A MACROSCOPIC TURBULENCE MODEL FOR NON-EQUILIBRIUM CONVECTIVE HEAT TRANSFER IN POROUS MEDIA

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Abstract. The present paper presents an analysis of turbulent heat transfer in two-energy equation model for conduction and convection in porous media, which is needed when the local thermal equilibrium between the fluid and solid phases breaks down. Recently, Rocamora and de Lemos (2003) *have developed a macroscopic energy equation for homogeneous, rigid and saturated porous media, considering local thermal equilibrium. This work is intended to extend the transport model of Rocamora and de Lemos* (2003) *considering local thermal non-equilibrium. The similarity of periodically fully developed temperature profiles allows one to perform a numerical experiment using only a single structural unit for determining the fully developed heat transfer coefficient. The macroscopic time-average equations for mass, momentum and energy are obtained based on the Double Decomposition concept (spatial deviations and temporal fluctuations).The numerical technique employed for discretizing the governing equations is the control volume method with a boundary-fitted non-orthogonal coordinate system. The SIMPLE algorithm is used to handle the pressure-velocity coupling.*

Keywords: porous media, two-energy equation model, turbulent heat transfer coefficient.

1. Introduction

In many industrial applications, turbulent flow through a packed bed represents an important configuration for efficient heat and mass transfer. A common model for such systems is the so- called "*local thermal equilibrium*" where both solid and fluid phases are assumed to be represented by a unique temperature (de Lemos and Rocamora (2002)). However, in many instances it is important to take into account distinct temperatures for the porous material and for the working fluid. In transient heat conduction processes within porous media, for example, the assumption of local thermal equilibrium must be discarded, according Kaviany (1995) and Hsu (1999). When there is significant heat generations occurring in any one of the two phases (solid or fluid), the temperatures in the two phases are no longer identical, so the assumption of local thermal equilibrium must be discarded too. Kuznetsov (1998) presented same cases where the temperature difference between the fluid and solid phases is found to be small compared to the difference between the inlet temperature of the fluid phase and the initial temperature of the packed bed suggesting that equations governing thermal non-equilibrium forced flow through a packed bed contain a small parameter. The two- energy model is used for these cases where thermal equilibrium is assumed. Using the two energy equation model requires the knowledge of an extra parameter to be determined experimentally, namely the heat transfer coefficient between the fluid and solid phases.

Quintard, M., (1998) argues that assessing the validity of the assumption of local thermal equilibrium is not a simple task, since the temperature difference between the two phases cannot easily be estimated, and suggest that use of a two-energy equation model is a possible solution to the problem.

Kuwahara et. al (2001) propose a numerical procedure to determine the macroscopic transport coefficients from a theoretical basis without any empiricism. They used only a single structural unit to simulate a porous medium, and determine the interfacial heat transfer coefficient for the asymptotic case in which the conductivity of the solid phase is infinite. Nakayama et. al (2001) extend the closure model of Hsu (1999), so as to treat not only conduction but also convection in porous media. Having established the macroscopic energy equations for both phases, useful exact solutions were obtained for two fundamental heat transfer processes associated with porous media, namely, steady conduction in a porous slab with internal heat generation within the solid, and also, thermally developing flow through a semi-infinite porous medium.

Pedras and de Lemos (2000, 2001a-b-c, 2003) introduced a new concept called *Double Decomposition* and used it to develop a macroscopic model for turbulent momentum transport in porous media. This methodology, initially developed for the flow variables, has been extended by Rocamora and de Lemos (2000) and de Lemos and Rocamora (2002), to heat transfer in porous media where both time fluctuations and spatial deviations were considered for velocity and temperature. A general classification of all proposed models for turbulent flow and heat transfer in porous media has been recently published de Lemos and Pedras (2001). Based on this same concept, Rocamora and de Lemos (2003) have developed a macroscopic turbulent energy equation for a homogeneous, rigid and saturated porous medium, considering local thermal equilibrium between the fluid and the solid matrix.

This paper propose an analysis of macroscopic turbulent heat transfer using two-energy equation model for conduction and convection in porous media, extend the transport model of Rocamora and de Lemos (2003) considering the local thermal non-equilibrium based on the *Double Decomposition* concept.

