Flow Through Porous Media

Abstract—*In this exercise, steady two-dimensional flow through porous media is modeled. The dimensions of the pipe and porous zone can be specified. The flow can be modeled as laminar or turbulent. Coarse, medium, and fine mesh types are available. The material properties for the fluid and porous medium (porosity, viscous and inertial resistance) can be specified. The effects of inlet velocity and porous medium properties on pressure drop across the porous insert can be studied. Mass flow rate, total pressure drop, pressure drop in porous zone, and cross-sectional averaged velocity at the center of the porous insert are reported. Velocity vectors, pressure contours, and streamlines can be displayed.*

1 Introduction

Porous media can be used for modeling a wide variety of engineering applications, including flows through packed beds, filters, perforated plates, flow distributors, and tube banks. It is generally desirable to determine the pressure drop across the porous medium and to predict the flow field in order to optimize a given design.

2 Modeling Details

The fluid region is represented in two dimensions. The procedure for solving the problem is:

1. Create the geometry.
2. Set the material properties and boundary conditions.
3. Mesh the domain.

FlowLab creates the geometry and mesh, and exports the mesh to FLUENT. The boundary conditions and flow properties are set through parametrized case files. FLUENT converges the problem until the convergence limit is met, or the specified number of iterations is achieved.

2.1 Geometry

The geometry consists of a pipe wall, porous medium, velocity inlet, and a pressure outlet as shown in Figure 2.1. The length of the porous insert (P), the radius of the pipe (R), the length of the pipe (L), and the distance from the porous center to the inlet (Xc) can be specified.

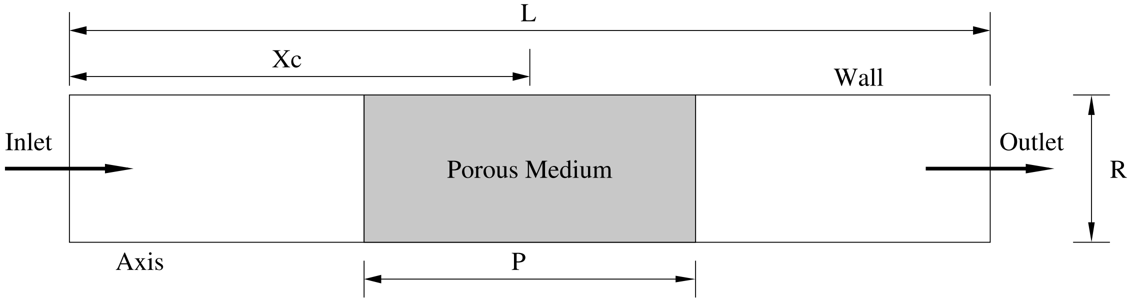

Figure 2.1: Geometry

2.2 Mesh

Coarse, medium, and fine mesh types are available. Mesh density varies based upon the assigned Refinement Factor. The Refinement Factor values for the mesh densities available in this exercise are given in Table 2.1.

Mesh Density	**Refinement Factor**
Fine	1
Medium	1.414
Coarse	2

Table 2.1: Refinement Factor

Using the Refinement Factor, First Cell Height is calculated using the following formula:

$$First\ Cell\ Height = Refinement\ Factor \times \left[\frac{Yplus \times (Characteristic\ Length^{0.125} \times Viscosity^{0.875})}{(0.199 \times Velocity^{0.875} \times Density^{0.875})}\right] \tag{2-1}$$

Reynolds number is used to determine Yplus. Yplus values for turbulent flow conditions are summarized in Table 2.2.

Reynolds Number	**Flow Regime**	**Yplus**
$Re \leq 2300$	Laminar	First Cell Height = Pipe Radius/24
$2300 < Re \leq 50000$	Turbulent, Enhanced Wall Treatment	Yplus < 10.0
$Re > 50000$	Turbulent, Standard Wall Functions	Yplus > 30.0

Table 2.2: Flow Regime Vs. Reynolds Number

The number of intervals along each edge is determined using geometric progression and the following equation:

$$Intervals = INT\left[\frac{Log\{\frac{Edge\_length \times (Growth\_ratio - 1)}{First\ Cell\ Height} + 1.0\}}{Log(Growth\_ratio)}\right] \qquad (2\text{-}2)$$

The edges are meshed using the First Cell Height and the calculated number of intervals. The entire domain is meshed using a map scheme. The resulting mesh is shown in Figure 2.2.

