INTERFACIAL HEAT TRANSFER COEFFICIENT IN TWO-ENERGY EQUATION MODEL FOR CONVECTION IN POROUS MEDIA

Marcelo B. Saito[1]
Marcelo J.S. De-Lemos[2]*****
Departamento de Energia - IEME
Instituto Tecnológico de Aeronáutica - ITA
12228-900 - São José dos Campos - SP – Brasil
E-mail: [1]mbsaito@mec.ita.br, [2]delemos@mec.ita.br
* Corresponding author

Abstract. *This paper presents a study on the interfacial convective heat transfer coefficient in two-energy equation model for convection in porous media. Such information is needed for turbulent heat transport modeling in porous media when local thermal non-equilibrium is considered. Recently, the literature documents proposals for macroscopic energy equation modeling for homogeneous, rigid and saturated porous media, considering the local thermal equilibrium hypothesis and laminar flow. This work intends to obtain functional relationships for the interfacial convective heat transfer coefficient closely packed beds. A periodical fully developed all is used to represent the entire domain. The macroscopic time-averaged 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, Heat Transfer Coefficient, Thermal Non-Equilibrium*

1. INTRODUCTION

In many industrial applications, turbulent flow through a packed bed represents an important configuration for efficient heat and mass transfer. Common models for such systems is the so-called "local thermal equilibrium hypothesis" where both solid and fluid phase temperatures are assumed to be represented by a unique value. 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 to references Kaviany (1995) and Hsu (1999). Also, when there is significant heat generation in any one of the two phases, namely solid or fluid, average temperatures are no longer identical, so that the assumption of local thermal equilibrium must be reevaluated. According by Kuznetsov (1998) presented some cases where the temperature difference between the fluid and solid phases was found being small compared to the difference between the inlet fluid temperature and the initial temperature of the bed. This suggested that equations governing thermal non-equilibrium forced flow through a packed bed contain a small parameter. The two- energy model was used for these cases where thermal equilibrium was 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 that since the temperature difference between the two phases cannot easily be estimated, he suggests that use of a two-energy equation model is a possible solution to the problem.

Kuwahara et. al (2001) proposes 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.

A new concept called double decomposition used to develop a macroscopic model for turbulent momentum transport in porous media was introduced by references, Pedras and de Lemos (2000), Pedras and de Lemos (2001a), Pedras and de Lemos (2001b), Pedras and de Lemos (2001c), Pedras and de Lemos (2003). This methodology, initially developed for the flow variables, has been extended by reference de Lemos and Rocamora (2002), to heat transfer in porous media. A general classification of all proposed models for turbulent flow and heat transfer in porous media has been recently published in de Lemos and Pedras (2001). Based on this same concept, Rocamora and de Lemos (2000) 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 work proposes to obtain a numerical correlation of interfacial convective heat transfer coefficient in two-energy equation model for convection in porous media, which is needed treat turbulent heat transport modeling of incompressible flows in porous media considering local thermal non-equilibrium.

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,

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

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

Fluid,

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

Solid - (Porous Matrix),

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

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, r 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 j, are defined as:

Time Average,

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

Intrinsic Volume Average,

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

Surface Volume Average (Fluid quantity),

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

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, f 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 j, one can write:

$$j = \overline{j} + j' = \langle \overline{j} \rangle^i + {}^i\overline{j} + \langle j' \rangle^i + {}^i j', \text{ or } j = \langle j \rangle^i + {}^i j = \overline{\langle j \rangle^i} + \langle j \rangle^{i\prime} + \overline{{}^i j} + {}^i j' \tag{9}$$

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

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,

$$\nabla \cdot \overline{\mathbf{u}}_D = 0, \tag{10}$$

Momentum,

$$r\left[\frac{\partial \overline{\mathbf{u}}_D}{\partial t} + \nabla \cdot \left(\frac{\overline{\mathbf{u}}_D \overline{\mathbf{u}}_D}{f}\right)\right] = -\nabla\left(f\langle \overline{p} \rangle^i\right) + m\nabla^2 \overline{\mathbf{u}}_D - \nabla \cdot \left(r f \langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^i\right) - \left[\frac{mf}{K}\overline{\mathbf{u}}_D + \frac{c_F f r |\overline{\mathbf{u}}_D| \overline{\mathbf{u}}_D}{\sqrt{K}}\right], \tag{11}$$

where the last two terms in equation (11), 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), $\langle \bar{p} \rangle^i$ is the intrinsic average pressure of the fluid, r is the fluid density, m represents the fluid viscosity and f is the porosity of the porous medium. The macroscopic Reynolds stress $-rf\langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^i$ is given as,

$$-rf\langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^i = m_{t_f} 2\langle \overline{\mathbf{D}} \rangle^v - \frac{2}{3} fr\langle k \rangle^i \mathbf{I}, \text{ where } \langle \overline{\mathbf{D}} \rangle^v = \frac{1}{2}\left[\nabla(f\langle \overline{\mathbf{u}} \rangle^i) + [\nabla(f\langle \overline{\mathbf{u}} \rangle^i)]^T\right], \tag{12}$$

