Hydrodynamics of Liquid Protection schemes for IFE Reactor Chambers

S. I. Abdel-Khalik and M. Yoda

IAEA Meeting - Vienna (November 2003)

G. W. Woodruff School of Mechanical Engineering
Atlanta, GA 30332–0405 USA
OUTLINE

• Introduction – Problem Definition
  ▪ Description of Liquid Protection Concept

• The Wetted Wall Concept
  ▪ Numerical Studies
  ▪ Experimental Verification

• Forced Liquid Film Concept

• Thick Oscillating Slab Jets (HYLIFE) Concept
Prometheus: 0.5 mm thick layer of liquid lead injected normally through porous SiC structure
Prometheus: Few mm thick Pb “forced film” injected tangentially at >7 m/s over upper endcap

~ 5 m

Injection Point

First Wall

Detachment Distance $x_d$

Forced Film

X-rays and Ions
Turbulent Liquid Sheets

**HYLIFE-II:** Use slab jets or liquid sheets to shield IFE chamber first walls from neutrons, X-rays and charged particles.

- Oscillating sheets create protective pocket to shield chamber side walls
- Lattice of stationary sheets (or cylindrical jets) shield front/back walls while allowing beam propagation and target injection

*Pictures courtesy P.F. Peterson, UCB*
Thin Liquid Protection

Major Design Questions

- Can a stable liquid film be maintained over the entire surface of the reactor cavity?

- Can the film be re-established over the entire cavity surface prior to the next target explosion?

- Can a minimum film thickness be maintained to provide adequate protection over subsequent target explosions?

Study wetted wall/forced film concepts over “worst case” of downward-facing surfaces
Numerical Simulation of Porous Wetted Walls

Summary of Results

Quantify effects of

- injection velocity $w_{in}$
- initial film thickness $z_o$
- Initial perturbation geometry & mode number
- inclination angle $\theta$
- Evaporation & Condensation at the interface

on

- Droplet detachment time
- Equivalent droplet diameter
- Minimum film thickness prior to detachment

Obtain Generalized Charts for dependent variables as functions of the Governing non-dimensional parameters
Numerical Simulation of Porous Wetted Walls
Effect of Evaporation/Condensation at Interface

- \( z_0^* = 0.1 \), \( w_{in}^* = 0.01 \), Re=2000

\[
\begin{align*}
& m_f^+ = -0.005 \\
& \tau^* = 31.35 \\
& \text{(Evaporation)}
\end{align*}
\]
\[
\begin{align*}
& m_f^+ = 0.0 \\
& \tau^* = 27.69
\end{align*}
\]
\[
\begin{align*}
& m_f^+ = 0.01 \\
& \tau^* = 25.90 \\
& \text{(Condensation)}
\end{align*}
\]
Numerical Simulation of Porous Wetted Walls

**Wetted Wall Parameters**

- Length, velocity, and time scales:
  \[
  l = \sqrt{\frac{\sigma}{g(\rho_L - \rho_G)}} \quad U_0 = \sqrt{gl} \quad t_0 = \frac{l}{U_0}
  \]

- Nondimensional drop detachment time:
  \[
  \tau^* \equiv \frac{t_d}{t_0}
  \]

- Nondimensional minimum film thickness:
  \[
  \delta^*_{\text{min}} \equiv \frac{\delta_{\text{min}}}{l}
  \]

- Nondimensional initial film thickness:
  \[
  z^*_o \equiv \frac{z_o}{l}
  \]

- Nondimensional injection velocity:
  \[
  w^*_\text{in} \equiv \frac{w_{\text{in}}}{U_0}
  \]
Experimental Validations

1  Constant-head supply tank w/var. height
2  Perforated tube
3  Shut off valve
4  Test section porous plate, 316L SS
5  Sump pump
6  Sub-micron filter
7  Fast stirrer
8  Unistrut frame
9  Air relief valve
10 Baffles
11 Porous plate plenum
Experimental Variables

