

Numerical Simulation Of Laminar Flow Through Rectangular Duct Filled With Discrete Porous Media

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Abstract— In the present study laminar flow through a rectangular duct filled with discrete porous media, with water as working fluid is investigated numerically. Simulation has been carried out using open source CFD package OpenFOAM. The effect of Reynolds number on the velocity profile is analyzed and discussed.

Keywords— Laminar flow, Porous media, Reynolds number, Porosity.

NOMENCLATURE

L	Length (m)
B	Breadth (m)
H	Height (m)
μ	Dynamic Viscosity (Ns/m ²)
ν	Kinematic Viscosity (m ² /s)
K	Permeability (m ²)
C	Form Coefficient (m ⁻¹)
u	Velocity (m/s)
ρ	Density (kg/m ³)
V	Volume
ϕ	Porosity = V_p / V
Re	Reynolds Number
Re _k	Permeability based Re
	$Re_k = \frac{\sqrt{K}}{\nu} u$

SUBSCRIPT

f	Fluid
e	Effective
i	Inlet
o	Outlet
p	Porous
s	Spacing
k	Permeability based

I. INTRODUCTION

The employment of different types of porous materials in forced convection heat transfer has been extensively studied due to wide engineering applications such as heat pipe, solid matrix heat exchanger, electronic cooling etc. Lage *et al.* [1] performed numerical study of a low permeability microporous heat sink for cooling phased array radar system. Porous layer is brazed to a plate on which radar components are mounted. Dimensionless pressure drop with porous media is found to be approximately 40 times higher than that without porous media. The study showed that microporous layer was able to produce more uniform operating temperature for the radar components. Experimental and numerical investigation was carried out by Bodgan *et al.* [2] to study the effect of metallic porous material inserted in a pipe on heat transfer rate. Pipe is subjected to constant and uniform heat flux. Results revealed that average surface temperature of pipe decreased with the use of porous material in the core of pipe. It is also found that largest pressure drop corresponds to the case that offers the best thermal performance. Porous insert with larger diameter and smaller porosity leads to higher fluid velocities located much closer to the pipe wall, consequently high heat transfer rate. Flow redistribution and thermal conductivity modification due to the porous media resulted in the enhancement of heat transfer. Experiments were performed Huang *et al.* [3] on air flow through a tube filled with porous media in the core. Tube wall is subjected to constant and uniform heat. The numerical results show that the application of porous inserts effectively makes the temperature profiles of fluid flow become more uniform at the core of the tube which play more important role in heat transfer enhancement. Partial filling of tube with porous media reduced cross section of flow. This increased velocity gradient near the tube wall, resulting in increased heat transfer and flow resistance. Nimvari *et al.* [4] studied turbulent flow heat transfer in a channel partially filled with a porous media. Both central arrangement and boundary arrangement is considered for study. Channel is subjected to constant wall heat flux and it

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was found that for both the configuration there exist an optimum thickness ratio where the heat transfer is more.

In the recent years heat transfer through discrete porous media has acquired considerable attention due to its applications and enhanced heat transfer capacity. Electronic cooling involves mainly the application of discrete porous media since the heat rejecting components are spaced apart. Numerical investigation has been conducted to study enhanced heat transfer from multiple discrete heated sources in a horizontal channel filled with metal-foam porous layer by Chih *et al.* [5]. Flat velocity profile is obtained in the core flow and enhancement of heat transfer is achieved under the penalty of increased pressure drop in this case.

Analysis of above investigations disclosed that thorough flow analysis is necessary to understand the heat transfer mechanism through porous media and heat transfer can be enhanced under the expense of pressure drop. This paper presents a numerical analysis of a rectangular duct filled with discrete porous media with water as working fluid. Most of the investigations done in the field of porous media either used commercial CFD package or were experimental based. In this work open source CFD software package OpenFOAM is used and the porosity is modelled using Darcy Forchheimer model.

II. NUMERICAL ANALYSIS

A. Physical Model

The schematic diagram of the rectangular duct filled with discrete porous medium is shown in Fig 1. Dimension of the duct is 2.5 x 0.02 x 0.02 (L x B x H). Hydraulic diameter of the duct is 20 mm. The length L_i and L_o is taken as 1.4 m and 0.9 m respectively for the flow to become fully developed before it enters the porous medium and at the exit of the duct. Duct has four porous mediums each having 20mm length (L_p) spaced at a distance (L_s) of 30 mm apart.