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 m_{t_f}, is the turbulent viscosity which is modeled in de Lemos and Pedras (2001) similarly to the case of clear flow, in the form,

$$m_{t_f} = r c_m f_m \frac{\langle k \rangle^{i^2}}{\langle e \rangle^i}, \tag{13}$$

Turbulent kinetic energy per unit mass,

$$\begin{aligned} &r\left[\frac{\partial}{\partial t}\left(f\langle k \rangle^i\right) + \nabla \cdot \left(\overline{\mathbf{u}}_D \langle k \rangle^i\right)\right] = \\ &\nabla \cdot \left[\left(m + \frac{m_{t_f}}{s_k}\right)\nabla\left(f\langle k \rangle^i\right)\right] - r\langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^i : \nabla \overline{\mathbf{u}}_D + c_k r \frac{f\langle k \rangle_f^i |\overline{\mathbf{u}}_D|}{\sqrt{K}} - rf\langle e \rangle^i \end{aligned} \tag{14}$$

Turbulent energy dissipation rate,

$$\begin{aligned} &r\left[\frac{\partial}{\partial t}\left(f\langle e \rangle^i\right) + \nabla \cdot \left(\overline{\mathbf{u}}_D \langle e \rangle^i\right)\right] = \\ &\nabla \cdot \left[\left(m + \frac{m_{t_f}}{s_e}\right)\nabla\left(f\langle e \rangle^i\right)\right] + c_1\left(-r\langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^i : \nabla \overline{\mathbf{u}}_D\right)\frac{\langle e \rangle^i}{\langle k \rangle^i} + c_2 f_2 c_k r \frac{f\langle e \rangle_f^i |\overline{\mathbf{u}}_D|}{\sqrt{K}} - c_2 f_2 r f \frac{\langle e \rangle^{i^2}}{\langle k \rangle^i} \end{aligned} \tag{15}$$

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:

$$\begin{aligned} &\left(r c_p\right)_f \left[\frac{\partial f\langle \overline{T_f} \rangle^i}{\partial t} + \nabla \cdot \left\{f\left(\langle \overline{\mathbf{u}} \rangle^i \langle \overline{T_f} \rangle^i + \langle {}^i\overline{\mathbf{u}}^i \overline{T_f} \rangle^i + \langle \overline{\mathbf{u}' T_f'} \rangle^i\right)\right\}\right] = \\ &\nabla \cdot \left[k_f \nabla\left(f\langle \overline{T_f} \rangle^i\right)\right] + \nabla \cdot \left[\frac{1}{\Delta V}\int_{A_i} \mathbf{n} k_f \overline{T_f}\, dS\right] + \frac{1}{\Delta V}\int_{A_i} \mathbf{n} \cdot k_f \nabla \overline{T_f}\, dS \end{aligned} \tag{16}$$

$$\begin{aligned} &\left(r c_p\right)_s \left\{\frac{\partial (1-f)\langle \overline{T_s} \rangle^i}{\partial t}\right\} = \\ &\nabla \cdot \left\{k_s \nabla\left[(1-f)\langle \overline{T_s} \rangle^i\right]\right\} - \nabla \cdot \left[\frac{1}{\Delta V}\int_{A_i} \mathbf{n} k_s \overline{T_s}\, dS\right] - \frac{1}{\Delta V}\int_{A_i} \mathbf{n} \cdot k_s \nabla \overline{T_s}\, dS \end{aligned} \tag{17}$$

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 (16) and (17) 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. (16) can be expressed as:

$$\langle \overline{\mathbf{u}' T_f'} \rangle^i = \langle \overline{(\langle \mathbf{u}' \rangle^i + {}^i\mathbf{u}')(\langle T_f' \rangle^i + {}^i T')} \rangle^i = \overline{\langle \mathbf{u}' \rangle^i \langle T_f' \rangle^i} + \langle \overline{{}^i\mathbf{u}' \, {}^i T_f'} \rangle^i \tag{18}$$