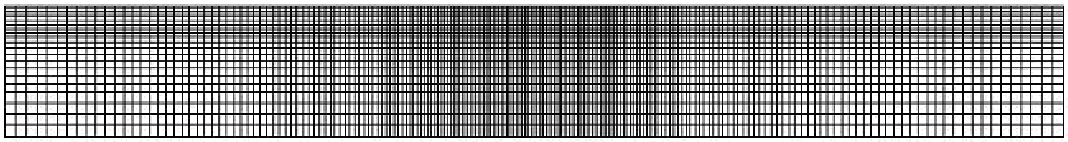

Figure 2.2: Mesh Generated by FlowLab

2.3 Physical Models for FLUENT

Based on the Reynolds number, the following physical models are recommended:

$Re \leq 2300$	Laminar Flow
$Re > 2300$	$k - \epsilon$ Model

Table 2.3: Recommended Physical Model Based on Reynolds Number

However, it is possible to select any model regardless of the Reynolds number.

The appropriate wall treatment is applied based on the Reynolds number.

2.4 Fluid Material Properties

The default fluid properties provided in this exercise represent water. Properties for other fluids such as air, engine-oil, and glycerin are also available. Properties for any fluid of interest may also be specified. The following properties are required:

- Density
- Viscosity

2.5 Porous Media Properties

The default porous media properties provided in this exercise represent black slate powder. Properties for other media such as sand, soil, wire crimps, and silica powder are also available. Properties for any porous media of interest may also be specified. The following properties are required:

- Porosity
- Viscous resistance
- Inertial resistance

2.6 Boundary Conditions

A fully developed velocity profile may be supplied at the Inlet. The following boundary conditions are assigned in FLUENT:

Boundary	Assigned As
Inlet	Velocity inlet
Outlet	Pressure outlet
Wall	Wall

Table 2.4: Boundary Conditions Assigned in FLUENT

For laminar flow, the parabolic velocity profile is defined as follows:

$$V_r = 2 \times U_\infty \times \left(1 - \frac{R_{\max}^2}{r^2}\right) \tag{2-3}$$

where,

V_r = Velocity at radial location, r
U_∞ = Mean velocity
$R_{\max}$ = Radius of the pipe

For turbulent flow, the velocity profile is defined by the power law as follows:

$$V_r = U_{\max} \times \left(\frac{R_{\max} - r}{R_{\max}}\right)^B \tag{2-4}$$

where,

V_r = Velocity at radial location, r
$U_{\max}$ = Maximum velocity, calculated as $U_{\max} = U_\infty \times (1 + B)$
U_∞ = Mean velocity
$R_{\max}$ = Radius of the pipe
$B = \frac{1}{7}$

2.7 Solution

The Reynolds number at the inlet is calculated based on the boundary conditions and fluid properties specified.

The mesh is exported to FLUENT along with the physical properties and the initial conditions specified. The material properties and the initial conditions are read through the case file. Instructions for the solver are provided through a `journal` file. When the solution is converged or the specified number of iterations is met, FLUENT exports the data to a `neutral` file and to `.xy` plot files. GAMBIT reads the `neutral` file for postprocessing activities.

3 Scope and Limitations

Difficulty in obtaining convergence, or poor accuracy may result if input values are used outside of the upper and lower limits suggested in the problem overview.

4 Exercise Results

4.1 Reports

The following reports are available:

- Mass flow rate
- Pressure drop across the porous zone
- Total pressure drop
- Sectional-averaged velocity in the porous zone
- Mass imbalance

4.2 XY Plots

The following plots are available:

- Residuals
- Axial velocity distribution
- Axial pressure distribution
- Wall Yplus distribution *

* *Available only when the flow is modeled as turbulent.*

Figures 4.1 and 4.2 present axial velocity and pressure distributions respectively.