- Plate porosity
- Plate inclination angle $\theta$
- Differential pressure
- Fluid properties

Independent Parameters

- Injection velocity, $w_{in}$
- “Unperturbed” film thickness, $z_0$

Dependent Variables

- Detachment time
- Detachment diameter
- Maximum penetration depth
Experiment #W090 --

Evolution of Maximum Penetration Distance

![Graph showing the evolution of maximum penetration distance over time.](image)
Wetted Wall Summary

- Developed general non-dimensional charts applicable to a wide variety of candidate coolants and operating conditions

- Stability of liquid film imposes
  - Lower bound on repetition rate (or upper bound on time between shots) to avoid liquid dripping into reactor cavity between shots
  - Lower bound on liquid injection velocity to maintain minimum film thickness over entire reactor cavity required to provide adequate protection over subsequent fusion events

- Model Predictions are closely matched by Experimental Data
Forced Film Concept

Problem Definition

Prometheus: Few mm thick Pb “forced film” injected tangentially at >7 m/s over upper endcap

~ 5 m

Injection Point

First Wall

Detachment Distance $x_d$

Forced Film

X-rays and Ions
Forced Film Parameters

- Weber number $We$
  - Liquid density $\rho$
  - Liquid-gas surface tension $\sigma$
  - Initial film thickness $\delta$
  - Average injection speed $U$

\[
We \equiv \frac{\rho U^2 \delta}{\sigma}
\]

- Froude number $Fr$
  - Surface orientation $\theta$ ($\theta = 0^\circ \Rightarrow$ horizontal surface)

\[
Fr \equiv \frac{U}{\sqrt{g(\cos \theta)\delta}}
\]

- Mean detachment length from injection point $x_d$
- Mean lateral extent $W$
- Surface radius of curvature $R = 5$ m
- Surface wettability: liquid-solid contact angle $\alpha_{LS}$
- In Prometheus: for $\theta = 0 - 45^\circ$, $Fr = 100 - 680$ over nonwetting surface ($\alpha_{LS} = 90^\circ$)

Contact Angle, $\alpha_{LS}$

<table>
<thead>
<tr>
<th>Material</th>
<th>Contact Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>25°</td>
</tr>
<tr>
<td>Coated Glass</td>
<td>85°</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>50°</td>
</tr>
<tr>
<td>Plexiglas</td>
<td>75°</td>
</tr>
</tbody>
</table>
Experimental Apparatus

A Flat or Curved plate (1.52 × 0.40 m)
B Liquid film
C Splash guard
D Trough (1250 L)
E Pump inlet w/ filter
F Pump
G Flowmeter
H Flow metering valve
I Long-radius elbow
J Flexible connector
K Flow straightener
L Film nozzle
M Support frame
Experimental Parameters

• Independent Variables
  - Film nozzle exit dimension $\delta = 0.1–0.2$ cm
  - Film nozzle exit average speed $U_0 = 1.9 – 11.4$ m/s
  - Jet injection angle $\theta = 0^\circ$, 10°, 30° and 45°
  - Surface inclination angle $\alpha$ ($\alpha = \theta$)
  - Surface curvature (flat or 5m radius)
  - Surface material (wettability)

• Dependent Variables
  - Film width and thickness $W(x)$, $t(x)$
  - Detachment distance $x_d$
  - Location for drop formation on free surface
Detachment Distance

1 mm nozzle
8 GPM
10.1 m/s
10° inclination
Re = 9200
Detachment Distance Vs. Weber Number

\[ \theta = 0^\circ \]
\[ \delta = 1 \text{ mm} \]

- Glass (\(\alpha_{LS}=25^\circ\))
- Stainless Steel (\(\alpha_{LS}=50^\circ\))
- Plexiglas (\(\alpha_{LS}=75^\circ\))
- Rain-X® coated glass (\(\alpha_{LS}=85^\circ\))
Penetrations and Beam Ports