So, in view of equation (18), equation (16) can be rewritten as:

$$\begin{aligned} &(r\,c_p)_f \left[\frac{\partial f \langle \overline{T_f} \rangle^i}{\partial t} + \nabla \cdot \left\{ f \left(\langle \overline{\mathbf{u}} \rangle^i \langle \overline{T_f} \rangle^i + \underbrace{\langle {}^i\overline{\mathbf{u}} \, {}^i\overline{T_f} \rangle^i}_{I} + \underbrace{\overline{\langle \mathbf{u}' \rangle^i \langle T_f' \rangle^i}}_{II} + \underbrace{\langle \overline{{}^i\mathbf{u}' \, {}^i T_f'} \rangle^i}_{III} \right) \right\} \right] = \\ &\nabla \cdot \left[k_f \nabla \left(f \langle \overline{T_f} \rangle^i \right) \right] + \underbrace{\nabla \cdot \left[\frac{1}{\Delta V} \int_{A_i} \mathbf{n} \, k_f \, \overline{T_f} \, dS \right]}_{IV} + \frac{1}{\Delta V} \int_{A_i} \mathbf{n} \cdot k_f \nabla \overline{T_f} \, dS \end{aligned} , \tag{19}$$

where to the underscored terms in equation (19) 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 $\left(\overline{\langle \mathbf{u}' \rangle^i \langle T_f' \rangle^i} = \overline{\langle \mathbf{u} \rangle^{i\,\prime} \langle T_f \rangle^{i\,\prime}} \right)$.

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,

$$\begin{aligned} &(r\,c_p)_f \left[\frac{\partial f \langle \overline{T_f} \rangle^i}{\partial t} + \nabla \cdot \left\{ f \left(\langle \overline{\mathbf{u}} \rangle^i \langle \overline{T_f} \rangle^i + \langle {}^i\overline{\mathbf{u}} \, {}^i\overline{T_f} \rangle^i + \langle \overline{\mathbf{u}' T_f'} \rangle^i \right) \right\} \right] = \\ &\nabla \cdot \left[k_f \nabla \left(f \langle \overline{T_f} \rangle^i \right) \right] + \nabla \cdot \left[\frac{1}{\Delta V} \int_{A_i} \mathbf{n} \, k_f \, \overline{T_f} \, dS \right] + h_{sf} \, a_i \left(\langle \overline{T_s} \rangle^i - \langle \overline{T_f} \rangle^i \right) \end{aligned} , \tag{20}$$

$$\begin{aligned} &(r\,c_p)_s \left\{ \frac{\partial (1-f) \langle \overline{T_s} \rangle^i}{\partial t} \right\} = \\ &\nabla \cdot \left\{ k_s \nabla \left[(1-f) \langle \overline{T_s} \rangle^i \right] \right\} - \nabla \cdot \left[\frac{1}{\Delta V} \int_{A_i} \mathbf{n} \, k_s \, \overline{T_s} \, dS \right] - h_{sf} \, a_i \left(\langle \overline{T_s} \rangle^i - \langle \overline{T_f} \rangle^i \right) \end{aligned} , \tag{21}$$

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_{sf} and a_i are the interfacial convective heat transfer coefficient and specific surface area, respectively. Where, h_{sf} is given by,

$$h_{sf} a_i \equiv \frac{\frac{1}{\Delta V}\int_{A_i} \mathbf{n} \cdot k_f \nabla \overline{T_f}\, dS}{\left(\langle \overline{T_s} \rangle^i - \langle \overline{T_f} \rangle^i\right)} \equiv \frac{\frac{1}{\Delta V}\int_{A_i} \mathbf{n} \cdot k_s \nabla \overline{T_s}\, dS}{\left(\langle \overline{T_s} \rangle^i - \langle \overline{T_f} \rangle^i\right)} \,. \tag{22}$$

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.

3. PERIODIC CELL AND BOUNDARY CONDITIONS

In order to evaluate the numerical tool to be used in the determination of the film coefficient given by (22), a test 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.

All computations have been carried out for a one structural unit 2H x H using a non-uniform grid arrangement of size 90×70 nodes, as shown in Figure 2, to ensure that the results were independent of the grid system. The Reynolds number was varied from $4x10^0$ to $4x10^2$ and the porosity f was equal to 0.65.

