Modeling of Inertial Fusion Chamber

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Why We Need Chamber Modeling

• Key IFE chamber uncertainty is whether or not the chamber environment will return to a sufficiently quiescent and clean low-pressure state following a target explosion to allow a second shot to be initiated within 100–200 ms
  - Target and driver requirement on chamber conditions prior to each shot

• Chamber condition following a shot in an actual chamber geometry is not well understood
  - Dependent on multiple processes and variables
  - A predictive capability in this area requires a combination of computer simulation of increasing sophistication together with simulation experiments to ensure that all relevant phenomena are taken into account and to benchmark the calculations

• The proposed modeling effort includes:
  - Scoping calculations to determine key processes to be included in the code
  - Development of main hydrodynamic code
  - Development of wall interaction module
Chamber Dynamics

Cavity Gas, Target, and Wall Species

Time of flight to wall:
X-rays  ~20 ns
Neutrons ~100 ns
Alphas  ~400 ns
Fast Ions ~1 µs
Slow Ions ~1-10 µs

- Photon transport & energy deposition
- Ion transport & energy deposition
- Heating & ionization
- Radiation
- Gas dynamics (shock, convective flow, large gradients, viscous dissipation)
- Condensation
- Conduction
- Cavity clearing

Timescale: ns to 100 ms

Chamber Wall Interaction

- Photon energy deposition
- Ion energy deposition
- Neutron & α energy deposition
- Conduction
- Melting
- Vaporization
- Sputtering
- Thermo-mechanics/ macroscopic erosion
- Radiation damage
- Blistering (from bubbles of implanted gas)
- Desorption or other degassing process

Timescale: ns to 100 ms

Coolant

- Convection & cooling
  Timescale: ms
Scoping Calculations Were First Performed to Assess Importance of Different Effects and Conditions

• **Chamber Gas**
  – At high temperature (> ~ 1 ev), radiation from ionized gas can be effective
  – In the lower temperature range (~ 5000K back to preshot conditions)
    • Conduction (neutrals and some electrons)
    • Convection
    • Radiation from neutrals
    • Other processes?
  – The temperature of the gas might not equilibrate with the wall temperature
    • May have implications for target injection
Effectiveness of Conduction Heat Transfer to Cool Chamber Gas to Preshot Conditions

- Simple transient conduction equation for a sphere containing gas with an isothermal boundary condition ($T_w$)
  - $k_{Xe}$ is poor (~0.015 W/m-K at 1000K, and ~0.043 W/m-K at 5000 K)
  - At higher temperature electron conductivity of ionized gas in chamber will help
    (assumed ~ 0.1 W/m-K for $n_e = n_o$ and 10,000 K)
  - Argon better conducting gas

- $T$ decreases from 5000K to 2000K in ~2 s for $k_g = 0.03$ W/m-K

- Even if $k_g$ is increased to 0.1 W/m-K, it does not help much (~ 0.6 s)

Temperature History Based on Conduction from 50 mTorr Gas in a 5 m Chamber to a 1000K Wall

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Effectiveness of **Convection** Heat Transfer to Cool Chamber Gas to Preshot Conditions

- Simple convection estimate based on flow on a flat surface with the fluid at uniform temperature
- Use Xe fluid properties
- Assume sonic velocity
  - $c \approx 500 \text{ m/s}$
  - $Re \approx 700$ for $L = 1 \text{ m}$
  - $Nu \approx 13$
  - $h \approx 0.4 \text{ W/m}^2\text{-K}$
- Lower velocity would result in lower $h$ but local eddies would help
  - Set $h$ between 0.1 and 1 W/m$^2$-K representing an example range
- $T$ decreases from 5000K to 2000K, in ~0.1 s for $h = 0.4 \text{ W/m}^2\text{-K}$
- Increasing $h$ to 1 W/m$^2$-K helps but any reduction in $h$ rapidly worsens the situation (e.g. ~0.4 s for 0.1 W/m$^2$-K)
Effectiveness of **Radiation Heat Transfer to Cool Chamber Gas from Mid-level Temperature (~5000K) to Preshot Conditions**