• Cylindrical obstructions modeling protective dams around penetrations and beam ports incompatible with forced films

• Film either detaches from, or flows over, dam
Forced Film Summary

- Design windows for streamwise (longitudinal) spacing of injection/coolant removal slots to maintain attached protective film
  - Detachment length increases with Weber and Froude numbers

- Wetting chamber first wall surface requires fewer injection slots than nonwetting surface $\Rightarrow$ wetting surface more desirable

- Cylindrical protective dams around chamber penetrations incompatible with effective forced film protection
  - “Hydrodynamically tailored” protective dam shapes may also fail
HYLIFE-II: Use slab jets or liquid sheets to shield IFE chamber first walls from neutrons, X-rays and charged particles.

- Oscillating sheets create protective pocket to shield chamber side walls
- Lattice of stationary sheets (or cylindrical jets) shield front/back walls while allowing beam propagation and target injection

*Pictures courtesy P.F. Peterson, UCB*
Major Design Questions

• Is it possible to create “smooth” prototypical turbulent liquid sheets?
  - 5 mm clearance between driver beam, sheet free surface in protective lattice ⇒ > 30 year lifetime for final focus magnets

• Can adjacent sheets, once they collide, separate and re-establish themselves before the next fusion event?

• Can the flow be re-established prior to the next fusion event?
  - Chamber clearing
  - Hydrodynamic source term – Beam propagation requirements
Flow Loop

- Pump-driven recirculating flow loop
- Test section height ~1 m
- Overall height ~5.5 m

A  Pump        B  Bypass line
C  Flow meter  D  Pressure gage
E  Flow straightener
F  Nozzle      G  Oscillator (Not used)
H  Sheet       I  400 gal tank
J  Butterfly valve  K  700 gal tank
Flow Conditioning

- Round inlet (12.7 cm ID) to rectangular cross-section 10 cm × 3 cm (y × z)
- Perforated plate (PP)
  - Open area ratio 50% with staggered 4.8 mm dia. holes
- Honeycomb (HC)
  - 3.2 mm dia. × 25.4 mm staggered circular cells
- Fine mesh screen (FS)
  - Open area ratio 37.1%
  - 0.33 mm dia. wires woven w/ open cell width of 0.51 mm (mesh size 30 × 30)
- 5th order contracting nozzle
  - Contraction ratio = 3
- Note: No BL trimming
Experimental Parameters

- $\delta = 1 \text{ cm}; \text{ aspect ratio } AR = 10$
- Reynolds number $Re = 130,000$ [$U_0$ average speed; $\nu$ liquid kinematic viscosity]
- Weber number $We = 19,000$ [$\rho_L$ liquid density; $\sigma$ surface tension]
- Froude number $Fr = 1,400$
- Fluid density ratio $\rho_L / \rho_G = 850$ [$\rho_G$ gas density]
- Near-field: $x / \delta \leq 25$
Surface Ripple Measurements

- Free surface $\Rightarrow$ interface between fluorescing water and air
  - Planar laser-induced fluorescence (PLIF)
- Free surface found w/edge detection
  - Threshold individual images
- $\sigma_z =$ standard deviation of free surface $z$-position spatially averaged over central 7.5 cm of flow
Surface Ripple: Nozzle H

- $\sigma_z$ measure of average surface ripple
- $\sigma_z/\delta < 4.3\%$ for $x/\delta < 25$
- $\sigma_z$ essentially independent of $Re$
- $\sigma_z \uparrow$ slightly as $x \uparrow$

![Graph showing $\sigma_z/\delta$ vs. $x/\delta$ for different Re values (25,000, 50,000, 97,000).]
Turbulent Breakup

- **Turbulent primary breakup**
  - Formation of droplets along free surface: “hydrodynamic source term”
  - Due to vorticity imparted at nozzle exit

- **Onset of breakup, $x_i$**
  - Location of first observable droplets
  - $x_i \downarrow$ as Weber number $We \uparrow$
Total droplet mass ejection rate $\approx 1300$ kg/s

