Compressible gas flow through micro-capillary fill-tubes on NIF targets - modeling and experiments

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Compressible gas flow through micro-capillary fill-tubes on NIF targets- modeling and experiments

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NIF targets have two separate chambers (capsule/hohlraum) which are pressurized using filltubes

- Fill tubes supply gases to the two chambers – capsule and hohlraum
  - Capsule fill tube specification: 5µm inner dia
  - Small volume

- Fill tubes need to be about 115mm long and be flexible

- Hohlraum filltubes
  - 75µm ID x 150µm OD polyimide coated silica capillary

- Composite tube for capsule
  - Majority of length is 30µm ID x 150µm OD polyimide coated silica
  - A 5µm borosilicate capillary penetrates the capsule to meet the physics specs
Impedance to flow due to the small diameters of the capillaries presents a few challenges

- Knowing the changes in pressure and composition inside the capsule or hohlraum due to temperature or pressure variations on the outside
- Sharp pressure differentials across the hohlraums can stretch or damage 500nm thick LEH windows
- Condensation of ice or debris on the inside can easily plug the capillaries
- Flow of permeated tritium out of the hohlraum

Importance of Response Time

LEH window
Extending the Hagen Poiseuille equation for compressible fluid flow through a tube

Limit to:

- Low Reynolds number regime
  - Fully developed laminar flow
  - Small $\beta = R/L$ (inner radius/length)
- Small pressure drops
  - Small $\varepsilon = (P_0 - P_L)/P_0$, where $P_0$ & $P_L$ are pressures at lengths 0 and L
  - In the limit, we get Hagen-Poiseuille equation
- Chose a perturbation based solution by Prud’homme et al*

Volumetric flow-rate $Q$:

$$Q = \frac{\pi (P_0 - P_L) R^4}{8 \mu L} \left[ 1 - \frac{1}{2} \varepsilon - (0.02919 \kappa) \varepsilon \beta + (0.02919 \kappa) \varepsilon^2 \beta + \left( \frac{2}{3} + 0.00227 \kappa^2 \right) \varepsilon^2 \beta^2 + ... \right]$$

where $\mu$ is viscosity, $\rho_0$ is the mass density at $P_0$ and $\kappa = R^3 \rho_0 (P_0 - P_L)/L \mu$

We are interested in the gas composition and pressure in the two chambers within the target.

For a chamber with volume $V_c$ at pressure $P_c$ and containing $n_c$ moles:

$$\frac{dn_c}{dt} = \frac{n_c(t)}{V_c} Q(n) \quad \text{or} \quad \frac{dP_c}{dt} = \frac{P_c}{V_c} Q$$

$$\ln(P_c) + Const = \frac{Q}{V_c} t$$

**Evacuation of air from target:**

Pressure vs time profile

- **Evacuation Profiles**
  - *Cap***ule
  - Hohl thru 1 line
  - Hohl thru 2 lines
A baratron with a fixed known volume can be used to generate pressure vs time data to verify model.

\[ V_{\text{baratron}} = 3.4 \text{ccs} \]

Pressure: measured data vs simulation

75µm ID, 115mm long

Data vs Model
Transition region between continuum flow and free molecular flow

- Continuum flow model deviates at $K_n$ (Knudsen number) of about 0.005
  - $K_n$ is the ratio of molecular mean free path $\lambda$ to capillary diameter $D$
- $K_n$ is no high enough to consider free molecular flow, instead points to transition region
- Deviation increases with increasing $K_n$
  - Model that account for transition flow using $K_n$
Slip flow model for flow behavior at low pressures before onset of free molecular flow