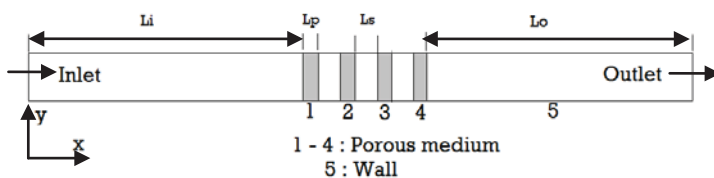


Figure 1 : Schematic of domain

B. Governing Equations

Flow is assumed to be steady incompressible and laminar. The governing equations are,

Conservation of mass

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

Conservation of momentum

$$\rho_f \left[\frac{1}{\phi} \mathbf{u} \cdot \frac{1}{\phi} \nabla \mathbf{u} \right] = -\nabla P + \mu_e \nabla^2 \mathbf{u} - \frac{\mu}{K} \mathbf{u} - \rho C |\mathbf{u}| \mathbf{u} \tag{2}$$

C. Boundary Conditions

Flow enters the channel inlet with uniform velocity and temperature. The fully developed conditions are specified for all variables at exit. No slip boundary condition is specified for walls of the duct and slip condition at porous wall.

a. Inlet

$$u = \text{Constant}, v = 0, w = 0, T_{\text{inlet}} = \text{Constant}$$

b. Outlet

$$\frac{\partial u}{\partial x} = 0 \quad \frac{\partial v}{\partial x} = 0 \quad P_{\text{outlet}} = P_{\text{atm}}$$

D. Numerical Simulation

Numerical simulation is done by using the open source software OpenFOAM. Fluid enters the inlet at constant velocity. While using OpenFOAM the meshing of the porous zone is done by defining it as a separate block. Porosity of the porous zone is specified by using Darcy's and Forchheimer constant. Porosity can be specified for three directions, in this case porosity is assumed to be vary in flow direction only. Iterations are carried out for a residual level of 10^{-5} . Relaxation factor used for pressure and velocity equation is 0.7. Grad scheme used for velocity and pressure is Gauss linear. Divergence scheme used is Gauss upwind.

The analysis is conducted by varying the inlet velocity from 0.001 m/s to 0.08 m/s to cover a Reynolds number from 99.87 to 1997.5. This ensures that flow is in laminar regime. Permeability (K) of $3.88 \times 10^{-10} \text{ m}^2$ and form coefficient (C) 5518 m^{-1} is chosen in this case. The final computational domain along with grid used in numerical simulation is shown in Fig 2a (2D view in x-y plane) and Fig 2b (3D view)

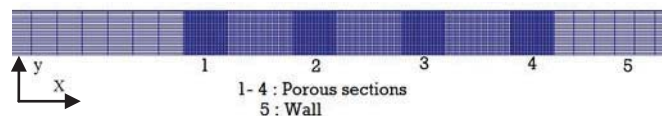


Figure 2a: 2D representation (x - y plane)

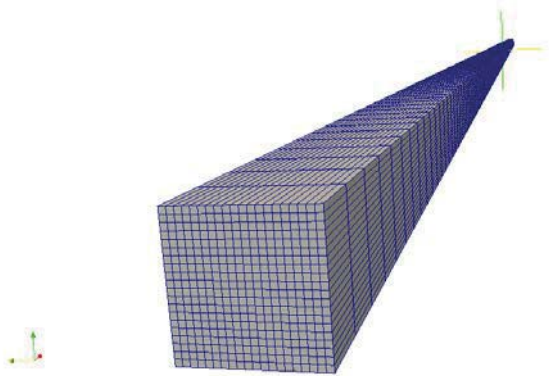


Figure 2b: 3D representation

E. Grid Independence Study

Grid independent study is conducted for duct filled with porous media. Table 1 shows the grid sensitivity study conducted for duct filled with porous media. As seen in Table 1 beyond cell size of more than 156000 cells, the results are independent of grid size. So grid with 156000 cells is used for the simulation.

