Collaborative Fluid Dynamics Research: Porous Media, Microfluidics, and Bio-Flows

OU Supercomputing Symposium
Oct. 7, 2009

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Overview

Background

Simulations

Flow Through Porous Media (FTPM)
Flow in Junctions/Microjunctions
Microelbows
Entrance Length in Microtubes

Experimental

Millijunctions
Bio-Scaffolds
Renal Artery Aneurysm
Microtubes

Future Directions
Applications

Flow in microfluidic flow networks and flow in porous networks are of interest in many engineering applications. Applications include porous media, micro-power generation, biomedical, computer chips, chemical separation processes, micro-valves, micro-pumps, and micro-flow sensors.


Flow in these applications is usually laminar

Porous Media

Highly porous magnesian limestone. (www.dawntnicholson.org.uk)

Microfluidic Devices

Microfluidic Valve Structure. (http://www.cchem.berkeley.edu/sjmggrp/people/boris/boris.htm)
Artificial Porous Media

Packed Beds, Gas and Liquid Filters

Sphere sizes $\text{mm}$ to $\text{cm}$

Hold-up for chemical reaction, thermal processing, or filtering
**Basics of Porous Media**

**Low Speed Flow – Darcy's Law**

\[
\frac{\phi}{\kappa} = \frac{\mu}{\kappa} u
\]

- \(\phi\) = pressure
- \(\kappa\) = position
- \(\mu\) = viscosity
- \(\kappa\) = permeability
- \(u\) = filtration velocity

**High Speed Flow – Forschheimer's Law**

\[
\frac{\phi}{\kappa} = \frac{\mu}{\kappa} u + \rho \beta u^2
\]

- \(\rho\) = density
- \(\beta\) = Forschheimer's Coefficient

**Packed Beds – Ergun's Equation (empirical)**

\[
\frac{-\Delta p}{\Delta L} = \frac{150 \mu (1-\phi)^2}{d_p^2 \phi^3} u + \frac{175 \rho (1-\phi)}{d_p \phi^3} u^2
\]

- \(\phi\) = porosity
- \(d_p\) = mean sphere diameter
Flow Through Porous Media

Collaborative Effort with Dimitrios Papavassiliou and Henry Neeman from OU (began Fall 2004)
Simulation of Flow of Fluids through Porous Media
Flow Network Analysis

Design and Analysis of networks depends on knowledge of flow and energy losses in arbitrary branches. No systematic studies to generalize these bifurcations.
Porous Network Simulator (Collaboration with Univ. of Oklahoma)

3D Monte Carlo networks from normal, beta, or empirical distribution (pore size pdf)
Coordination Number (1, 2, 3)
number of pores entering and leaving a junction $\theta \pm 90^\circ$

Projection on the xy plane of a 3D network that has 200 entry points at x=0, porosity equal to 10% and a range of $\pm 60^\circ$ relative to the x axis and $\pm 30^\circ$ relative to the y axis.
FTPM Results

Beta vs. k for phi from 0.02 to 0.26 glass_beads

Tests from 26JUL06 and 28MAR06

- FTPM Runs 26JUL06
- beta = 6.092e-6*k^-1
- FTPM Runs 28MAR06
- Ergun’s Equation
FTPM Results

Forchheimer Coefficient versus Permeability Comparison
of Simulation to Empirical Results

- Sandstone Data of Jones
- Simulation Results (Porosity 7.3% - 24.8%)
T's and Y's – limited configurations and most are for turbulent flow


Laminar loss coefficients and elbows, reductions, contractions – much larger loss coefficients than turbulent case – strong dependence on Reynold's number.