2. Mathematical Model

2.1 Microscopic Transport Equations

The microscopic transport equations for the flow and energy for an incompressible fluid are given by:

Continuity,

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

Momentum,

$$\rho\left[\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u})\right] = -\nabla p + \mu \nabla^2 \mathbf{u} \tag{2}$$

The microscopic energy equations for the fluid and solid phases in a rigid homogeneous porous medium can be stated as:

Fluid,

$$(\rho c_p)_f \left\{\frac{\partial T_f}{\partial t} + \nabla \cdot (\mathbf{u} T_f)\right\} = \nabla \cdot (k_f \nabla T_f) + S_f \tag{3}$$

Solid - (Porous Matrix),

$$(\rho c_p)_s \frac{\partial T_s}{\partial t} = \nabla \cdot (k_s \nabla T_s) + S_s \tag{4}$$

where the subscripts f and s refer to fluid and solid phases, respectively. Here T is the temperature, p is the pressure, $\mathbf{u}$ is the fluid instantaneous velocity, k is the thermal conductivity, ρ is the density, c_p is the specific heat and S is the heat generation term. If there is no heat generation either in the solid or in the fluid, one has further:

$$S_f = S_s = 0 \tag{5}$$

2.2 Macroscopic Transport Equations

2.2.1 Time and Volume average operators and the Double Decomposition concept

The macroscopic transport equations for a porous medium for the turbulent flow regime are obtained through the application of the time and volume average operators, with the help of the Local Volume Average Theorems (LVAT) [Pedras and de Lemos (2000, 2001a)]. These operators, for a generic quantity φ, are defined as:

Time Average,

$$\overline{\varphi} = \frac{1}{\Delta t}\int_t^{t+\Delta t} \varphi \, dt \tag{6}$$

Intrinsic Volume Average,

$$\langle \varphi \rangle^i = \frac{1}{\Delta V_f}\int_{\Delta V_f} \varphi \, dV \tag{7}$$

Surface Volume Average (Fluid quantity),

$$\langle \varphi \rangle^v = \frac{1}{\Delta V}\int_{\Delta V_f} \varphi \, dV = \frac{\langle \varphi \rangle^i \Delta V_f}{\Delta V} = \phi \langle \varphi \rangle^i \tag{8}$$

where ΔV is a Representative Elementary Volume (REV) over which the volume averages are taken, ΔV_f is the fluid volume contained in the REV, ϕ is the porosity and Δt is the time interval over which the time average is taken.

Besides, the Double Decomposition concept, introduced by Pedras and de Lemos (2000, 2001a-b-c, 2003), is used here to obtain the macroscopic equations for turbulent flow in a rigid, homogeneous and saturated porous medium. This concept establishes that, for a generic quantity φ, one can write:

$$\varphi = \overline{\varphi} + \varphi' = \langle \overline{\varphi} \rangle^{i} + {}^{i}\overline{\varphi} + \langle \varphi' \rangle^{i} + {}^{i}\varphi' \tag{9}$$

or

$$\varphi = \langle \varphi \rangle^{i} + {}^{i}\varphi = \overline{\langle \varphi \rangle^{i}} + \langle \varphi \rangle^{i\prime} + \overline{{}^{i}\varphi} + {}^{i}\varphi' \tag{10}$$

Equations (9) and (10) envisage the two sequences of application of the average operators (time and volume), where ${}^{i}\varphi'$ represents the spatial deviation of the time fluctuation or the time fluctuation of the spatial deviation of the quantity φ.

2.2.2 Macroscopic Flow Equations

For the flow equations, de Lemos and Pedras (2001) [(7), (8)] have shown that the macroscopic equations can be expressed as:

Continuity,

$$\nabla \cdot \overline{\mathbf{u}}_D = 0, \tag{11}$$

Momentum,

$$\rho\left[\frac{\partial \overline{\mathbf{u}}_D}{\partial t} + \nabla \cdot \left(\frac{\overline{\mathbf{u}}_D \overline{\mathbf{u}}_D}{\phi}\right)\right] = -\nabla(\phi \langle \overline{p} \rangle^{i}) + \mu \nabla^2 \overline{\mathbf{u}}_D - \nabla \cdot (\rho\phi \langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^{i}) - \left[\frac{\mu\phi}{K}\overline{\mathbf{u}}_D + \frac{c_F \phi \rho |\overline{\mathbf{u}}_D| \, \overline{\mathbf{u}}_D}{\sqrt{K}}\right], \tag{12}$$

