Escola de Primavera de Transição e Turbulência
Blumenau 2022

13th Spring School on Transition and Turbulence
September 19th-23rd, 2022, Blumenau, SC, Brazil

NUMERICAL SIMULATION OF TURBULENT FLOW AND HEAT TRANSFER IN A PARTIALLY POROUS PIPE

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Abstract. *The present work investigates the turbulence and the heat transfer in partially porous pipes under local thermal non-equilibrium condition. Heat transfer enhancements in pipes filled with porous media have a wide range of applications. Thermal insulation, cooling of electronic devices, catalytic reactors, biological systems, geothermal engineering, are some of the areas of applications. The governing equations were discretized using the finite volume procedure. The system of algebraic equations was solved through the semi-implicit procedure. The SIMPLE algorithm for the pressure-velocity coupling was adopted to correct both the pressure and the velocity fields. Turbulent flow in porous media is modeled using a modified version of* k–ε *model. The pressure drop, fluid and solid temperature distributions and the local Nusselt number are presented. A comparison is made between the results of turbulent and laminar simulations. The effects of turbulence on velocity and on the solid and fluid temperature distribution are analysed.*

Keywords: *Heat transfer enhancement, porous media, local thermal non-equilibrium, numerical simulation.*

1. INTRODUCTION

The use of layers of porous media inside of tubes have potential in different applications as heat exchangers, reformers, chemical reactors, thermal insulation, cooling of electronic devices, biological systems, geothermal engineering. In rocket engines the use of porous material in the cooling jacket improve the heat transfer efficiency. The use of lighter porous materials partially filling the tubes can enhance the heat transfer efficiency without increasing the load too much (Celone and Moro, 2017).

Mohamad (2003) investigated heat transfer enhancement in a pipe partially filled with porous medium and concluded that the thermally developing length can be reduced by 50% or more. He showed that heat transfer increases adding porous material at the core of the pipe. As far as the pressure drop concern, the optimum porous thickness or porous radius ratio is about 0.6.

Mahmoudi and Karimi (2014) studied a pipe partially filled with a porous medium under local thermal non-equilibrium condition. They investigated the effect of the porous layer thickness, Darcy number, inertia parameter and solid-to-fluid thermal conductivity ratio.

A parametric study was conducted by Xu et al. (2011) to investigate the influences of various factors on flow resistance and heat transfer performance in tube partially filled with metallic foam.

The present work presents some preliminary results of a pipe partially filled with porous medium. The problem is considered as a non-radiative case and solution is obtained with the geometry shown in Figure 1. A comparison of laminar and turbulent results is presented. Radiation is subject of ongoing investigations and will be addressed in subsequent paper.

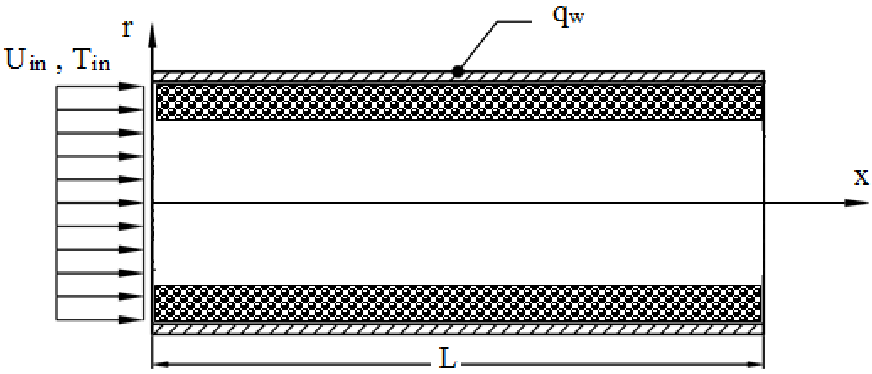

Figure 1. Geometry of a pipe partially filled with porous media and the coordinate system.

2. MACROSCOPIC TRANSPORT EQUATIONS

2.1. Macroscopic continuity equation

$$\nabla \cdot \bar{\boldsymbol{u}}_D = 0 \qquad (1)$$

where, where, $\bar{\boldsymbol{u}}_D = \varphi\langle\bar{\boldsymbol{u}}\rangle^i$ and $\langle\bar{\boldsymbol{u}}\rangle^i$ identifies the intrinsic average of the time-averaged velocity vector $\bar{\boldsymbol{u}}$, it is the average surface velocity, also known as seepage, superficial, filter or Darcy velocity. Equation (1) represents the macroscopic continuity equation for an incompressible fluid.

