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A NUMERICAL STUDY OF DIFFERENT CONFIGURATIONS OF PIPES FILLED WITH POROUS MEDIA

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Abstract. The present work investigates heat transfer in different configurations of pipes filled with porous media under local thermal non-equilibrium condition. Two configurations consider the pipe partially filled with porous media, a pipe with a porous layer inserted at the wall and a pipe with a porous media at the core. A third configuration is a pipe completely filled with porous media. The flow is assumed to be laminar. The pressure drop, fluid and solid temperature distributions are calculated. The local Nusselt number of the different configurations is presented. The effect of the porosity on the different configurations is analysed. The configuration of the tube with a porous layer on the wall presented a low heat transfer efficiency. The tubes filled with porous media in the core region presented a good heat transfer efficiency and a low pressure drop.

1. INTRODUCTION

Forced convection heat transfer in porous media have been studied extensively. 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.

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 radio 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.

The present work presents a numerical study of two configurations of pipes partially filled with porous medium and a comparison with a pipe fully filled with porous media. Figure 1 presents two configurations considering pipes partially filled with porous media. One configuration consists in a pipe filled with porous media at the core of the conduit and the other is a pipe filled with a porous layer at the wall. Xu et al. (2011) and Yanget al. (2012) presented analytical solutions for the problems showed in the Figure 1, but there are some coefficients not defined in the articles that makes impossible to use the analytical solutions. Xu et al. (2011) plotted some results, but they don't specify the Prandtl number making these results not possible to be utilized in some validation.
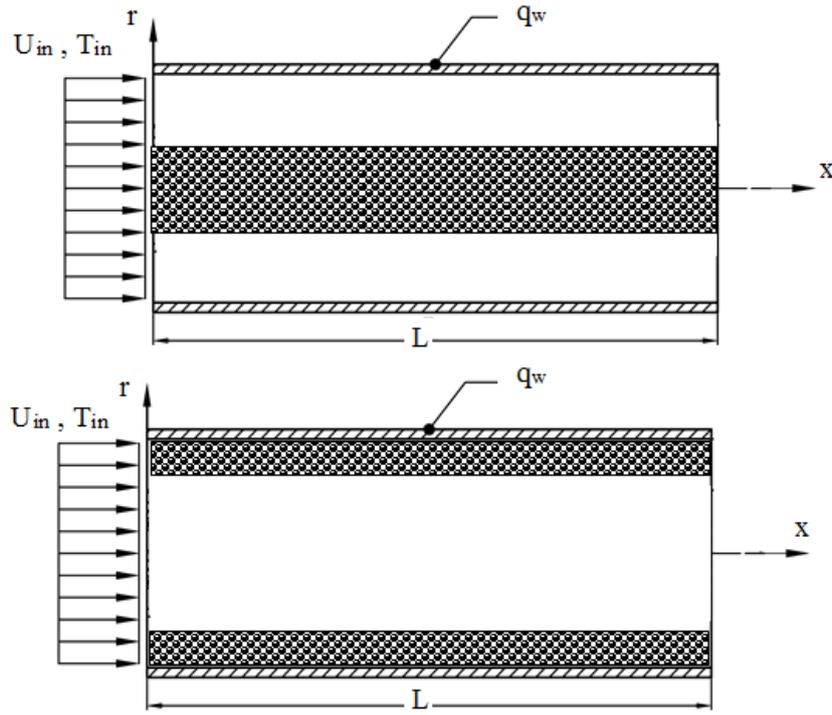
Figure 1. Two configurations of pipes partially filled with porous media.

2. MACROSCOPIC TRANSPORT EQUATIONS

2.1. Macroscopic continuity equation

$$\nabla.(\rho\mathbf{u}_{\mathrm{D}}) = 0 \tag{1}$$

where, $\mathbf{u}_{\mathrm{D}}$ 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(Kaviany, 1995; 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.

$$\nabla \cdot \left(\frac{\rho \mathbf{u}_{\mathrm{D}}\mathbf{u}_{\mathrm{D}}}{\phi} \right) = -\nabla(\phi p) + \mu\nabla^2\mathbf{u}_{\mathrm{D}} - \left[\frac{\mu\phi}{K}\mathbf{u}_{\mathrm{D}} + \frac{c_F\phi\rho|\mathbf{u}_{\mathrm{D}}|\mathbf{u}_{\mathrm{D}}}{\sqrt{K}} \right] \tag{2}$$

where the last two terms represent the Darcy-Forchheimer contribution (Pedras 2000). 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.