Importance of roughness at microscale
**Problem Description**

**Stagnation Loss Coefficient**

\[ K_2 = \left[ \left( \frac{p_1}{\rho} + \frac{u_1^2}{2} \right) - \left( \frac{p_2}{\rho} + \frac{u_2^2}{2} \right) \right] \]

Parameters:
\[ \frac{d_2}{d_1}, \frac{d_3}{d_1}, \theta_2 \text{ and } \theta_3 \]
\[ f_2 \text{ (this sets } f_3) \] – (why? other literature and possibility of simulations where this is unknown initially)
Custom Code was written to:
(a) create GAMBIT journal files that instantiate the desired geometry based on existing 2D geometries.
(c) create a script that loads journal files into GAMBIT and meshes
(d) create all necessary preprocessing files for FLUENT.
(e) create post-processing files for FLUENT results and to tabulate results for a complete set of runs
Solution Methodology

2D Geometry Generalization

$L_1 = 5 d_{\text{max}}$
$L_2$ and $L_3 = 10 d_{\text{max}}$

If $d_2 > d_{\text{avg}}$,
then $r_2 = 3d_2$;
else $r_2 = 2d_2$

If $d_3 > d_{\text{avg}}$,
then $r_3 = 3d_3$;
else $r_3 = 2d_3$

$r_4 = \frac{d_{\text{max}}}{2}$

Generalized Geometry
larger and smaller outlet ducts; 2Dim. - 3Dim are underway

avoid sharp edges; 5 – 90 degrees for angles
3D Geometry – Mark I
Simulation Parameters

Re_D was maintained at constant value at the inlet duct. d_1 was 30 microns. The fluid was chosen to be liquid water at 20°C. The inlet flow velocity, u_1, was set to 0.5 m/s giving a Reynolds number of 15. Le_D = 0.06Re_D D --- gives 0.9 D for Re_D = 15. FLUENT output files contain surface averaged static pressure and magnitude of flow velocity at duct cross-sections at the duct inlets and exits.
**Duct Inlet/Outlets**

Duct inlet and exit sections considered to be where geometry of duct is the same as the downstream portion for outlets and upstream portion for inlet.
Mesh was set to 1/4 of the smallest duct. Tetrahedral mesh was used. Large number of tests were conducted to assess the ability to generalize the mesh (1/4 factor determined in this manner). Some testing was conducted to verify no change in results with change in mesh size. Inlet was specified as velocity inlet. Outlets were specified as outflow boundaries – allowing specification of flow fraction.
Numerical Methods

Finite Volume solution of integral Navier Stokes Steady-State 3D Implicit SIMPLE for pressure velocity coupling 1st order upwind scheme of momentum discretization Max number of iterations Convergence criterion = 0.1%
Parameter Values

\[
d_2/d_1 \text{ and } d_3/d_1 = 0.5, 1.0, 1.5 \\
f_2 = 0.1, 0.3, 0.5, 0.7, 0.9 \\
\theta_2 \text{ and } \theta_3 = 5^\circ, 25^\circ, 45^\circ, 65^\circ, 85^\circ
\]

600 runs attempted – 475 completed (geometry issues on remainder)

Suite of C++ procedures to create geometries, input files, read and collate results
Create GAMBIT script to create geometries
Create input files for GAMBIT and FLUENT
Read results files for static pressures and velocities averaged over surfaces in and out of junctions.
Fluent Result

\[ f_2 = 0.1, \frac{d_2}{d_1} = 0.5, \theta_2 = 5^\circ, \frac{d_3}{d_1} = 0.5, \text{ and } \theta_3 = 45^\circ \]
$f_2 = 0.1$, $\theta_2 = 45^\circ$, $\theta_3 = 45^\circ$, $d_2/d_1 = 0.5$, $d_3/d_1 = 1.5$.

$K_2 = 5.47$
$f_2 = 0.3, \theta_2 = 65^\circ, \theta_3 = 45^\circ, d_2/d_1 = 0.5, d_3/d_1 = 1.5.$

$K_2 = 11.6$
f_2 = 0.5, \theta_2=65^\circ, \theta_3=45^\circ, d_2/d_1=0.5, d_3/d_1=1.5.

K_2 = 18.4
f_2 = 0.7, \theta_2 = 65^\circ, \theta_3 = 45^\circ, d_2/d_1 = 0.5, d_3/d_1 = 1.5.