where the last two terms in equation (12), represent the so-called Darcy and Forchheimer (1901) contributions. The symbol K is the porous medium permeability, c_F is the form drag coefficient (Forchheimer coefficient), $\langle \overline{p} \rangle^{i}$ is the intrinsic average pressure of the fluid, ρ is the fluid density, μ represents the fluid viscosity and ϕ is the porosity of the porous medium. The macroscopic Reynolds stress $-\rho\phi \langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^{i}$ is given as,

$$-\rho\phi \langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^{i} = \mu_{t_\phi} 2 \langle \overline{\mathbf{D}} \rangle^{v} - \frac{2}{3}\phi\rho \langle k \rangle^{i} \mathbf{I}, \tag{13}$$

where

$$\langle \overline{\mathbf{D}} \rangle^{v} = \frac{1}{2}\left[\nabla(\phi \langle \overline{\mathbf{u}} \rangle^{i}) + [\nabla(\phi \langle \overline{\mathbf{u}} \rangle^{i})]^{T}\right], \tag{14}$$

is the macroscopic deformation tensor, $\langle k \rangle^{i} = \langle \overline{\mathbf{u}' \cdot \mathbf{u}'} \rangle^{i} / 2$ is the intrinsic turbulent kinetic energy, k and μ_{t_ϕ}, is the turbulent viscosity which is modeled in de Lemos and Pedras (2001) similarly to the case of clear flow, in the form,

$$\mu_{t_\phi} = \rho c_\mu f_\mu \frac{\langle k \rangle^{i2}}{\langle \varepsilon \rangle^{i}}, \tag{15}$$

Turbulent kinetic energy per unit mass,

$$\rho\left[\frac{\partial}{\partial t}\left(\phi \langle k \rangle^{i}\right) + \nabla \cdot \left(\overline{\mathbf{u}}_D \langle k \rangle^{i}\right)\right] = \nabla \cdot \left[\left(\mu + \frac{\mu_{t_\phi}}{\sigma_k}\right)\nabla\left(\phi \langle k \rangle^{i}\right)\right] - \rho \langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^{i} : \nabla \overline{\mathbf{u}}_D + c_k \rho \frac{\phi k_\phi |\overline{\mathbf{u}}_D|}{\sqrt{K}} - \rho\phi \langle \varepsilon \rangle^{i} \tag{16}$$

Turbulent energy dissipation rate,

$$\rho\left[\frac{\partial}{\partial t}\left(\phi\langle\varepsilon\rangle^{i}\right)+\nabla\cdot\left(\overline{\mathbf{u}}_{D}\langle\varepsilon\rangle^{i}\right)\right]=$$
$$\nabla\cdot\left[\left(\mu+\frac{\mu_{t_\phi}}{\sigma_\varepsilon}\right)\nabla\left(\phi\langle\varepsilon\rangle^{i}\right)\right]+c_1\left(-\rho\langle\overline{\mathbf{u}'\mathbf{u}'}\rangle^{i}:\nabla\overline{\mathbf{u}}_{D}\right)\frac{\langle\varepsilon\rangle^{i}}{\langle k\rangle^{i}}+c_2 f_2 c_k\rho\frac{\phi\,\varepsilon_\phi|\overline{\mathbf{u}}_{D}|}{\sqrt{K}}-c_2 f_2\rho\phi\frac{\langle\varepsilon\rangle^{i\,2}}{\langle k\rangle^{i}} \tag{17}$$

2.3 Macroscopic Energy Equation

In this section, the macroscopic energy equation is obtained for a porous medium starting from the microscopic energy equations for the fluid and solid phases. Then, time averaging is applied followed by volume averaging (or vice versa).

Applying the time average and then the volume average, or vice-versa, to equations (3) and (4) in a Representative Elementary Volume (REV), one obtains:

$$\left(\rho c_p\right)_f\left[\frac{\partial\phi\langle\overline{T_f}\rangle^{i}}{\partial t}+\nabla\cdot\left\{\phi\left(\langle\overline{\mathbf{u}}\rangle^{i}\langle\overline{T_f}\rangle^{i}+\langle{}^{i}\overline{\mathbf{u}}^{\,i}\,\overline{T_f}\rangle^{i}+\langle\overline{\mathbf{u}'T_f'}\rangle^{i}\right)\right\}\right]=\nabla\cdot\left[k_f\nabla\left(\phi\langle\overline{T_f}\rangle^{i}\right)\right]+$$
$$\nabla\cdot\left[\frac{1}{\Delta V}\int_{A_i}\mathbf{n}\,k_f\,\overline{T_f}\,dS\right]+\frac{1}{\Delta V}\int_{A_i}\mathbf{n}\cdot k_f\nabla\overline{T_f}\,dS \tag{18}$$