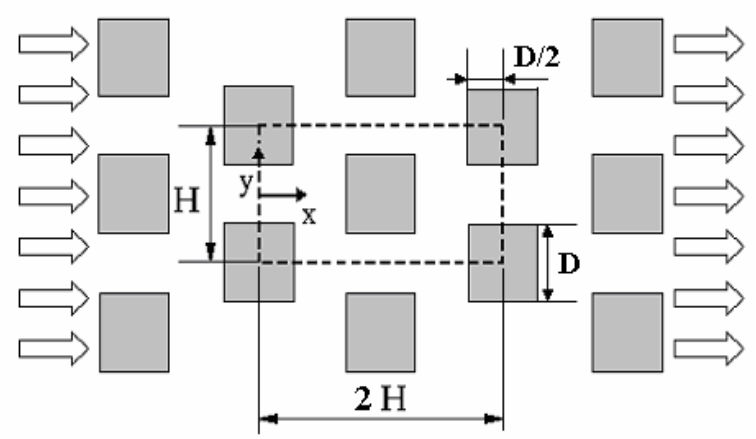


Figure 1. Physical model and its coordinate system.

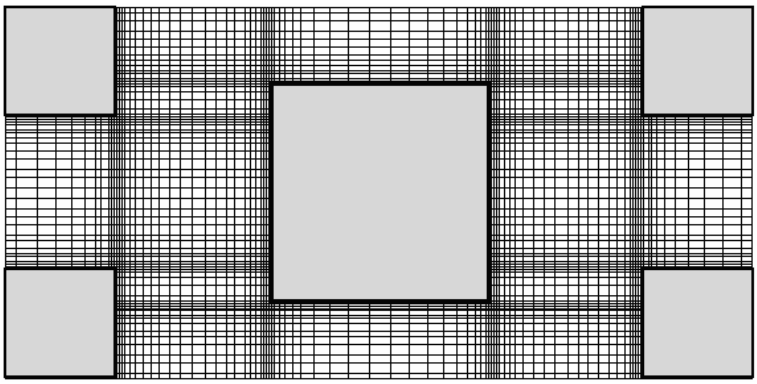


Figure 2. Non uniform computational grid used for running laminar calculations.

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,

$$\mathbf{u} = 0, \quad T = T_w \tag{23}$$

On the periodic boundaries:

$$\left.\begin{aligned} \overline{\mathbf{u}}\big|_{x=0} &= \overline{\mathbf{u}}\big|_{x=2H} \\ \overline{\mathbf{u}}\big|_{y=0} &= \overline{\mathbf{u}}\big|_{y=H} \end{aligned}\right\}, \tag{24}$$

$$\int_0^H \overline{u}\, dy\Big|_{x=0} = \int_0^H \overline{u}\, dy\Big|_{x=2H} = H\left|\langle \overline{\mathbf{u}} \rangle\right| \tag{25}$$

$$(T - T_w)\big|_{x=2H} = q\,(T - T_w)\big|_{x=0}, \text{ where } \quad q \equiv \frac{\int_0^H \overline{u}(T - T_w)dy\big|_{x=2H}}{\int_0^H \overline{u}(T - T_w)dy\big|_{x=0}} = \frac{(T_B - T_w)\big|_{x=2H}}{(T_B - T_w)\big|_{x=0}} \tag{26}$$

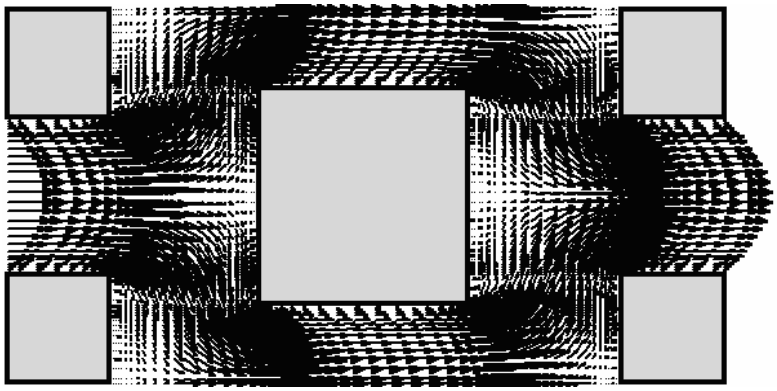
$$T_{B(x)} = \frac{\int_0^H \overline{u} T dy}{\int_0^H \overline{u} dy}, \tag{27}$$

$T_B(x)$ 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 D as $\mathrm{Re}_D = \langle \overline{\mathbf{u}} \rangle D/n$ and $f = 1 - (D/H)^2$.