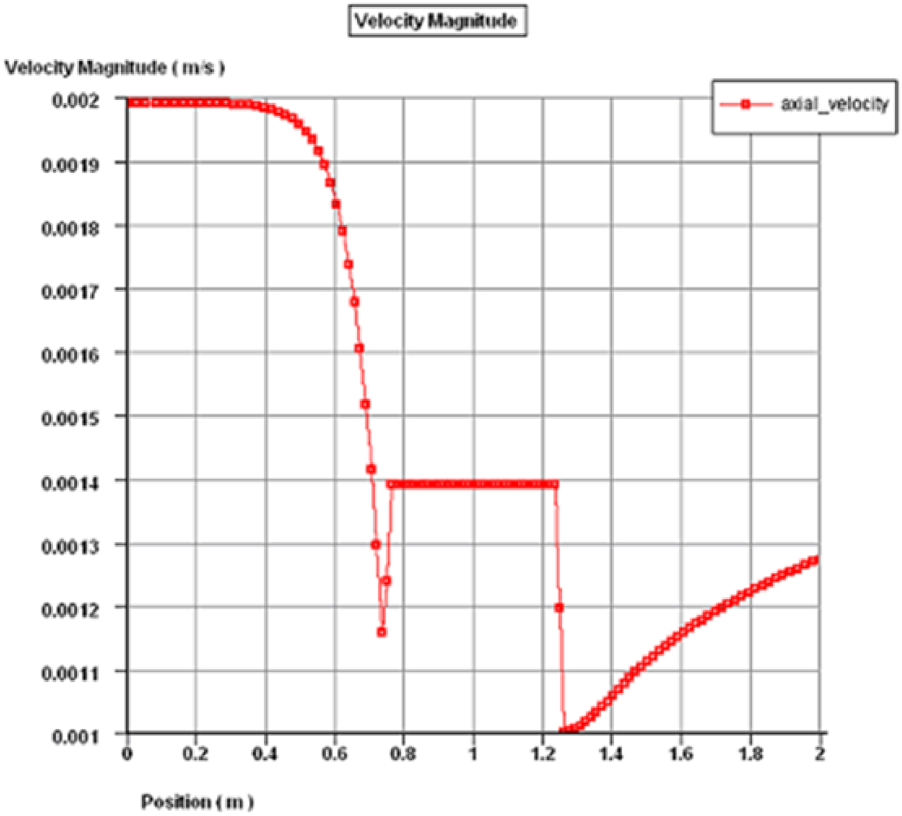

Figure 4.1: Axial Velocity Distribution

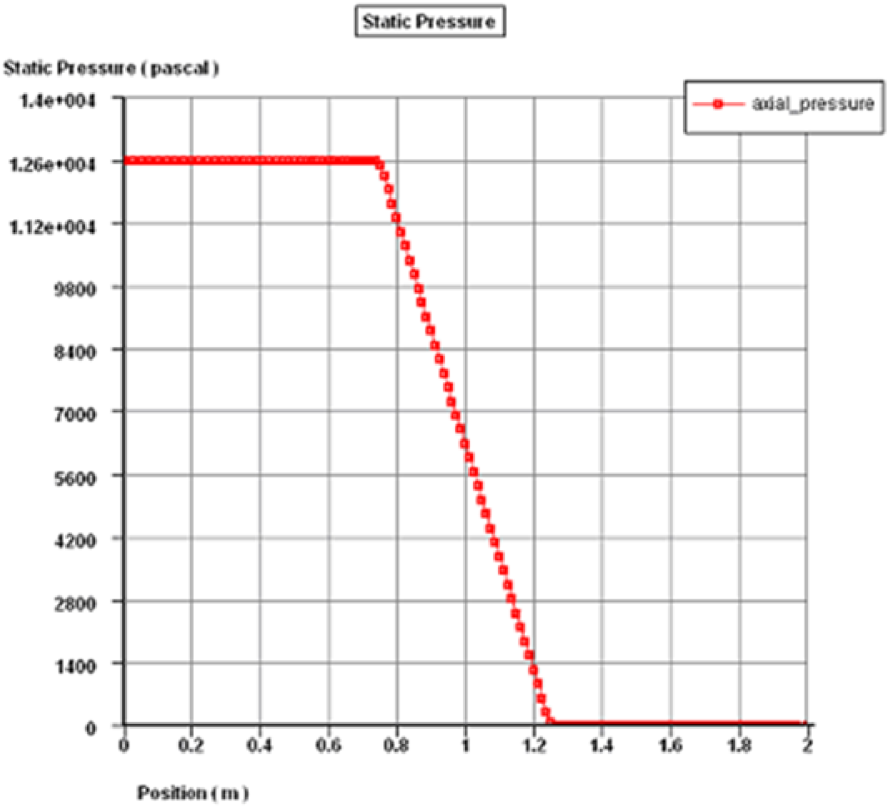

Figure 4.2: Axial Pressure Distribution

4.3 Contour Plots

Contours of velocity magnitude, x-velocity, y-velocity, turbulence intensity and dissipation rate, stream function, density, viscosity, specific heat, thermal conductivity, and temperature can be displayed. Figure 4.3 presents contours of static pressure.