- Assumes $G(x = 1 \text{ m})$ over entire surface area of each respective jet (Mean value of predictions)
- $\sim 3\%$ of total jet mass flow rate

Sauter mean dia. $\approx 5.7$ mm for all jets at $x = 1 \text{ m}$

- SMD at $x_i \approx 0.82 - 1.0$ mm for $d = 4.61 - 15.6$ cm, respectively
Implications for Beam Propagation

- Droplets enter into beam footprint

- Radial standoff, $\Delta r_s$
  - Measured from nominal jet surface

- Equivalent number density dependent on $x$ and $\Delta r_s$
  - Ignores jet-jet interactions
Implications for Typical RPD-2002 Jet: \( d = 4.61 \) cm (Row 0)

- Normalized effective density, \( \frac{\rho_{\text{eff}}}{\rho_{\text{FLIBE}}} \)
- Equivalent average number density, \( N \) (\# / m\(^3\))
- Radial standoff distance, \( \Delta r_s \) (mm)

Graph showing trends with different standoff distances: 
- \( x = 0.5 \) m
- \( x = 1 \) m
- \( x = 1.5 \) m
- \( x = 2 \) m

Beam / jet standoff distance
Beam Propagation Implications

• Model predictions imply protection concept is incompatible with beam propagation requirements

• However, model is based on:
  ▪ Fully developed turbulent pipe flow at exit
  ▪ No flow conditioning, nozzle or BL cutting

• Can nozzles / jets be designed to reduce these number densities to a level compatible with beam propagation requirements?
Boundary Layer Cutter

- “Cut” (remove BL fluid) on one side of liquid sheet

- Independently control:
  - Cut depth, $\Delta z_{\text{cut}}$
  - Downstream location of cut, $x$

- Removed liquid (~0.18 kg/s) diverted to side
Cutter Details

• Aluminum blade inserted into flow
  ▪ Remove high vorticity / low momentum fluid near nozzle wall
  ▪ Blade face tilted 0.4° from vertical
  ▪ Blade width (y-extent) 12 cm

• Relatively short reattachment length
  ▪ Nozzle contraction length 63 mm
Mass Collection Procedure

- Cuvette opening = 1 cm × 1 cm w/0.9 mm wall thickness

- Five adjacent cuvettes
  - Cuvette #3 centered at y = 0

- Located at x, Δzs away from nominal jet position
  - Δzs ≅ 2.5–15 mm
  - Experiments repeated to determine uncertainty in data

- Mass collected over 0.5–1 hr
Experimental Number Density

\( x / \delta = 25 \)

Equivalent average number density, \( N \) (# / m\(^3\))

Cuvette standoff distance, \( \Delta z_s \) (mm)

Standard Design
No Fine Mesh
Closed – No cutting
Open – 0.25 mm cut
Summary: Mass Collection

- Flow straightening and contracting nozzle significantly reduce ejected droplet mass (by 3–5 orders of magnitude) compared w/model

- BL cutting has considerable impact on collected droplet mass

- BUT: proper flow conditioning more important

- Flow conditioning and BL cutting reduce collected droplet mass by orders of magnitude (compared with model predictions)
Conclusions

- Hydrodynamic source term sensitive to initial conditions
- Jet geometry, surface ripple and breakup affected by flow conditioning
- Flow conditioning / converging nozzle reduces droplet mass flux (and number density) by 3–5 orders of magnitude over model predictions
- BL cutting appears to eliminate droplet ejection for a “well-conditioned” jet
- Preventing blockage of fine mesh screens major issue
Acknowledgements

**Georgia Tech**

- **Academic Faculty**: Damir Juric and Minami Yoda
- **Research Faculty**: D. Sadowski and S. Shin

**DOE**

- W. Dove, G. Nardella, A. Opdenaker

**ARIES-IFE Team**

**LLNL/ICREST**

- W. Meier, R. Moir