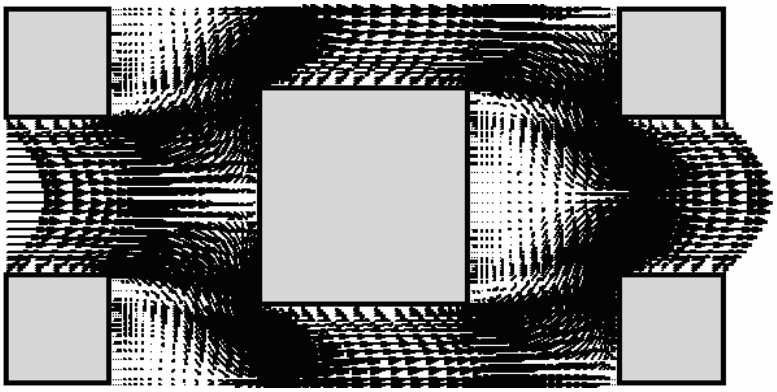
4. PRELIMINARY LAMINAR RESULTS AND DISCUSSION

The preliminary results were velocity and temperature fields obtained for different Reynolds numbers, as shown in Figure 3 and Figure 4, respectively. When the Reynolds number is low (Re_D = 10); Figure 3 (a), the velocity field at entrance and exit of the periodic cell appears to be very

much similar to what we observe in a parallel plate channel. As increases Re (Figure 3 (b)), recirculation bubbles appear behind the rods.



a)



b)

Figure 3. Velocity vectors for Pr = 1: a) Re_D = 10; b) Re_D = 100

A numerical correlation of interfacial convective heat transfer coefficient was assumed the following function:

$$\frac{h_{sf} D}{k_f} = \left(1 + \frac{4(1-f)}{f}\right) + \frac{1}{2}(1-f)^{1/2}\,\mathrm{Re}_D\,\mathrm{Pr}^{1/3}, \text{ for } 0.2 < f < 0.9 \tag{28}$$

based on the porosity dependency , which is in agreement with Kuwahara et. al (2001) for packed bed of particle diameter D.

Before carrying out numerical experiments to determine h_{sf}, the validity of the present numerical procedure based on the periodic boundary conditions must be substantiated.

The average cell heat transfer coefficient is calculated as:

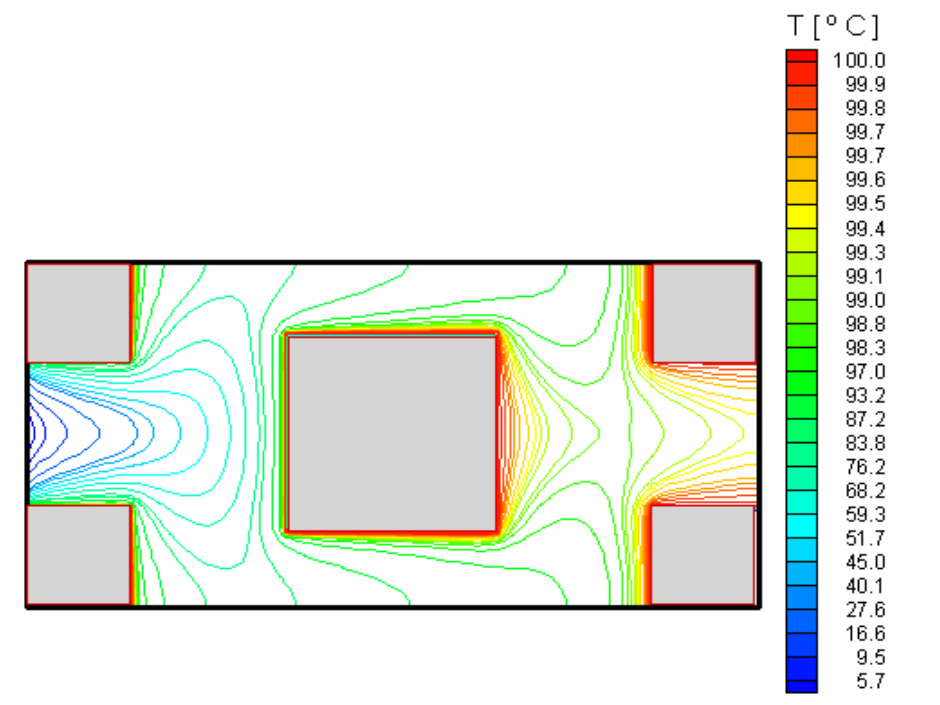
$$h = \frac{Q_{total}}{(8D)\Delta T_{ml}} \tag{29}$$