$$\left(\rho c_p\right)_s\left\{\frac{\partial(1-\phi)\langle\overline{T_s}\rangle^{i}}{\partial t}\right\}=\nabla\cdot\left\{k_s\nabla\left[(1-\phi)\langle\overline{T_s}\rangle^{i}\right]\right\}-\nabla\cdot\left[\frac{1}{\Delta V}\int_{A_i}\mathbf{n}\,k_s\,\overline{T_s}\,dS\right]-\frac{1}{\Delta V}\int_{A_i}\mathbf{n}\cdot k_s\nabla\overline{T_s}\,dS \tag{19}$$

where A_i is the interface area between the fluid and solid phases within the REV, ΔV is the REV volume, and n is the unit vector normal to the fluid-solid interface.

Equations (18) and (19) are the macroscopic energy equations for the fluid and the porous matrix (solid) taking first the time average followed by the volume average operator.

Further, using the double decomposition concept, Rocamora and de Lemos (2000) have shown that the fourth term on the left hand side of equation. (18) can be expressed as:

$$\langle\overline{\mathbf{u}'T_f'}\rangle^{i}=\langle\overline{(\langle\mathbf{u}'\rangle^{i}+{}^{i}\mathbf{u}')(\langle T_f'\rangle^{i}+{}^{i}T')}\rangle^{i}=\overline{\langle\mathbf{u}'\rangle^{i}\langle T_f'\rangle^{i}}+\langle\overline{{}^{i}\mathbf{u}'\,{}^{i}T_f'}\rangle^{i} \tag{20}$$

So, in view of equation (20), equation (18) can be rewritten as:

$$\left(\rho c_p\right)_f\left[\frac{\partial\phi\langle\overline{T_f}\rangle^{i}}{\partial t}+\nabla\cdot\left\{\phi\left(\langle\overline{\mathbf{u}}\rangle^{i}\langle\overline{T_f}\rangle^{i}+\underbrace{\langle{}^{i}\overline{\mathbf{u}}^{\,i}\,\overline{T_f}\rangle^{i}}_{I}+\underbrace{\overline{\langle\mathbf{u}'\rangle^{i}\langle T_f'\rangle^{i}}}_{II}+\underbrace{\langle\overline{{}^{i}\mathbf{u}'\,{}^{i}T_f'}\rangle^{i}}_{III}\right)\right\}\right]=\nabla\cdot\left[k_f\nabla\left(\phi\langle\overline{T_f}\rangle^{i}\right)\right]+$$
$$\underbrace{\nabla\cdot\left[\frac{1}{\Delta V}\int_{A_i}\mathbf{n}\,k_f\,\overline{T_f}\,dS\right]}_{IV}+\frac{1}{\Delta V}\int_{A_i}\mathbf{n}\cdot k_f\nabla\overline{T_f}\,dS \tag{21}$$

where to the underscored terms in equation (21) the following physical significance can be attributed:

I Thermal dispersion associated with deviations of microscopic time average velocity and temperature. Note that this term is also present when analyzing laminar convective heat transfer in porous media.

II Turbulent heat flux due to the fluctuating components of macroscopic velocity and temperature $\left(\overline{\langle\mathbf{u}'\rangle^{i}\langle T_f'\rangle^{i}}=\overline{\langle\mathbf{u}\rangle^{i}{}'\,\langle T_f\rangle^{i}{}'}\right)$.

III Turbulent thermal dispersion in a porous medium due to both time fluctuations and spatial deviations of both microscopic velocity and temperature.

IV Tortuosity based on microscopic time average temperature.

Two-energy equation model for conduction and convection in porous media considering a heat transfer coefficient between the fluid and solid phases are given by, respectively,

$$\left(\rho c_p\right)_f\left[\frac{\partial \phi\langle\overline{T_f}\rangle^i}{\partial t}+\nabla\cdot\left\{\phi\left(\langle\overline{\mathbf{u}}\rangle^i\langle\overline{T_f}\rangle^i+\langle{}^i\overline{\mathbf{u}}^{\,i}\overline{T_f}\rangle^i+\langle\overline{\mathbf{u}'T_f'}\rangle^i\right)\right\}\right]=$$
$$\nabla\cdot\left[k_f\nabla\left(\phi\langle\overline{T_f}\rangle^i\right)\right]+\nabla\cdot\left[\frac{1}{\Delta V}\int_{A_i}\mathbf{n}\,k_f\overline{T_f}\,dS\right]+ha_i\left(\langle\overline{T_s}\rangle^i-\langle\overline{T_f}\rangle^i\right) \quad (22)$$