- Viscous flow uses a no slip boundary condition at the wall
  - But Navier Stokes equation ceases to be valid as $K_n > 0.01$
- For free molecular flow (neglect intermolecular collisions), incident and reflected tangential velocities are equal
- In between, invoke a slip flow model, with a small but non-zero tangential wall velocity

\[
Q = \frac{\pi(\Delta P)R^4}{8\mu L} \left[ 1 - \frac{1}{2} \varepsilon - (0.02919\kappa)\varepsilon\beta + \ldots \right] \left( 1 + 4 \left( \frac{2}{f_s} - 1 \right) \frac{\lambda}{R} \right)
\]

where $f_s$ is the fraction of molecules impinging on the walls of the tube

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Using slip flow equation

Unraveling slip flow parameters – effect of molecular diameter

- Slip flow has two parameters that need to be specified
  - $f_s$,
  - hard sphere molecular diameter $d$, for calculation of $\lambda$

- Since air is mixed fluid, $d$ is best specified for single component gases

- We find that $f_s$ is constant

<table>
<thead>
<tr>
<th></th>
<th>d (Å)</th>
<th>$f_s$</th>
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<td>0.43</td>
</tr>
<tr>
<td>Ar</td>
<td>4.0</td>
<td>0.43</td>
</tr>
<tr>
<td>Air</td>
<td>4.57</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Some important conclusions from application of slip flow model to the capillary flow data

- $f_s$, the fraction of molecules impinging on the walls of the tube is consistently 0.43 @ RT
  - For capillaries of different dia
  - For different gases

- Slip flow model fits the data for a large range of $K_n$
  - from 0.005 to 18
  - at higher $K_n$, it approaches free molecular flow

- Data here indicates that conventional free molecular flow equation ($K_n > 1$) over-predicts the flow
Slip flow model can be used for flow at cryogenic temperatures as well

- Gases flow faster at lower temperatures as
  - Lower viscosity
  - Greater density

- Model takes into account two temperature zones
  - RT for baratron
  - Cryogenics temp for the capillary

- Viscosities from NIST for Helium can be used get an exact fit to the cryogenic data
Accounting for changing radii

- Fill tubes used on NIF targets are combinations of tubes of different diameters and lengths.

- For a conical tube, with inner radii $R_0$ and $R_L$ and length $L$:
  \[
  R_{\text{eff}} = R_0 \left[ \frac{3\alpha^3}{1 + \alpha + \alpha^2} \right]^{0.25}
  \]
  where $\alpha = R_0 / R_L$.

- For two tubes of inner radii $R_1$ and $R_2$ and lengths $L_1$ and $L_2$:
  Let $x = L_2 / L_1$; then
  \[
  Q = \frac{\pi (\Delta P) R_1^4}{8 \mu L} \left( \frac{x}{R_2^4 + xR_1^4} \right) [1 - \frac{1}{2} \varepsilon - (0.02919\kappa)\varepsilon\beta + (0.02919\kappa)\varepsilon^2 \beta + ...]
  \]
Verification of the model for composite and conical tubes

Composite fill-tube for capsule

Composite tube - data vs model

Pressure (torr)

Time (min)
Model can be used to predict rate permeation of He from the polymeric films on the target

- Permeation depends on pressure
  - Pressure depends on capillary conductance

- Permeation is instantaneous compared to filling through capillary
Extending the model to a dual chamber system allows prediction of the return line pressure.

Cascading flow model

- Once the volumes are known, we can accurately model the return line pressure and therefore the conditions in the hohlraum.

Data from target on NIF

- 

\[ V_H \sim 0.3 \text{ ccs} \]
Summary

• Model has been set-up and validated to predict the flow through micro-capillaries
  — Covers the range of pressures
    - Continuum to molecular flow
  — Accounts for composite capillaries connected to a series of chambers
  — Extends to cryogenic temperatures

• Data suggests that
  — Modified Hagen Poiseuille equation can be used for simulating viscous flow of compressible fluids for low $\Delta P$
  — Slip flow extends to Knudsen numbers to at least 18
  — Data yields a consistent fraction of molecules reflecting specularly from the walls- 0.43 to 0.51

• This can be used to predict the hohlraum and capsule pressures and compositions for various external perturbations