where,

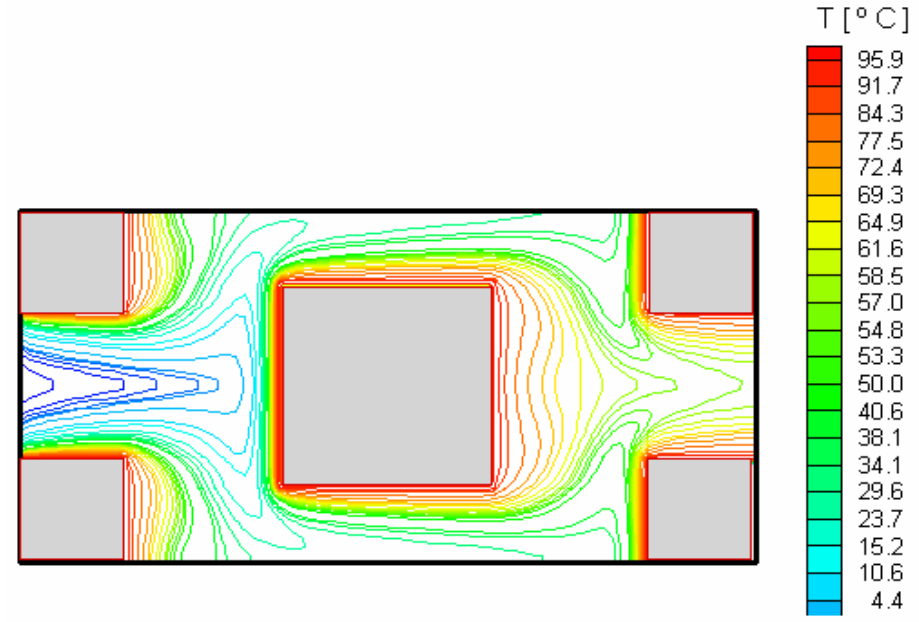
$$Q_{total} = (H - D)\, r \langle \bar{\mathbf{u}} \rangle c_p \left(T_B(2H) - T_B(0)\right) \tag{30}$$

$$\Delta T_{ml} = \frac{\left(T_w - T_B(2H)\right) - \left(T_w - T_B(0)\right)}{\ln\left[\dfrac{\left(T_w - T_B(2H)\right)}{\left(T_w - T_B(0)\right)}\right]} \tag{31}$$

When the Reynolds number is sufficiently high (Figure 4 (b)) the cooling effect due to the cold inlet fluid is pronounced within the fluid phase. Such convective heat transfer overwhelms thermal diffusion.



(a)



(b)

Figure 4. Isotherms for Pr = 1: a) Re_D = 10; b) Re_D = 100.

The velocity profiles for Re = 10 and Re = 100 are shown in Figure 5 and Figure 6 such that the resulting satisfy the boundary conditions and periodic constraints given by Eqs. (24) to (26). For entrance (x = 0) and exit (x= 2H) of the periodic cell the velocity profiles presents the similar results. When x = 2H – D/2 the velocity profile behind crushed because recirculation bubbles appear behind the rods for Reynolds number sufficiently high, as shown in Figure 6.