- Xe is monoatomic and has poor radiation properties
  - Complete radiation model quite complex
  - Simple engineering estimate for scoping calculations
  - No emissivity data found for Xe
  - Simple conservative estimate for Xe using CO$_2$ radiation data

- T decreases from 5000K to 2000K, in ~1 s
  (would be worse for actual Xe radiation properties)

\[ q_r'' = \sigma \varepsilon_w (\varepsilon_g T_g^4 - \alpha_g T_w^4) \]

**Temperature History Based on Radiation from 50 mTorr Gas in a 5 m Chamber to a 1000K Wall**

For CO$_2$ at 2000 K, $\varepsilon_g \sim 10^{-5}$

$\alpha_g \sim \varepsilon_g$ at $T_w$ (1000 K); $\alpha_g \sim 10^{-4}$
Effectiveness of Heat Transfer Processes to Cool Chamber Gas (Xe) to Preshot Conditions is Poor

Conservative estimate of Xe temperature (K) following heat transfer from 5000K

<table>
<thead>
<tr>
<th>Time:</th>
<th>0.1 s</th>
<th>0.2 s</th>
<th>0.5s</th>
<th>~1 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conduction:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>k=0.03 W/m-K</td>
<td>4700</td>
<td>4500</td>
<td>3600</td>
<td>2700</td>
</tr>
<tr>
<td>k=0.1 W/m-K</td>
<td>3900</td>
<td>3200</td>
<td>2200</td>
<td>1500</td>
</tr>
<tr>
<td>Convection:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h=0.1 W/m²-K</td>
<td>3800</td>
<td>3000</td>
<td>1650</td>
<td>1200</td>
</tr>
<tr>
<td>h=0.4 W/m²-K</td>
<td>1950</td>
<td>1220</td>
<td>~1000</td>
<td>~1000</td>
</tr>
<tr>
<td>h=1 W/m²-K</td>
<td>1250</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xe Radiation: (assum. CO₂ ε and α)</td>
<td>3500</td>
<td>2850</td>
<td>2300</td>
<td>2200</td>
</tr>
</tbody>
</table>

• It seems that only possibility is convection with high velocity and small length scales (optimistic requiring enhancement mechanisms) and/or appreciable gas inventory change per shot (by pumping)

• Background plasma in the chamber might help in enhancing heat transfer (e.g. electron heat conduction, recombination)
Chamber Physics Modeling

- **Energy Equations**
  - Condensation
  - Radiation transport
- **Momentum Conservation Equations**
  - Pressure (T)
  - Viscous dissipation
  - Wall momentum transfer (impulse)
- **Mass Conservation Equations**
  - Condensation
  - Aerosol formation
  - Evaporation
  - Sputtering
  - Other mass transfer
  - Condensation
- **Phase change**
  - Energy deposition
- **Convection**
  - Pressure (T)
- **Conduction**
  - Thermal capacity
- **Thermal stress**
  - Thermal shock
  - Stress/strain analysis
- **Evacuation**
- Source
- Chamber Region
- Wall Region

Driver beams

Energy input

Momentum input

Mass input

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Numerical Modeling of IFE Chamber Gas Dynamics

- **Build Navier-Stokes solver for compressible viscous flow**
  - Second order Godunov algorithm.
  - Riemann solver used as a form of upwinding.
- Progressive approach
  - 1-D --> 2-D
  - inviscid --> viscous flow
  - rectangular geometry --> 2-D and 3-D arbitrary geometry (to be done)
  - grid splitting into sub-domains for multi-geometry modeling

- **Perform code verification**
  - 1-D and 2-D acoustic wave propagation
  - Conservation laws
Example Case to Illustrate Code Capability: Square Chamber Cavity With a Rectangular Beam Channel – Centered Initial Disturbance

- Inviscid flow
- Initial pressure and density disturbance centered, zero velocity field
- Reflective wall boundary conditions
- Ambient Xe \((T = 800K, \rho = 1.3028 \times 10^{-4} \text{ kg/m}^3, p = 7.857 \text{ Pa})\)
Comparison Between Viscous and Inviscid Flow for Example Xe Case

Inviscid

\[ v_{\text{max}} = 0.0975 \, \text{m/s} \]
\[ p_{\text{max}} = 7.86 \, \text{Pa} \]
\[ \rho_{\text{max}} = 1.3032 \times 10^{-4} \, \text{kg/m}^3 \]

The effect of viscosity is significant.