K_2 = 25.7
**2D vs. 3D Differences**

\[
\left[ \frac{k_2^{3D}}{k_2^{2D}} \right]_{\text{average}} = 1.55 \quad \text{(std. dev.)} = 0.45
\]

\[
k_2 = \frac{\Delta p/\rho}{u_1^2/2} - \frac{u_2^2}{u_1^2} + 1
\]

- pressure effects
- kinetic energy effects
3D Mark II Junction

Junction Without Surface Fills

Junction With Surface Fills
Initial Simulations – 3D Mark II

Small batch

Comparable results to original 3D runs
Pipe Mesh Testing

Flow-aligned hex core
Varied axial and radial spacing
MySQL results database
Automated
Results database easy to setup for junction runs
Pipe Mesh Testing

“Bell Shaped” Axial Spacing
Pipe Mesh Testing

Uniform Axial Spacing
Entrance Length in Microtubes

0.50*L

Uniform Inlet Profile  Fully Developed Paraboloid Profile

Circumferential Spacing
Entrance Length Results
Entrance Length Results
Loss Coefficients in Microelbows

\[ K = \frac{\Delta p}{\frac{1}{2} \rho V^2} \]
Microelbow Loss Coefficients

\[ K = \frac{\Delta p}{\frac{1}{2} \rho V^2} \]
Millijunction Experiments
Objectives:

✓ Design improved sealing method for part and increase re-usability of parts
✓ Test the new designs
✓ Document the production process
New Seal Design

We needed a seal design that would be leak-free and allow for quick and easy assembly and re-usability. The chosen design is loosely based on fuel injector seals.

New tap blocks were milled to allow for flexibility in pressure tap placement. By adapting the smaller OD tubing to ½” we can use one block design for multiple sizes of tubing. The left is the inlet block and the right is the ⅛” outlet.

Two o’rings are placed on the ends of each connecting pipe downstream from the head tank.

The existing flow straightener was reused by manufacturing an adapter that converted the threaded end to the new o’ring type. This design has the advantage that there is no time spent waiting for sealant to dry so parts can be swapped out with no down time.
Here is the Solidworks model as well as the physical realization of our efforts to create a useable bifurcation.

Upstream from the head tank and downstream from the junction are our new, highly sensitive needle valves used to adjust the head tank flow and the flow fraction through the bifurcation.

The flow straightener we designed has a replaceable core made of glass micropipettes that can be removed completely for unrestricted flow.
Data Acquisition

Jesse Haubrich
Collecting Data

Sensor
- Submersible
- Internal Instrumentation Op-Amp

Filter
- 750Hz Low Pass
- Reduces Noise from 10mV to 2mV

ADC
- 12 bit
- 11 Channel

Basic Stamp
- Easy to program
- Affordable

Computer
```python
if __name__ == '__main__':
    serial = connect_serial()
    filesave = csv.writer(open("data.csv","wb"))
    while True:
        data = serial.readline().split()
        filesave.writerow(data)
        plot(data)
```
Basic Stamp
Passive Filter
Pressure Sensors
Flow Sensors
Python Interface
Loss Coefficient Experimental Results
Using Network Simulations to Understand Non-Darcy Flow

Objectives

Develop an algorithm to create, mesh, and perform CFD on simplified models of real porous media networks.

Equal number of entry and exit pores (no splits)

$90^\circ$ elbows only

No overlap of pores within media

Compare results of CFD to FTPM and empirical data in literature.

Modify algorithm to allow for complex models of real porous media.

Splits with arbitrary angles

Overlaps
Using Network Simulations to Understand Non-Darcy Flow

Implementation of Objectives

Use custom codes to extract FTPM networks from code
Using Network Simulations to Understand Non-Darcy Flow

Implementation of Objectives

Use Solidworks to create network designs

Phase 1

90° elbows

No overlapping

Phase 2

Arbitrary angles

Possible overlaps
Using Network Simulations to Understand Non-Darcy Flow

Implementation of Objectives

Use Gambit to mesh networks

Close up of 90° elbow

Close up of arbitrary junction
Using Network Simulations to Understand Non-Darcy Flow

Implementation of Objectives

Use Fluent (CFD) to obtain $\kappa$ and $\beta$ from pressure and velocity data
Bio-Scaffold Testing
Renal Artery Aneurysm Experiments
Acknowledgments

The Office of Research and Grants at the University of Central Oklahoma is acknowledged for support of this research. The Donors of The Petroleum Research Fund, administered by the American Chemical Society, are also acknowledged for support of this research through grant PRF# 47193-B9. National Science Foundation EPSCoR Research Opportunity Award Program