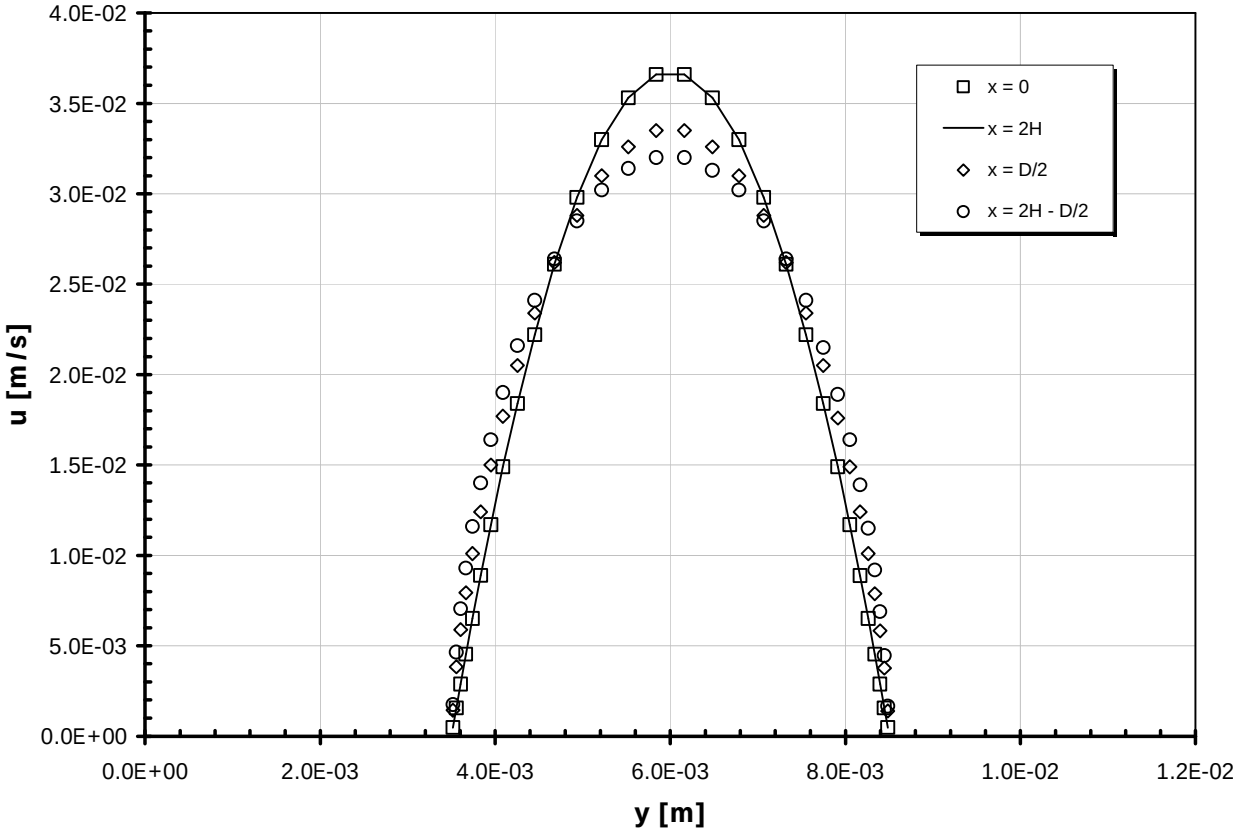


Figure 5. Velocity profiles for $Re_D = 10$.

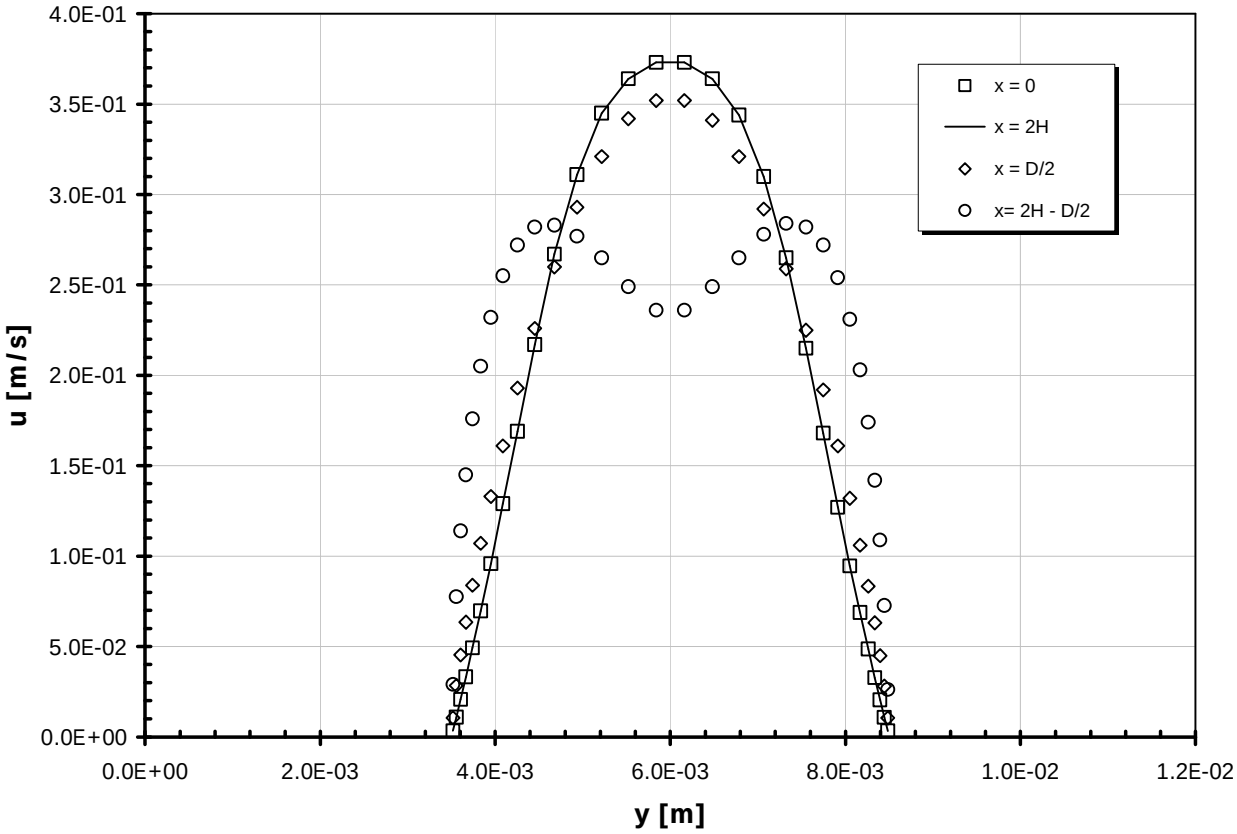


Figure 6. Velocity profiles for $Re_D = 100$.