$$\left(\rho c_p\right)_s\left\{\frac{\partial(1-\phi)\langle\overline{T_s}\rangle^i}{\partial t}\right\}=\nabla\cdot\left\{k_s\nabla\left[(1-\phi)\langle\overline{T_s}\rangle^i\right]\right\}$$
$$-\nabla\cdot\left[\frac{1}{\Delta V}\int_{A_i}\mathbf{n}\,k_s\overline{T_s}\,dS\right]-ha_i\left(\langle\overline{T_s}\rangle^i-\langle\overline{T_f}\rangle^i\right) \quad (23)$$

where, $\langle\overline{T_s}\rangle^i$ and $\langle\overline{T_f}\rangle^i$ denote the intrinsically averaged temperature of solid phase and fluid phase, h and a_i are the interfacial convective heat transfer coefficient and specific surface area, respectively. Where, h is given by,

$$ha_i\equiv\frac{\frac{1}{\Delta V}\int_{A_i}\mathbf{n}\cdot k_f\nabla\overline{T_f}\,dS}{\left(\langle\overline{T_s}\rangle^i-\langle\overline{T_f}\rangle^i\right)}\equiv\frac{\frac{1}{\Delta V}\int_{A_i}\mathbf{n}\cdot k_s\nabla\overline{T_s}\,dS}{\left(\langle\overline{T_s}\rangle^i-\langle\overline{T_f}\rangle^i\right)} \quad (24)$$

The proposed model by Kuwahara et. al (2001) describing the microscopic structure of a porous medium will be used to obtain the interfacial heat transfer coefficient for the macroscopic transport model and a porous medium for the turbulent flow regime.

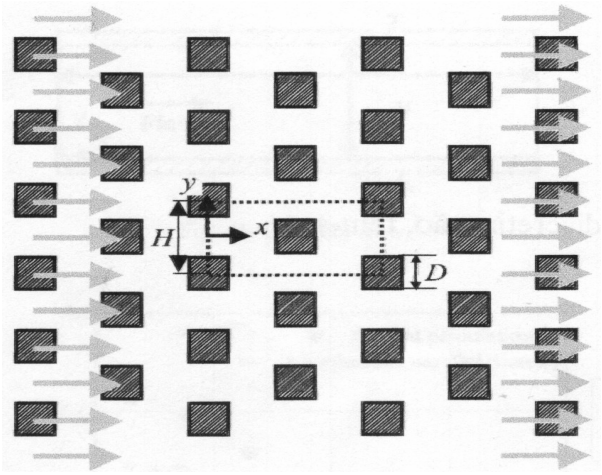


Figure 1. Physical model and its coordinate system.

3. Preliminary Laminar Results

In order to evaluate the numerical tool to be used in the determination of the film coefficient given by (24), a tes case was run for obtaining the flow field in a periodic cell, which is here assumed to represent the porous medium. Accordingly, consider now a macroscopically uniform flow through an infinite number of square rods placed in a staggered fashion, as shown in Figure 1. All square rods, which may be regarded as heat sinks (or sources), are isothermal and maintained at a constant temperature T_w, which is lower (higher) than the bulk mean temperature of the flowing fluid.

The representative elementary volume ΔV, which should be smaller than a macroscopic characteristic length, can be taken as 2H x H for this periodic structure. Due to the periodicity of the model, only one structural unit as indicated by dashed lines in the Figure 1 may be taken as a calculation domain.

The numerical method utilized to solve the microscopic flow and energy equations in the unit cell is the Finite Volume with Generalized Coordinates. The SIMPLE method of Patankar (1980) is used for the velocity-pressure coupling. Convergence is measured in terms of the normalized for each variable during iteration. The maximum residue allowed for the convergence check is set to 10^{-7}, as the variables are normalized by appropriate references.