2.2. Macroscopic momentum equation

The heuristic macroscopic momentum equation utilized in this work is found in the literature(Pedras, 2000) and corresponds to an attempt of the scientific community to develop an equation, based on a volume-averaged treatment of the flow field, along the lines of Navier-Stokes equation. Another desirable characteristic of this heuristic equation is that it can describe both the momentum transport through the porous media as well as that in the plain media.

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

where the last two terms represent the Darcy-Forchheimer contribution. The symbol K is the porous medium permeability, $c_F = 0.55$ is the form drag coefficient (Forchheimer coefficient), p is the intrinsic (volume-averaged on fluid phase) pressure of the fluid, ρ is the fluid density and is a function of temperature, μ represents the fluid dynamic viscosity and ϕ is the porosity of the porous medium.

The intrinsic turbulent kinetic energy per unit mass and its dissipation rate are governed by the following equations,

$$\rho\left[\frac{\partial}{\partial t}\left(\phi\langle k\rangle^i\right) + \nabla\cdot\left(\bar{\mathbf{u}}_D\langle k\rangle^i\right)\right] = \nabla\cdot\left[\left(\mu + \frac{\mu_{t_\phi}}{\sigma_k}\right)\nabla\left(\phi\langle k\rangle^i\right)\right] - \rho\langle\overline{\mathbf{u}'\mathbf{u}'}\rangle^i : \nabla\bar{\mathbf{u}}_D + c_k\rho\frac{\phi\langle k\rangle^i|\bar{\mathbf{u}}_D|}{\sqrt{K}} - \rho\phi\langle\varepsilon\rangle^i \qquad (3)$$

$$\rho\left[\frac{\partial}{\partial t}\left(\phi\langle\varepsilon\rangle^i\right)+\nabla\cdot\left(\bar{\mathbf{u}}_D\langle\varepsilon\rangle^i\right)\right]=\nabla\cdot\left[\left(\mu+\frac{\mu_{t_\phi}}{\sigma_\varepsilon}\right)\nabla\left(\phi\langle\varepsilon\rangle^i\right)\right]+c_1\left(-\rho\langle\overline{\mathbf{u}'\mathbf{u}'}\rangle^i:\nabla\bar{\mathbf{u}}_D\right)\frac{\langle\varepsilon\rangle^i}{\langle k\rangle^i}$$
$$+c_2 c_k\rho\frac{\phi\langle\varepsilon\rangle^i|\bar{\mathbf{u}}_D|}{\sqrt{K}}-c_2\rho\phi\frac{\langle\varepsilon\rangle^{i^2}}{\langle k\rangle^i} \tag{4}$$

where, c_k, c_1, c_2 and c_μ are nondimensional constants.

2.3. Macroscopic Two-Energy Equations Model

In this work the effects of dispersion and tortuosity are neglected.

$$\left\{\left(\rho c_p\right)_f\phi\right\}\frac{\partial\langle\bar{T}\rangle^i}{\partial t}+\left(\rho c_p\right)_f\nabla\cdot\left(\mathbf{u}_D\langle\bar{T}_f\rangle^i\right)=\nabla\cdot\left\{\mathbf{K}_{eff,f}\cdot\nabla\langle\bar{T}_f\rangle^i\right\}+h_i a_i\left(\langle\bar{T}_s\rangle^i-\langle\bar{T}_f\rangle^i\right) \tag{5}$$

and

$$\left\{(1-\phi)\left(\rho c_p\right)_s\right\}\frac{\partial\langle\bar{T}\rangle^i}{\partial t}=\nabla\cdot\left\{\mathbf{K}_{eff,s}\cdot\nabla\langle\bar{T}_s\rangle^i\right\}-h_i a_i\left(\langle\bar{T}_s\rangle^i-\langle\bar{T}_f\rangle^i\right) \tag{6}$$

represent the energy equation for fluid and solid phase, respectively, where, $\langle\bar{T}_f\rangle^i$ and $\langle\bar{T}_s\rangle^i$ are the intrinsic average of the temperatures of the fluid phase and solid phase (Saito, 2006), h_i and a_i are the interfacial convective heat transfer coefficient and surface area per unit volume, respectively and $\mathbf{K}_{eff,f}$ and $\mathbf{K}_{eff,s}$ are the effective conductivity tensors for the fluid and the solid phase, respectively, given by:

$$\mathbf{K}_{eff,s}=\left[\phi k_f\right]\mathbf{I} \tag{7}$$

$$\mathbf{K}_{eff,s}=(1-\phi)[k_s]\mathbf{I} \tag{8}$$

where, k_f and k_s are the thermal conductivities for the fluid and for the solid, respectively.