2.3. Macroscopic Two-Energy Equations Model

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

$$\left(\rho c_p\right)_f \nabla \cdot \left(\mathbf{u}_D T_f\right) = \nabla \cdot \left\{\mathbf{K}_{eff,f} \cdot \nabla T_f\right\} + h_v\left(T_s - T_f\right) \tag{3}$$

and

$$\nabla \cdot \left\{\mathbf{K}_{eff,s} \cdot \nabla T_s\right\} - h_v\left(T_s - T_f\right) = 0 \tag{4}$$

represent the energy equation for fluid and solid phase, respectively, where, T_f and T_s are the intrinsic volume average of the temperatures of the fluid phase and solid phase ((Kaviany, 1995; Saito, 2006), h_v is the volumetric heat transfer coefficient 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:

$$\mathbf{K}_{eff,s} = \left[\phi k_f\right]\mathbf{I} \tag{5}$$

$$\mathbf{K}_{eff,s} = (1 - \phi)[k_s]\mathbf{I} \tag{6}$$

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 porosity on the velocity distributions for the two configurations of tubes partially filled with porous media and the comparison with the tubes fully filled with porous media. The velocity distributions presented are for developed flow. 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 and the maximum permeability Reynolds number calculated was 60, which is less than 100. Hence, in the present work it is assumed laminar flow. The two configurations of tubes partially filled with porous media are that with porous media on the wall region and in the core region. The inlet velocity is 0.17 m/s for all the configurations. The ratio of the porous substrate thickness to the pipe ratio, in the tubes partially filled with porous media, is 0.6 for the two configurations. The increase of the porosity decreases the flow resistance in the foam region. Increasing the porosity causes an increase in the velocity on the foam region and a decrease in the velocity on the clean region, as presented in Figure 2. In the tubes fully filled with porous media, the effect of porosity in developed flows is weak, changing the porosity from 0.6 to 0.9 affect just a little the velocity profiles.
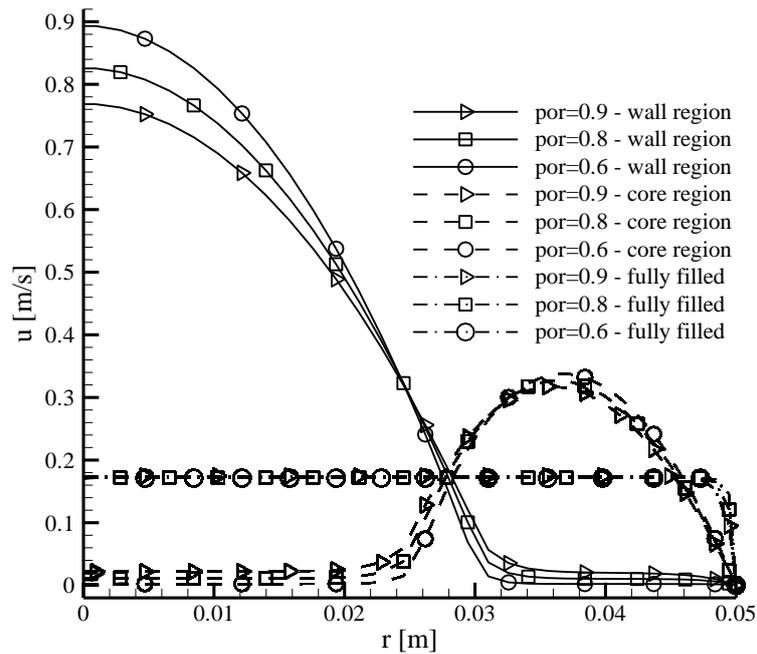
Figure 2. Effect of the porosity on the velocity distributions for the tubes filled
with porous media in the core region and on the wall region.