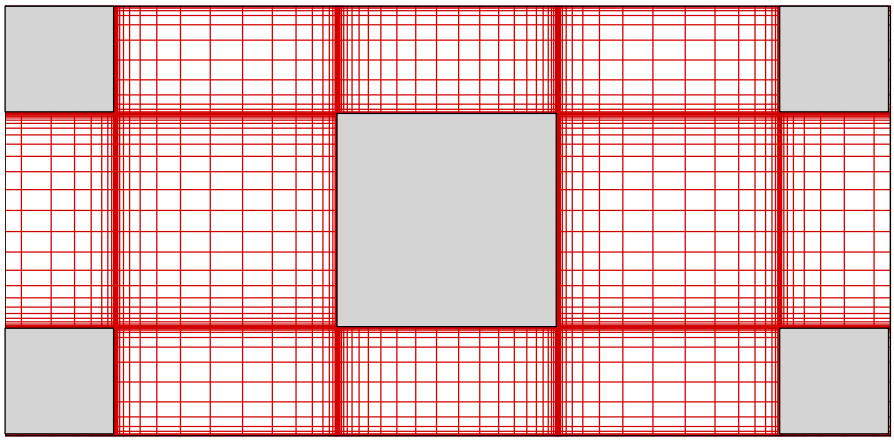


Figure 2. Non uniform computational grid used for running preliminary laminar calculations.

All computations have been carried out for a one structural unit $2H \times H$ using a non-uniform grid arrangement of size 90×60 nodes, as shown in Figure 2, to ensure that the results were independent of the grid system. The Reynolds number was varied from 10^0 to 10^2 and the porosity ϕ was equal to 0.75.

At the periodically fully developed stage, the velocity must be identical to that at the inlet, whereas the temperature profile at the exit must be similar to that at the inlet. The situation is analogous to the case of forced convection in a channel with isothermal walls. Thus, the boundary, compatibility and periodic constraints are given by:

On the solid walls,

$$\mathbf{u} = 0\,, \quad T = T_w \tag{25}$$

On the periodic boundaries:

$$\begin{aligned} \overline{\mathbf{u}}\big|_{x=0} &= \overline{\mathbf{u}}\big|_{x=2H} \\ \overline{\mathbf{u}}\big|_{y=0} &= \overline{\mathbf{u}}\big|_{y=H} \end{aligned} \tag{26}$$

$$\begin{aligned} \int_0^H \overline{u}\, dy\Big|_{x=0} &= \int_0^H \overline{u}\, dy\Big|_{x=2H} = H\left|\langle \overline{\mathbf{u}} \rangle\right| \\ \int_0^H \overline{v}\, dx\Big|_{y=0} &= \int_0^H \overline{v}\, dx\Big|_{y=H} = H\left|\langle \overline{\mathbf{u}} \rangle\right| \end{aligned} \tag{27}$$

$$(T - T_w)\big|_{x=2H} = \tau (T - T_w)\big|_{x=0} \tag{28}$$

where

$$\tau \equiv \frac{\int_{-H/2}^{H/2} \overline{u}(T - T_w)dy\big|_{x=2H}}{\int_{-H/2}^{H/2} \overline{u}(T - T_w)dy\big|_{x=0}} = \frac{(T_B - T_w)\big|_{x=2H}}{(T_B - T_w)\big|_{x=0}} \tag{29}$$

