Dynamics of Liquid-Protected Fusion Chambers

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Outline: Thick liquids can replace fusion materials questions with fluid mechanics questions

• The scaling basis for understanding and predicting thick-liquid IFE chamber performance
• Recent progress
  – RPD 2002
  – Chamber gas dynamics
  – Molten salt vapor pressure
    » Liquid disruptions
• Vortex flows and vortex chambers
• Power conversion for fusion chambers
IFE system phenomena cluster into distinct time scales

• Nanosecond IFE Phenomena
  – Driver energy deposition and capsule drive (~30 ns)
  – Target x-ray/debris/neutron emission/deposition (~100 ns)

• Microsecond IFE Phenomena
  – X-ray ablation and impulse loading (~1 µs)
  – Debris venting and impulse loading (~100 µs)
  – Isochoric-heating pressure relaxation in liquid (~30 µs)

• Millisecond IFE Phenomena
  – Liquid shock propagation and momentum redistribution (~50 ms)
  – Pocket regeneration and droplet clearing (~100 ms)
  – Debris condensation on droplet sprays (~100 ms)

• Quasi-steady IFE Phenomena
  – Structure response to startup heating (~1 to $10^4$ s)
  – Chemistry-tritium control/target fabrication/safety ($10^3$-$10^9$ s)
  – Corrosion/erosion of chamber structures ($10^8$ sec)

Principal focus for IFE Technology R&D...
Validation of the gas dynamics code TSUNAMI through LLNL’s Condensation Debris Experiment

Experimental and numerical results are in good qualitative and quantitative agreement
Gas dynamics studies address key design issues and support novel beam lines and thick-liquid chambers

- Beam and target propagation sets stringent requirements for the background gas density and the cleanliness of the beam tubes.
- Thick-liquid structure response mostly determined by gas dynamics.

The TSUNAMI code has been tailored to model ablation and venting phenomena in thick-liquid chambers.
Scaled water experiments are demonstrating the capability to form the jets used in RPD-2002

- High-Re Cylindrical Jets
- Vortex Layers for Beam Tubes
- Oscillating Voided Liquid Slabs

Re = 100,000

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**Penreco® Drakesol® 260 AT** light mineral oil allows molten salt scaled experiments with low distortion

<table>
<thead>
<tr>
<th>Adjustable Parameters</th>
<th>Oil Temperature</th>
<th>Flibe at 600°C</th>
<th>Flibe at 900°C</th>
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<td>Length-Scale</td>
<td>( \frac{L_s}{L_p} )</td>
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<td>Velocity-Scale</td>
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<td>( \Delta T )-Scale</td>
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<td>Froude Number</td>
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<td>Prandtl Number</td>
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<td>Nusselt Number</td>
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<td>Pumping Power</td>
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<tr>
<td>Heating Power</td>
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</table>
Millisecond phenomena

UCB is now doing detailed experimental measurements of turbulence and surface topology in vortex tubes
Millisecond phenomena

Particle image velocimetry is providing detailed velocity and turbulence information

- Ar CW laser allows visualization of micron particles
- Water has been replaced by Mineral Oil for improved visualization
- Evidence for intense turbulence at small length scales

Layer vorticity structure

200 µs exposure time

1000 µs exposure time

If surface-renewal frequency is 1 kHz, 2MW/m² is possible with a surface temperature 50°C greater than bulk temperature

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Millisecond phenomena

**Modular solenoid HIF chamber could potentially use a large-scale vortex flow**

- **Issues:**
  - Using injection and suction to maintain vortex flow on substrate with non-uniform radius
  - Response of liquid layer to x-ray ablation (surface waves, substrate stresses, droplet ejection)
  - Effects of turbulent surface renewal on surface temperature and condensation
A large variable recirculation flow loop was constructed

- Pump is rated for 500-gpm at 300-ft of head
- Thanks to the frequency controller, the flow rate can be accurately varied between 0 and ~4000-gpm
An improved device was constructed, based on the previous experiment

- A test device was fabricated from a segment of cylindrical pipe (25.4-cm diameter, 14-cm wide)
- Injection and suction holes were fabricated with precision
- Eight pressurized plenums provided blowing flow
- Perforations between injection plenums provided suction
  - \( A_{\text{suction}} = 2A_{\text{injection}} \)
- End walls produced modest non-ideality

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2-mm diameter injection hole
4-mm diameter suction hole
Millisecod phenomena

**Different layer thicknesses have been obtained with Froude number as low as 3**

- $\delta/R = 5\%$
- $Fr = U^2/gR = 13.6$
- $Re = UR/\nu = 5 \cdot 10^5$

- the layer is inhomogeneous, due to sharp angle of injection
  hexagon shape layer

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Different layer thicknesses have been obtained with Froude number as low as 3, cont

- $\delta/R = 20\%$
- $Fr = 3.6$
- $Re = 3 \cdot 10^5$ (\sim 20\% of prototype)

- $\delta/R = 28\%$
- $Fr = 3.7$
- $Re = 3 \cdot 10^5$ (\sim 20\% of prototype)
Millisecond phenomena

Based on the previous experiment a new modular nozzle will be developed

- the new modular nozzle will have 8 to 12 interchangeable modules to study the influence of the injection and suction angles
  the injection will be homogeneously distributed over the circumference
- the modules will be built with rapid prototyping
- D-shape complex geometries (tokamak like) will also be investigated
Quasi-steady phenomena

UCB has completed a pre-conceptual design study for a MCGC power conversion system

- Pre-conceptual design allows comparison of “molten coolant gas cycle (MCGC)” versus gas-cooled reactor power conversion
  - Based on GT-MHR PCU design
  - Includes detailed calculations for MS-to-He heat exchangers
- Results for high-temperature design
  - 2400 MW(t)
  - 900°C turbine inlet temp.
  - 54% thermal efficiency
  - 1300 MW(e)
- Power density comparison
  - GT-MHR: 230 kW(e)/m³
  - MCGC: 360 kW(e)/m³
  - Additional MCGC savings expected due to non-nuclear grade turbine building

Quasi-steady phenomena

A scaled comparison of the 1380 MWe ABWR turbine building and ~1300 MWe MCGC equipment

ABWR

He-MCGC

• MCGC turbine building must also contain crane, turbine laydown space, compressed gas storage, and cooling water circulation equipment

• MCGC requires ~1100 MWt of cooling water capacity, compared to 2800 MWt for ABWR

The MCGC can likely achieve a substantial reduction of the turbine building volume
Conclusions

• Substantial progress has been made in understanding thick-liquid IFE chamber response

• Vortex flows are interesting and have substantial promise
  – Potential for very high surface heat fluxes
  – Issues:
    » droplet ejection from surface
    » effects of ablation impulse loading
    » control of flow for complex geometries

• The Next Generation Nuclear Plant will advance and demonstrate key fusion chamber technologies
  – advanced materials
  – molten salt heat transfer fluids
    » materials compatibility
    » target debris recovery
  – helium Brayton cycle power conversion
  – tritium safety and management