Table 1: Grid sensitivity study
 (Re = 251, $\phi = 0.92$)

Number of cells	Velocity in x direction at midpoint of different porous media (m/s)			
	1	2	3	4
65000	0.001611	0.001600	0.001585	0.001591
156000	0.001643	0.001624	0.001624	0.001621
243750	0.001651	0.001632	0.001632	0.001629

III. RESULT AND DISCUSSIONS

A. Validation

Initially to validate the proposed methodology using OpenFOAM simulation has been performed to analyze the flow through a rectangular duct filled with single porous media. The geometry considered here is same as that of Wilson *et al.* [6] in his experimental work. Figure 3 shows comparison of pressure drop per unit length along the duct of the present work with that of experimental work of Wilson *et al.* [6]. The comparison exercise shows a great agreement with numerical and experimental pressure drop at low velocity. However at higher velocity results deviate due to experimental uncertainties. It is worth to mention here that the nature of two curves is similar. This establishes the efficacy of proposed methodology in solving this type of problems.

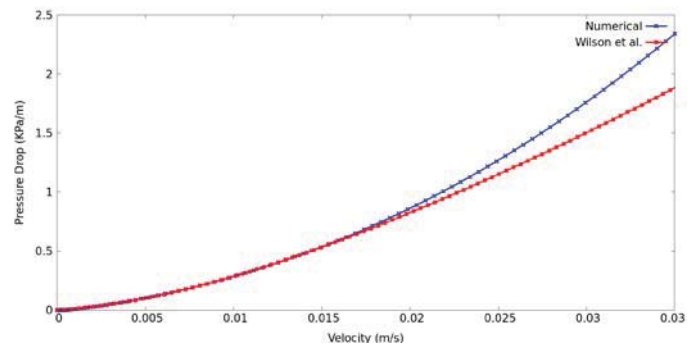


Figure 3: Pressure drop per unit length at different velocities

B. Duct With Discrete Porous Media

Figure 4 shows the pressure contour obtained from numerical simulation across the duct filled with four discrete porous media. The simulation results shows pressure drop across the channel. This implies that the simulation is able to capture the flow through duct

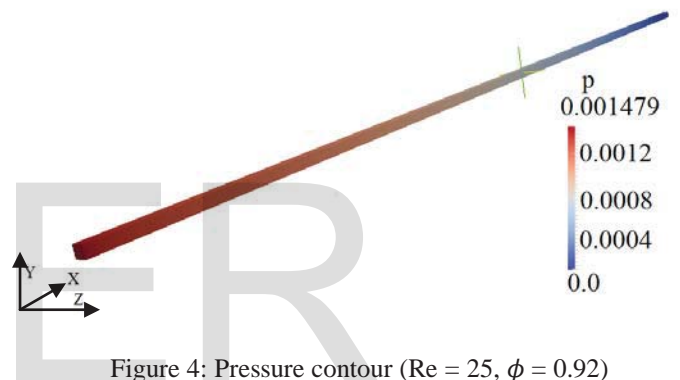


Figure 4: Pressure contour (Re = 25, $\phi = 0.92$)

At the solid wall the fluid adheres to the surface (no slip boundary condition) where as at the surface of porous section the slip boundary condition is employed. This can be clearly seen in velocity contour depicted in the Fig 5.

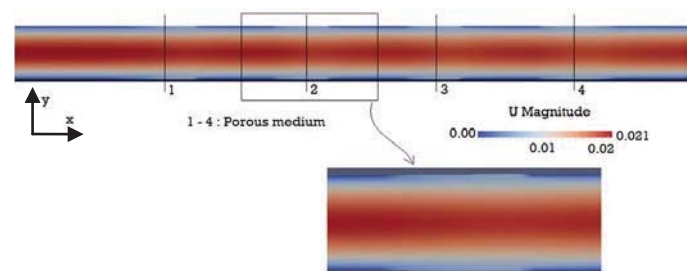


Figure 5: Velocity contour (Re = 25, $\phi = 0.92$)

1) Flow development in porous media

Figure 6 shows the velocity profile plotted at different sections of first porous media. As the flow proceeds through a porous media, centre line velocity decreases along the flow

direction with a corresponding increase in velocity near wall of the porous section. Since $Re_k < 1$ viscous force dominates. As the flow proceeds through the porous section due to hydrodynamic dispersion momentum exchange takes place within the fluid resulting in increased velocity near the wall and reduced velocity at the centre. This can be clearly seen from Fig 6 wherein velocity profile changes from parabolic to flat profile as flow proceeds towards exit.