Figure 3 presents the effect of the porosity on the Nusselt number for different configurations of pipes filled with porous media. In the configuration partially filled with porous media in the core region, the ratio of the porous substrate thickness to the pipe ratio is 0.6. The same value was adopted to the configuration with the porous media covering the wall. The tube fully filled with porous media has the best heat transfer efficiency, but, the highest pressure drop as presented in the Figure 4. In the tubes fully filled with porous media, the effect of the porosity on the Nusselt number is higher than in the tubes partially filled with porous media.
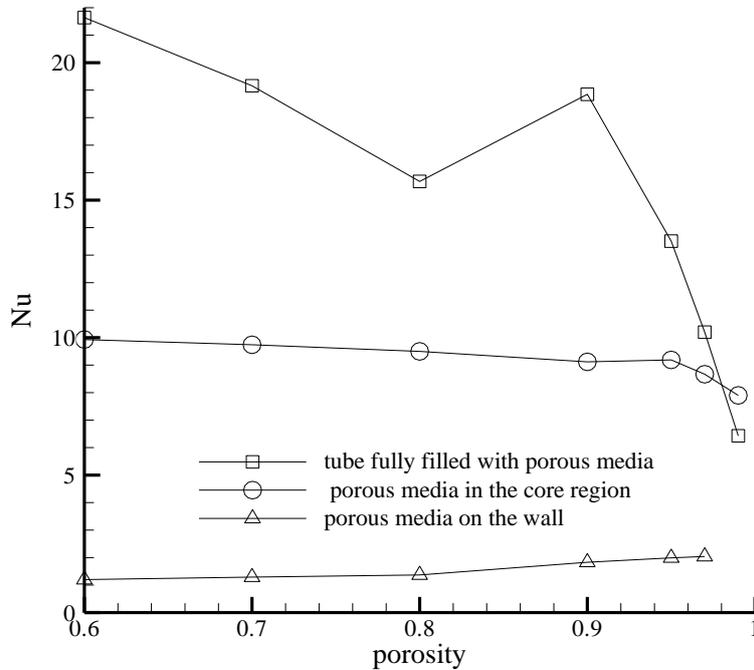

Figure 3. Nusselt number for different configurations of pipes filled with
porous media.

The Figure 4 presents the pressure drop in the center line of the tube for different configurations of tubes filled with porous media (porosity=0.9) and a comparison with a tube without porous media (clean media).
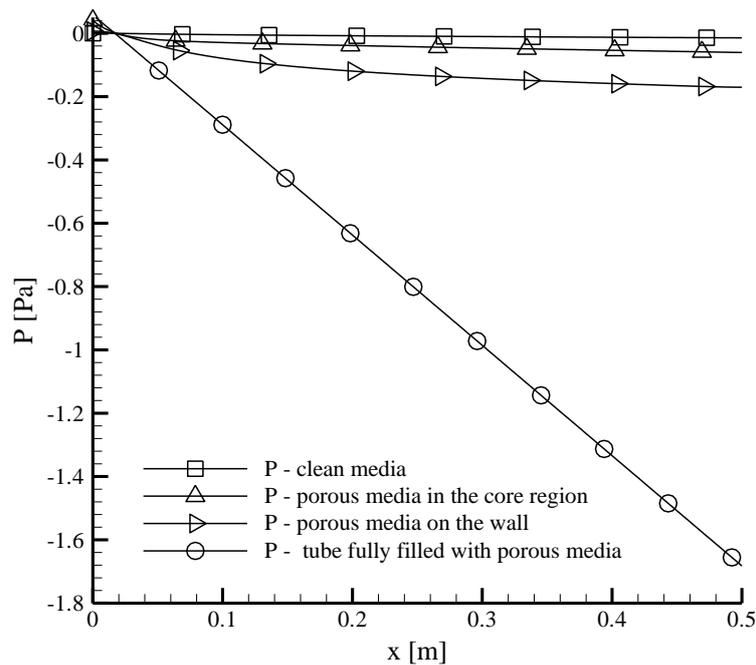
Figure 4. Pressure drop distribution in the center line of the tube for different configurations of pipes filled with porous media. The porosity is 0.9 in the configurations with porous media.

5. CONCLUSION

Enhancement of forced convection heat transfer in pipes partially filled or fully filled with porous media was investigated numerically. The best heat transfer efficiency was obtained with the tube fully filled with porous media, but the pressure drop is very high. The configuration of the tube with a porous layer on the wall presented a low heat transfer efficiency. The tubes filled with porous media in the core region presented a good heat transfer efficiency and a low pressure drop. This kind of solution can be employed in many areas. The author of the present work is developing studies about the use of tubes partially filled with porous media in the area of regenerative cooling systems for rocket engines. In rocket engines the use of porous tubes in the cooling jacket would improve the heat transfer efficiency, but would increase the rocket load. The use of lighter materials partially filling the tubes can enhance the heat transfer efficiency without increasing the load too much.

6. ACKNOWLEDGEMENTS

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