Three-Dimensional Simulation of Neutral Pressure Measurement Experiments on NSTX and Alcator C-Mod

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Note: This poster is available on the Web at:
http://w3.pppl.gov/degas2/
Introduction

- NSTX considering options for 2006 particle control milestone, e.g.,
  - Cryopump,
  - Flowing liquid lithium module,
  - Lithium coatings.

- Validate 3-D DEGAS 2 Monte Carlo neutral transport simulation capability in preparation for evaluation of options.

- Progress to date:
  1. Simulate gas flow through a pipe,
     - Compare with expected conductance over range of Knudsen numbers.
  2. Benchmark against measurements of C-Mod gas conductances.
  3. Begin assembly of corresponding 3-D model of NSTX.
Summary

1. Pipe flow benchmark successful for molecular & transition regime,
   - Simulation of viscous flow limited by computational resources.

2. 3-D DEGAS 2 simulated C-Mod conductances match measured values to within factor of two.
   - Remaining differences may be due to details not simulated,
   - And / or inadequate spatial resolution.

3. Fully detailed 3-D simulations of molecular & transition regime gas flows in tokamaks possible,
   - In some case, practical with massively parallel computers.
Use Two Chamber Model To Relate Physical Quantities

\[ U_{12} \equiv \frac{Q_{12}}{(p_1 - p_2)}. \]

- Solve equations with constant \( U_{12} \), initial \( p_1, p_2 \), and \( Q_2 = 0 \),
  - For \( t \gg \frac{V_1 V_2}{U_{12}(V_1 + V_2)} \), \( p_1 - p_2 = \frac{1}{U_{12}} \frac{V_2 Q_1}{V_1 + V_2} \).

- If \( Q_2 \) due to pump of speed \( S \), \( Q_2 = S p_2 \), have steady state solution
  \[ p_1 = Q_1 \left( \frac{1}{S} + \frac{1}{U_{12}} \right); p_2 = \frac{Q_1}{S}. \]
D₂ - D₂ Collisions Only - No Plasma

- Only treating D₂ - D₂ elastic scattering,
  - Iterative, BGK treatment with \( \vec{v} \)-independent \( \langle \sigma v \rangle \),
  - Set \( \langle \sigma v \rangle = kT/\eta \) using measured viscosities \( \eta \).

- Molecules striking walls absorbed / desorbed with 100% recycling,

- Sample desorbed molecules with 300 K Maxwell flux distribution.

- Gas source also 300 K, Gaussian in energy, cosine in angle.
Use Simple Pipe Flow Case to Validate DEGAS 2 Physics & Illustrate Conductance Changes with Flow Regime

• Flow regime characterized by Knudsen number $K = \frac{\lambda}{d}$,

  – $K \gtrsim 1 \Rightarrow$ “molecular flow” regime, $U_{12} \propto p^0$,

  – $K \lesssim 0.01 \Rightarrow$ “viscous flow” or “continuum” regime, $U_{12} \propto p^1$,

  * Subdivided into “viscous laminar” ($\mathcal{R} < 1200$) & “turbulent”.

  – In between: “transition” regime.
Consider flow through 0.205 m long, 0.1 m square pipe,

- Molecular flow: \( U_{mf} = A \frac{v}{4} W \),

- Long pipe viscous flow governed by Poiseuille equation:
  \[
  U_{vf} = \frac{1}{12\eta} \frac{a^2 b^2}{L} \bar{p} Y.
  \]
  * Use \( U \) definition and \( p_2 = Q_1/S \) to get \( U_{vf}(Q_1) \).

  * For these simulations, correction for finite pipe length \( \lesssim 15\% \).

- Knudsen gave an empirical fit for transition conductance,
  * But, not directly applicable here,

  * Instead, plot shows smooth curve connecting limiting expressions.
Comparison of Simulated & Predicted Pipe Conductances

Multiple points at a $Q_1$ show $U_{12}$ increasing with spatial resolution

(a) Conductance

(b) Knudsen Number

Viscous Flow
Molecular Flow
Simulation
Transition

Viscous
Molecular
Velocity Shear Across Pipe Center in Q₁ = 0.4 Simulation

\[ \rightarrow = 81 \text{ m/s} \]
Code Works Well for Molecular Flow / into Transition Regime; Denser Flows More Difficult

- Low $Q_1$ results agree with $U_{mf}$ to within 2%.

- Have viscous flow for $Q_1 > 40$ Pa-m$^3$/s.

- Points at $Q_1 = 0.4$ have 16, 64, and 256 zones spanning pipe cross section,
  - Impacts $U$ because need to resolve flow shear across pipe,
  - Finer resolution runs do not differ significantly $\Rightarrow$ adequate resolution.