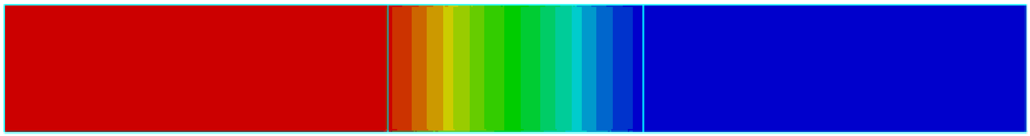

Figure 4.3: Contours of Static Pressure

4.4 Comparative Study

Figure 4.4 shows the axial pressure distribution for different porous medium lengths. It can be observed that the pressure drop increases as the length of the porous medium increases. Further, for a constant Reynolds number, the rate of pressure drop remains unchanged.

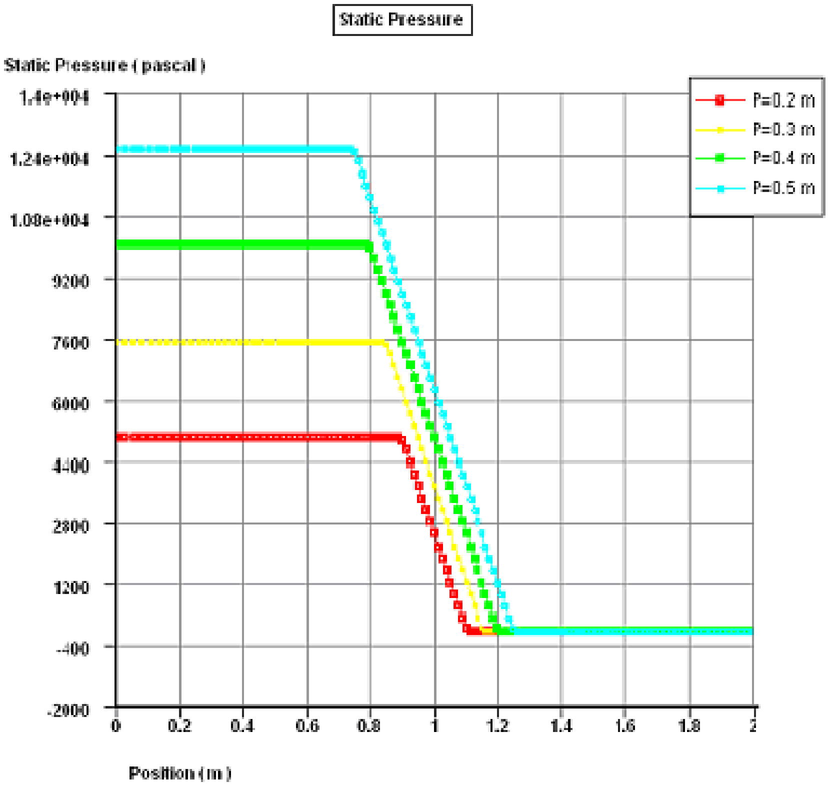

Figure 4.4: Axial Pressure Distribution for Different Porous Media Lengths

5 Verification of Results

The results for pressure drop verification are presented in Table 5.1. These results were obtained using the fine mesh option, default fluid material properties, and the following geometric dimensions:

Length of the pipe (L) = 2 m
Radius of the pipe (R) = 0.25 m
Length of the porous zone (P) = 0.5 m
Porous location (Xc) = 1 m

The mean inlet velocity was maintained constant at 0.001 m/s and the porous media properties were varied to obtain the desired pressure drop per unit length. In each run, the porosity value was set to 1.

Table 5.1 compares the pressure drop predicted by FlowLab with the theoretical prediction.

Viscous Resistance ($1/m^2$)	**Inertial Resistance (1/m)**	**Pressure drop per unit length (Pa/m)**	
		FlowLab	**Theory**
2.5e+10	700	2.48e+04	2.51e+04
1.0e+10	100	9.94e+03	1.00e+04
1.339e+11	300	1.39e+05	1.40e+05
1.56e+12	500	1.55e+06	1.56e+06
7.2e+08	1000	7.16e+02	7.23e+02

Table 5.1: Pressure Drop Verification

The theoretical pressure drop per unit length presented in Table 5.1 was predicted using the following relation:

$$\frac{\Delta p}{l} = \frac{\mu}{K} U_\infty + \frac{1}{2} c \, \rho \, U_\infty^2 \tag{5-1}$$

where,

$\frac{\Delta p}{l}$ = Pressure drop per unit length
$\frac{1}{K}$ = Viscous resistance
μ = Fluid viscosity
ρ = Fluid density
U_∞ = Mean fluid velocity
c = Inertial resistance

6 Reference

[1] *Nield, A.D. and Bejan, A.*, "Convection in Porous Media", Springer Verlag, N.Y., 1999.