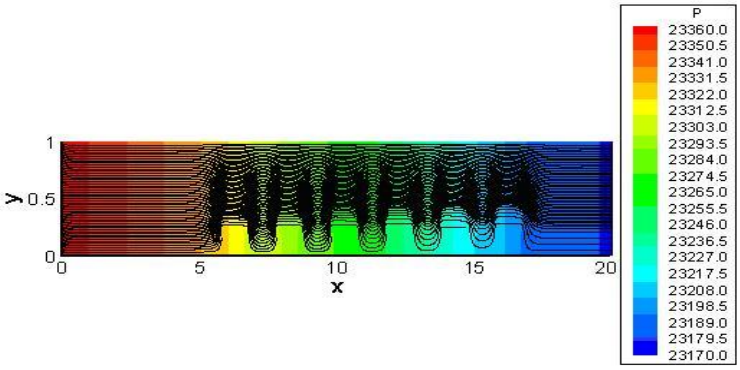

Fig. 6: The flow field of the air cooling in the channel filled with a porous medium with $Da = 10^{-2}$. The flow has some variation near the channel walls. The axial pressure drop is much smaller than that of the case with $Da = 10^{-9}$.

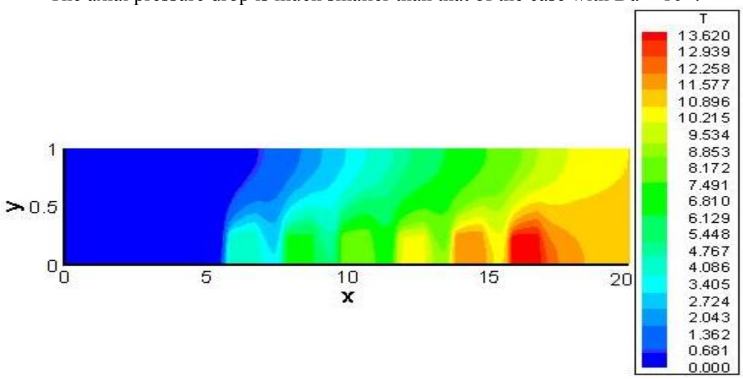

Fig. 7: The thermal field of the air cooling in the channel filled with a porous medium with $Da = 10^{-2}$. The thermal field is qualitatively and quantitatively similar to that obtained with $Da = 10^{-9}$.

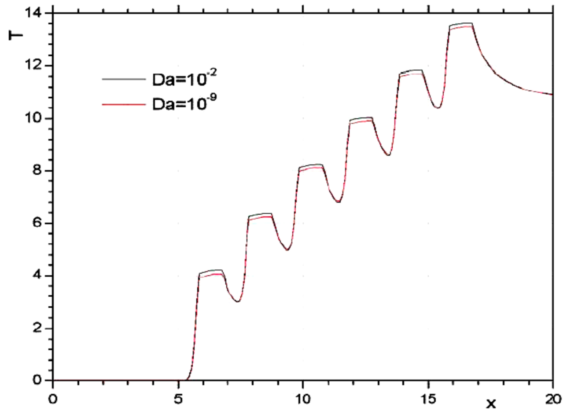

Fig. 8: The temperature axial profile at a height $y = 0.10625$. The qualitative and quantitative similarity of the profiles obtained with the two Darcy numbers is apparent.

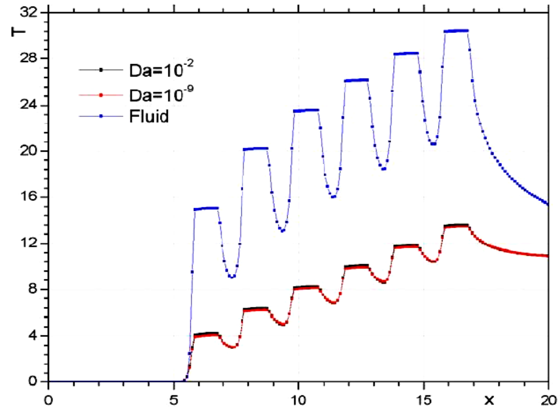

Fig 9: The temperature axial profile at a height $y = 0.10625$. The enhanced cooling achieved with the use of the porous media is remarkable.

5. CONCLUSION

This two dimensional numerical simulation of the convective cooling of six heated blocks mounted on the lower wall of a plane horizontal channel with adiabatic walls has led to the following conclusions that are limited to the used geometric, dynamic and thermal parameters. If the channel is filled with porous medium, the flow field just streams over the blocks and does not include vortices in the spaces between the blocks as is in the case of a channel not filled with a porous medium. The channel axial pressure drop is much higher with porous medium having a small Darcy number. If the porous medium porosity and thermal conductivity are fixed, the cooling of the blocks in a channel filled with this medium seems to be a little sensitive to a large variation of the Darcy number: from 10^{-9} to 10^{-2}. The cooling in the porous media is much better than the simple air cooling.

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