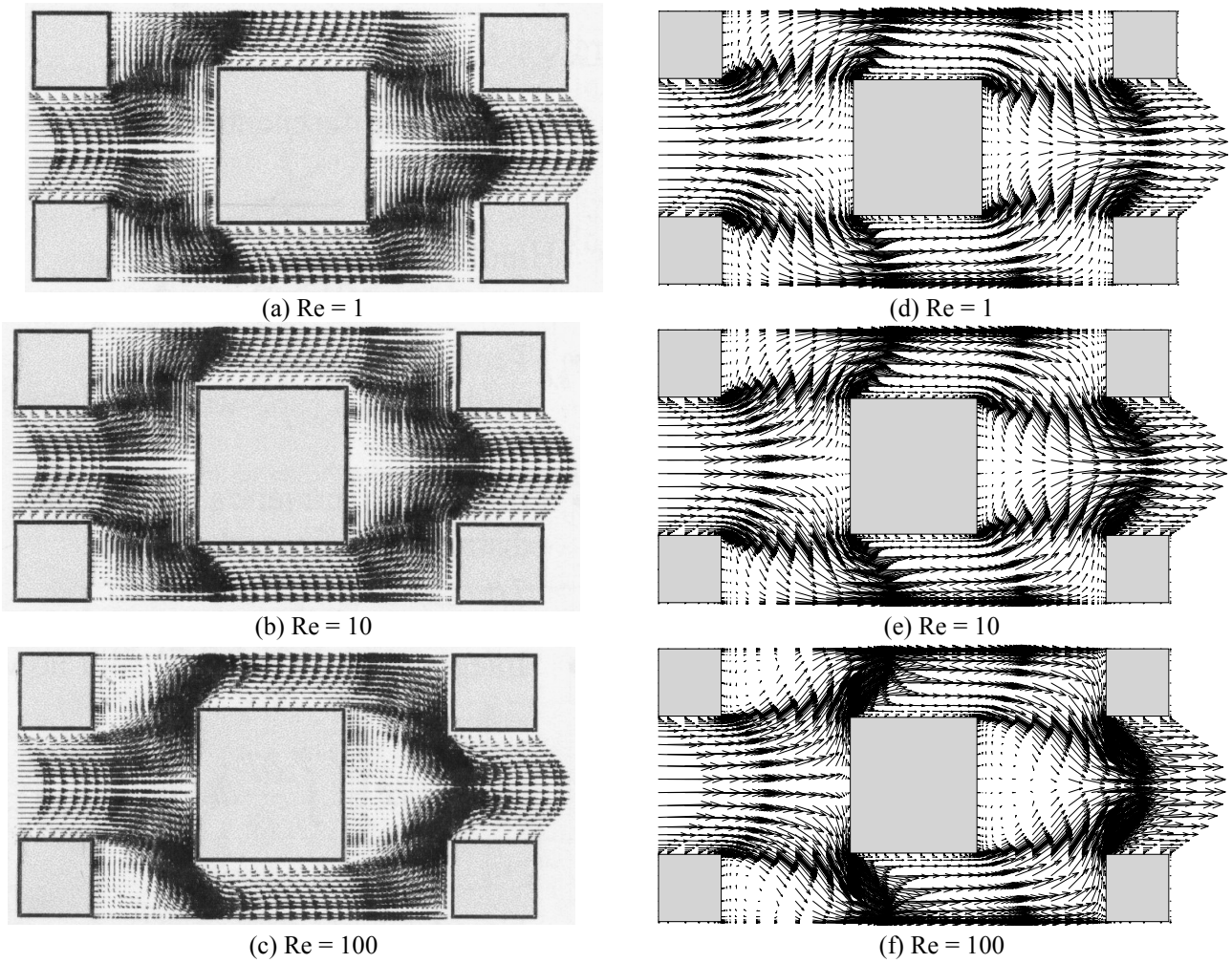
$T_B(x)$ is the bulk mean temperature of the fluid. Computations can be made using the equations based on the Darcy velocity, the length of structural unit H and the temperature difference $(T_B(0) - T_w)$ as references scales. For carrying out computations for a parametric study, it may be convenient to use the Reynolds number based on H as $\mathrm{Re} = \langle \overline{\mathbf{u}} \rangle H / \nu$ and $\phi = 1 - (D/H)^2$.

4. Preliminary Numerical Results and Discussion

The preliminary results were the velocity and temperature fields obtained for three different Reynolds numbers, as shown in Figure 3. When the Reynolds number is low (Re = 1), the velocity field around a rod appears very much similar to what we observe in a channel, namely the parabolic profile. As increasing Re, recirculation bubbles expand

further behind the rod. When the Reynolds number is sufficiently high, the thermal boundary layers cover around the rods as shown in Figure 4, such that convective heat transfer overwhelms thermal diffusion.

Kuwahara *et. al* (2001) modeled a porous medium in terms of obstacles arranged in a regular pattern, and solver the set of the microscopic governing equations, exploiting periodic boundary conditions. The results of Kuwahara *et. al* (2001) shown in Figure 3 and Figure 4 were processed using ϕ=0.7 while the present results were processed using ϕ=0.7.



(a) Re = 1 (d) Re = 1

(b) Re = 10 (e) Re = 10

(c) Re = 100 (f) Re = 100

Figure 3. Velocity vectors for *Pr* = 1:a), b), c) Kuwahara *et. al* (2001) results; d), e), f) Presents results.

5. Concluding remarks

A macroscopic models was presented, which take into consideration the exchange of heat between the porous substrate and the working fluid. As a preliminary result, a macroscopically uniform laminar flow through a periodic model of isothermal square rods was computed, considering periodically fully developed velocity and temperature fields. Upon noting the repetitiveness of flow and temperature profiles, only a single structural unit has been taken for a calculation domain. Qualitative agreement was obtained when comparing the preliminary results herein with simulation by Kuwahara *et. al* (2001). Further work will be carried out in order to simulate fully turbulent flow and heat transfer in porous media by means of the proposed two-energy equation. Ultimately, it is expected that a correlation for the heat transfer coefficient be obtained so that the exchange energy between the solid and the fluid can be accounted for.