Viscous

\[ v_{\text{max}} = 0.0078 \, \text{m/s} \]
\[ p_{\text{max}} = 7.8573 \, \text{Pa} \]
\[ \rho_{\text{max}} = 1.3035 \times 10^{-4} \, \text{kg/m}^3 \]
Wall Interaction Module Development

- Ion and photon energy deposition calculations based on spectra
  - Photon attenuation based on total photon attenuation coefficient in material
  - Use of SRIM tabulated data for ion stopping power as a function of energy
- Transient Thermal Model
  - 1-D geometry with temperature-dependent properties
  - Melting included by step increase in enthalpy at MP
  - Evaporation included based on equilibrium data as a function of surface temperature and corresponding vapor pressure
    - For C, sublimation based on latest recommendation from Philipps
- Model calibrated and example cases run
- To be linked to gas dynamic code
Other Erosion Processes to be Added (ANL)

- Scoping analysis performed
  - Vaporization, physical sputtering, chemical sputtering, radiation enhanced sublimation

These results indicate need to include RES and chemical sputtering for C (both increase with temperature)

Physical sputtering relatively less important for both C and W for minimally attenuated ions (does not vary with temperature and peaks at ion energies of ~ 1keV)

Plots illustrating relative importance of erosion mechanisms for C and W for 154 MJ NRL DD target spectra
Chamber radius = 6.5 m.
Example Cases Run for 154 MJ NRL Direct Drive Target Spectra

Photons

Fast Ions

Debris Ions
Spatial Profile of Volumetric Energy Deposition in C and W for Direct Drive Target Spectra

- Tabulated data from SRIM for ion stopping power used as input

Energy Deposition as a Function of Penetration Depth for 154 MJ NRL DD Target

Energy Deposition as a Function of Penetration Depth for 401 MJ NRL DD Target

C density = 2000 kg/m³
W density = 19,350 kg/m³
Spatial and Temporal Heat Generation Profiles in C and W for 154MJ Direct Drive Target Spectra

Temporal and Spatial Profile of Ion Power Deposition in C Armor from 154 MJ DD Target Spectrum

Temporal and Spatial Profile of Ion Power Deposition in W Armor from 154 MJ DD Target Spectrum

Assumption of estimating time from center of chamber at \( t = 0 \) is reasonable based on discussion with J. Perkins and J. Latkowski
Temperature History of C and W Armor Subject to 154MJ Direct Drive Target Spectra with No Protective Gas

- Initial photon temperature peak is dependent on photon spread time (sub-ns)

- For a case without protective gas and with a 500°C wall temperature:
  - C $T_{\text{max}} < 2000^\circ$C
  - W $T_{\text{max}} < 3000^\circ$C
  - Some margin for adjustment of parameters such as target yield, chamber size, coolant temperature and gas pressure
Future Effort Will Focus on Model Improvement and on Exercising the Code (1)

• Exercise code:
  - Investigate effectiveness of convection for cooling the chamber gas
  - Assess effect of penetrations on the chamber gas behavior including interaction with mirrors
  - Investigate armor mass transfer from one part of the chamber to another including to mirror
  - Assess different buffer gas instead of Xe
  - Assess chamber clearing (exhaust) to identify range of desirable base pressures
    - Assess experimental tests that can be performed in simulation experiments

• Improve Code
  - Extend the capability of the code (full inclusion of multi-species capability)
  - Implement adaptive mesh routines for cases with high transient gradients and start implementation if necessary
  - Implement aerosol formation and transport models (INEEL)
  - Implement more sophisticated mass transport models in wall interaction module (ANL)