2.4. Boundary conditions

Axisymmetric boundary conditions are adopted at r=0, i.e., v=0 with gradients of u and T in the r-directions set to zero. The v velocity component is set to zero, $u=u_{in}$ and $T=T_{in}$ at x=0. For x=L, the gradients of the variables in the x-direction are set to zero. At the walls, the no-slip condition is assumed, u=v=0 and a constant heat flux q_w is considered in all cases.

3. NUMERICAL MODEL

The governing equations were discretized using the finite volume procedure (Patankar, 1980). The system of algebraic equations was solved through the semi-implicit procedure according to Stone (1968). The SIMPLE algorithm for the pressure-velocity coupling was adopted to correct both the pressure and the velocity fields. The process starts with the solution of the two momentum equations. Then the velocity field is adjusted in order to satisfy the continuity principle. This adjustment is obtained by solving the pressure correction equation. A computational mesh of 266x34 is adopted in the simulations.

All computations were performed on an Intel(R) Xeon(R) E5-2690 v2 3.0 GHz, 32GB. For all cases, a relative convergence of 10^{-5} was specified. The grid effects on the solutions were examined by increasing the number of nodes and verifying the solutions until the results no longer changed in a specified tolerance.

4. RESULTS AND DISCUSSION

The Figure 2 presents the effect of the turbulent modeling on the velocity distributions for the configuration of a tube partially filled with porous media. It is presented by Nield and Bejan (2013) that the pore-scale turbulence occurs when the Reynolds number, based on the permeability, is higher than 100. The maximum permeability Reynolds number calculated was 60, but for a tube partially filled with porous media. The authors didn't find in the literature any experiment presenting measures of the turbulence intensity in a tube partially filled with porous media. The inlet velocity is 0.17 m/s and the ratio of the porous substrate thickness to the pipe radius is 0.4. The comparison with the results using the laminar model helps to understand the turbulence model and its parameters.

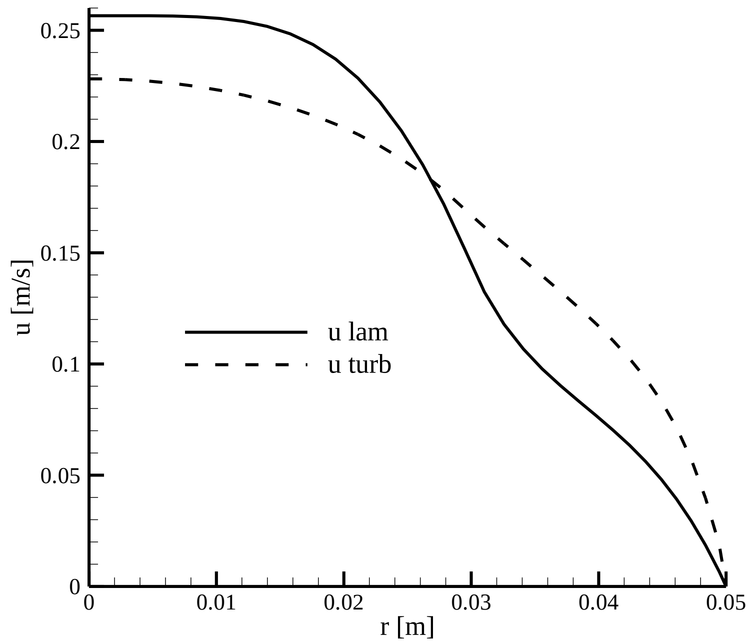

Figure 2. Velocity distributions considering laminar and turbulence model.

Figure 3 presents the pressure drop in the center line of the tube considering laminar and turbulence model. The results show that the model considering turbulence reduces the pressure drop in the pipeline.