- Appears to affect $Q_1 = 4.$ case even more strongly,
  - Points shown have 64 and 256 zones, neither is adequate.
C-Mod Conductance Measurements Provide Good Validation Data

- Install gas capillaries & pressure gauges to measure flow out of “open” and “closed” divertor ports,
  - “Closed”: main flow through slot under outer divertor,
  - “Open”: divertor plate / tiles removed for diagnostic access.
- Puff gas into gas box,
  - Calibrate $Q_1$ from $dp_2/dt$ in main chamber & known torus volume,
  - Measure $p_1$ at bottom of pumping port,
  - Take $p_2$ in main chamber,
  - $\Rightarrow$ compute $U_{12}$.
- Note that conductances hold steady as pressures rise.
Plan View of C-Mod Lower Divertor
DEGAS 2 Polygons Overlaid on C-Mod Closed Port Cross Section

- Top Pumping Port
- Gas Plate
- Poloidal Gap
- Gas Box / Mounting Hardware
- Gas Source
- Bottom Pumping Port
Experimentally Pressures Rise Linearly
Conductances Hold Steady
Use Pie Slice Model to Describe Toroidal Variation of C-Mod Hardware

- Represents modest extension of existing 2-D geometry setup tools.

- Principal toroidal variation:
  - Vertical pumping ports: $6^\circ$ wide, to $Z = \pm 1.9$ m,
  - Divertor mounting hardware: $6^\circ$ wide solid on either side of ports,
  - Vacuum elsewhere: gas box.
  - Outer divertor plate / tiles: solid except $6^\circ$ gaps at “open” ports & 3 mm gaps at “closed” ports.

- Also have 0, 2, or 4 mm gap at top of gas box.

- 10% sink at top of upper ports ⇒ steady state simulations.
Visualization of Open Port Simulated Neutral Pressure

Visualization by S. A. Klasky
Visualization of Closed Port Simulated Neutral Pressure

Visualization by S. A. Klasky
### Compare Simulated & Measured Pressures & Conductances

<table>
<thead>
<tr>
<th>Run</th>
<th>$p_1$ (Pa)</th>
<th>$p_2$ (Pa)</th>
<th>$Q_1$ (Pa·m$^3$/s)</th>
<th>$U_{12}$ (m$^3$/s)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open</td>
<td>1.46</td>
<td>1.22</td>
<td>1.86</td>
<td>7.8</td>
<td>16%</td>
</tr>
<tr>
<td>Open - expt.</td>
<td>1.46</td>
<td>1.05</td>
<td>1.86</td>
<td>4.5</td>
<td>-</td>
</tr>
<tr>
<td>Closed (base)</td>
<td>3.7</td>
<td>1.29</td>
<td>1.99</td>
<td>0.83</td>
<td>8.6%</td>
</tr>
<tr>
<td>Closed - expt.</td>
<td>3.7</td>
<td>2.04</td>
<td>1.99</td>
<td>1.2</td>
<td>-</td>
</tr>
<tr>
<td>2 mm pol. gap</td>
<td>3.9</td>
<td>1.30</td>
<td>1.99</td>
<td>0.76</td>
<td>3.9%</td>
</tr>
<tr>
<td>Reduce source</td>
<td>0.26</td>
<td>0.085</td>
<td>0.124</td>
<td>0.71</td>
<td>2.8%</td>
</tr>
</tbody>
</table>

(“Experimental” $p_2$ values computed from measured $U_{12}$, $Q_1$, and simulation $p_1$.)
Discussion of C-Mod Benchmark

- Fully detailed 3-D simulations of molecular and transition regime gas flows in tokamaks possible,

- Practical given inexpensive CPUs: baseline closed port case took 41 hours on 30 1.7 GHz AMD Athlon processors,
  - $\leq 10^5$ flights, 56,659 zones.

- Simulated “open” & “closed” conductances agree with measurements to within factor of 2.

- Consider remaining differences,
  - One too high, one too low $\Rightarrow$ still missing important details in geometry & experimental arrangement?
  - Pipe flow results suggest examining spatial resolution in gaps.
Neutral pressures surprisingly insensitive to plasma density,

Begin examining 3-D gas conductance pathways in search of explanations.

This work will feed into cryopump design effort.

Have laid out on paper approximate 3-D component configuration,

- Need more suitable engineering drawings!

Have done initial axisymmetric simulation,

Currently building 3-D DEGAS 2 geometry.
NSTX Vacuum Vessel
Full of 3-D Gas Pathways
DG File for DEGAS 2
Simulation of NSTX
Neutral Pressures in Axisymmetric NSTX Simulation

[Graph showing neutral pressures in an axisymmetric NSTX simulation, with color-coded pressure maps for D and D2 pressures.]