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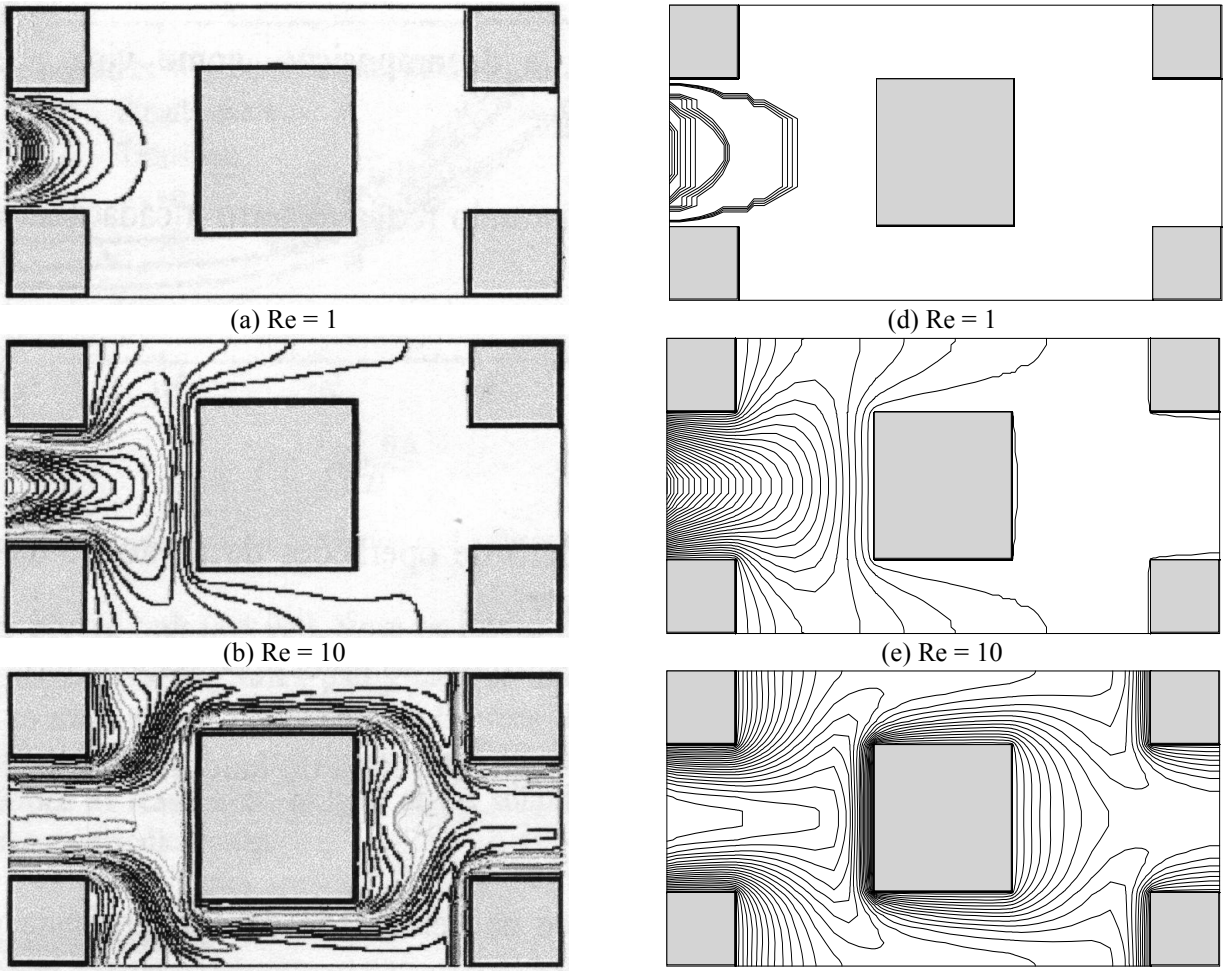

(a) Re = 1 (d) Re = 1

(b) Re = 10 (e) Re = 10

(c) Re = 100 (f) Re = 100

Figure 4. Isotherms for Pr = 1:a), b), c) Kuwahara *et. al* (2001) results; d), e), f) Presents results.