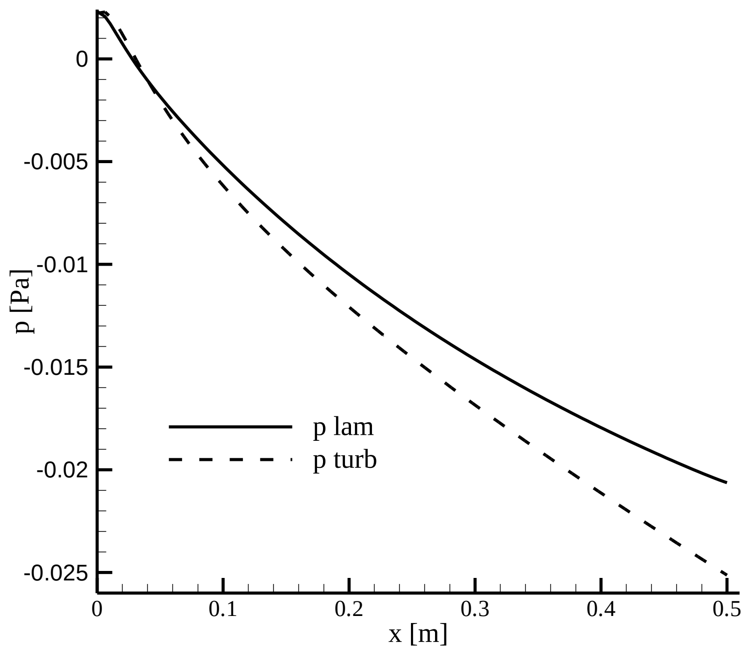

Figure 3. Pressure drop distribution in the center line of the tube considering laminar and turbulence model.

The Figure 4 presents the solid and fluid temperature distributions considering laminar and turbulence model. The solid phase temperatures are higher using the laminar model and lower using the turbulence model. The heat flux is constant at the pipe wall and the heat is transferred by conduction and convection through the porous layer along the pipe wall. The turbulence model causes an increase in energy transfer from the porous region to the region without porous material. It is possible to observe that the fluid phase temperatures at the region without porous media are higher considering the turbulence model.

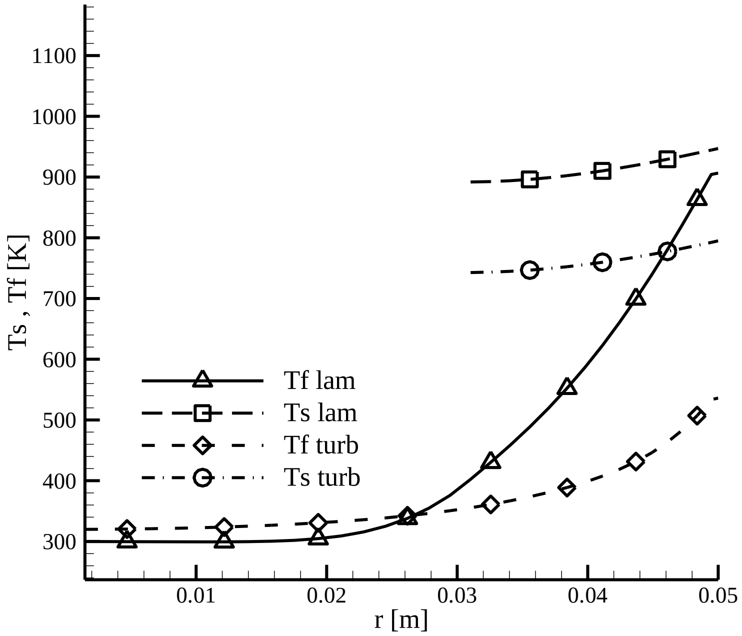

Figure 4. Solid and fluid temperature distributions considering laminar and turbulence models.

5. CONCLUSION

Enhancement of forced turbulent convection heat transfer in pipes partially filled with porous media was investigated numerically. The authors examined the turbulence model and the effects on the solid- and fluid-phase temperature fields and on the pressure and velocity fields. The results obtained using the turbulence model were compared with the results obtained using the laminar model. In general, the results showed that the turbulence model developed for porous media represents well the hydrodynamic and heat transport in a tube partially filled with porous media.

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