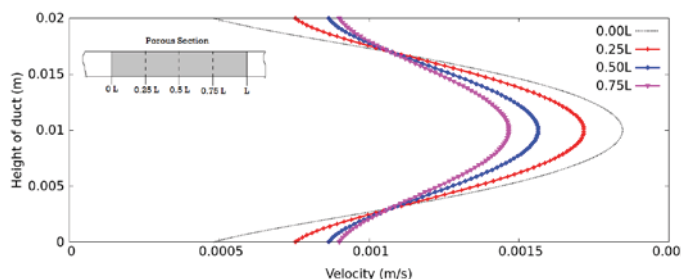


Figure 6: Velocity profile at different length of first porous media ($Re_k = 0.025$, $\phi = 0.92$)

Simulation have been performed for $Re_k = 1.23$. At this Reynolds number inertial force starts dominating over viscous force [8]. As the flow becomes inertial, the nature of flow will be that of Hagen Poiseuille flow with almost parabolic profile. However since the flow is in transition regime viscous forces will be still there and due to hydrodynamic dispersion the centre line velocity reduces as shown in Fig 7.

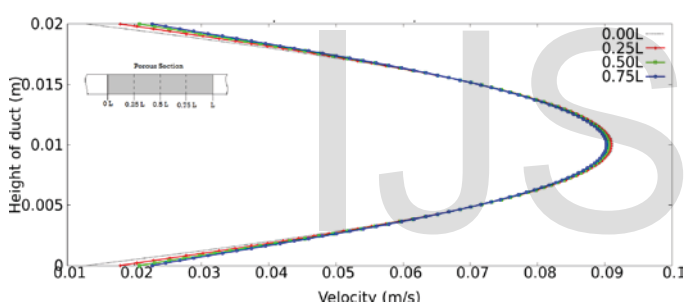


Figure 7: Velocity profile at different length of first porous media ($Re_k = 1.23$, $\phi = 0.92$)

2) Flow development in discrete porous media

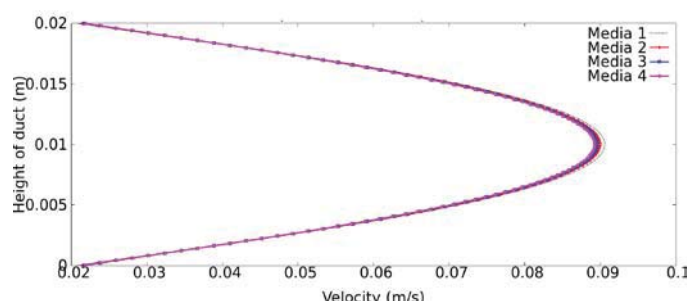


Figure 8: Velocity profile at midsection of each porous media ($Re_k = 1.23$, $\phi = 0.92$)

Velocity at midsection of each porous media for same inlet velocity is compared. From the profile in Fig 8 it can be observed that velocity along the centre line reduces when flow moves from one porous media to another. Boundary layer thickness increases as flow moves from first to last porous media.

IV. CONCLUSION

Numerical investigation has been performed for a flow in rectangular duct filled with porous medium. Simulation has been performed for a wide range of Reynolds number. The salient conclusions from the study are

- The pressure drop across the porous media obtained in numerical simulation is comparable with the result of Wilson *et al.*
- As the flow proceeds through the different section of a porous media, the velocity profile changes from a parabolic to flat. This is due to hydraulic dispersion.
- At higher Re_k inertial effects becomes predominant and the flow proceeds towards more Hagen Poiseuille type.
- When the flow passes through different porous media the velocity profile contracts towards the centerline because hydrodynamic boundary layer thickness increases lightly and the effect of inertial force decreases in the flow direction

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