The microscopic temperature results obtained with Pr = 1 for various values of Re_D are processed using Eq. (28) and Eq.(29), the resulting values of the interfacial convective heat transfer coefficient h_{sf} are plotted with Re_D in Figure 7. The figure compares both equations and suggest that high Reynolds number data vary in proportion to $Re^{0.6}$, besides the correlation established by Kuwahara et. al (2001) agree well with heat transfer coefficient calculate by theoretical basis.

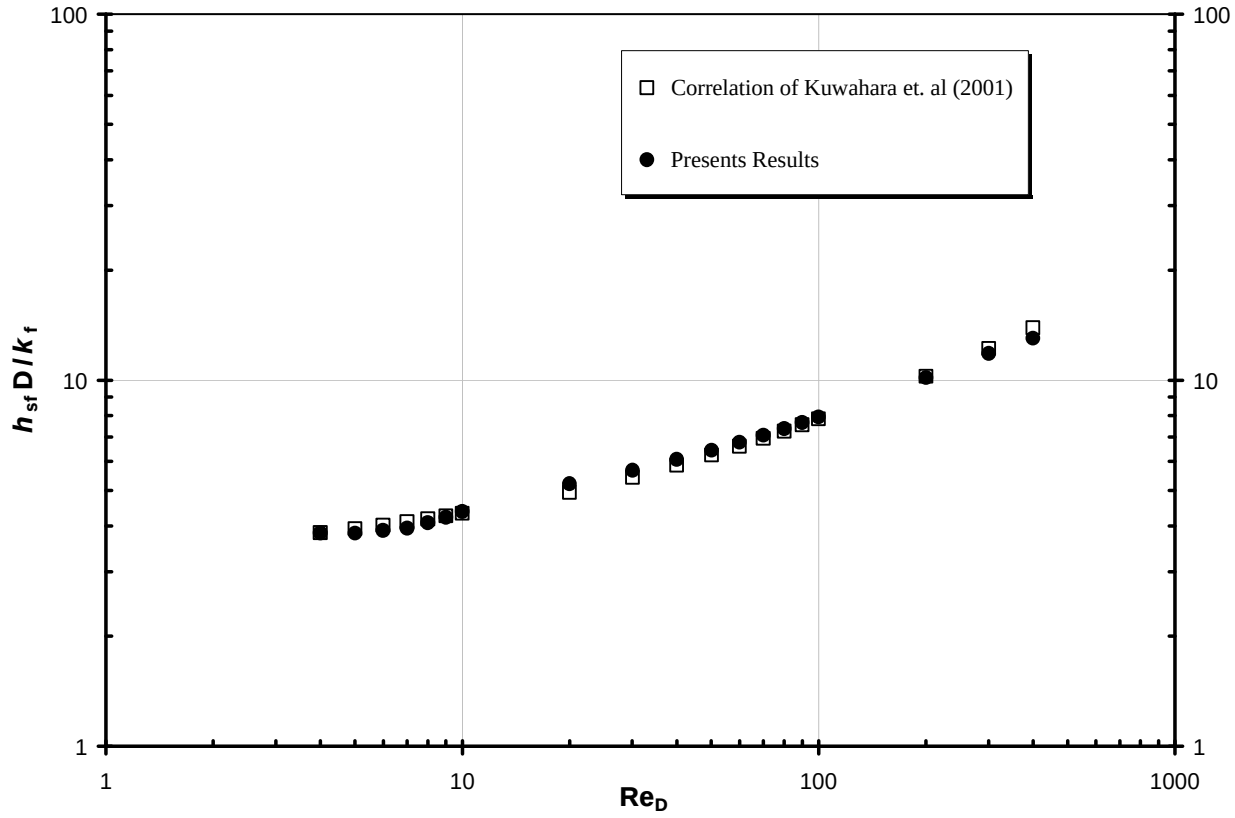


Figure 7. Effect of Re_D on h_{sf} for Pr = 1.

5. CONCLUDING REMARKS

The numerical correlation of interfacial convective heat transfer coefficient 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 fully developed velocity and temperature fields. Upon noting the repetitiveness of flow and temperature profiles, only a single structural unit has been taken as the calculation domain. Quantitative agreement was obtained when comparing the preliminary results of numerical correlation heat transfer coefficient by theoretical basis with correlation established 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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