Zero-Boil-Off Tank (ZBOT) Experiment – Ground-Based Validation of Self-Pressurization & Pressure Control Two-Phase CFD Model

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Cryogenic Fluid Management of propellant storage tanks is in the critical path of most envisioned NASA exploration mission including mission to Mars.

The Zero Boil Off Tank (ZBOT) experiment provides a small-scale simulant-fluid investigation of storage tank pressurization and pressure control in the Microgravity Science Glovebox (MSG) unit aboard the ISS. Its objectives are to:

- Elucidate the roles of the various interacting transport and phase change phenomena that impact tank pressurization and pressure control in microgravity to form a scientific foundation for storage tank engineering.
- Obtain microgravity data for tank stratification, pressurization, mixing, destratification, and pressure control time constants during storage.
- Develop a *state-of-the-art* CFD two-phase model for storage tank pressurization & pressure control.
- Validate and Verify the zonal- and CFD-based tank models using the microgravity data. **Use the model and correlations to optimize and scale-up future storage tank design.**
Notional Pathway to Mature Understanding Of CFM Fluid Physics and Validated Computational Models

- Natural Convection
- Forced Mixing
- Evaporation/Condensation
- Microg Superheats/Nucleate Boiling
- Droplet Breakup & Transport
- Droplet Phase Change
- Microgravity Two-Phase Flow & Heat Transfer Regimes/Transitions
- Interfacial Turbulence Effects
- Vapor-Side Turbulent Transport
- Non-Condensable Gas Transport
- Double Diffusive Barriers
- Marangoni Convection
- Interfacial Mass Transfer Kinetics
- Capillary Flow & Free Surface Dynamics
- Contact Angle Dynamics & Thin Film Evaporation
- Sloshing
- Phase Control/Positioning

1-g Data

\( \mu g \)-Fundamentals (Simulant Fluids)

\( \mu g \)-Subscale Experiments (Cryogens)

SOA Models

- Multinode Models: GFSSP, Sinda/Fluint
- CFD Models: Ansys/Fluent, Flow3D

Cryo Demonstrations

K-Site, MHTB

ZBOT, TPCE

RMM3, Other Notional ISS JEM Cryo Experiments
Experiment was installed by Astronaut Joe Acaba on September 19 & 20th in the MSG and powered up.

System thermal & fluid characterization started on September 24th.

Actual Test runs began on Oct 1st.

Currently the 70% test runs are being conducted and near completion.

Data and images are being downloaded continuously.
ZBOT Hardware Components

ZBOT Hardware Components in MSG

Acrylic Test Tank Dome

Stainless Steel Test Tank Base, Nozzle & Screen LAD
ZBOT Camera & Illumination Package for Image Capture & PIV

- Camera Acceptance Cone
- Tank
- Beam Dump
- Diode Laser
- Light Sheet Tilted 12°; eliminate tilt for ZBOT-2

Camera Package
Illumination Package
ZBOT Tank Pressurization & Mixing Cooling Test Matrix

- 68 pressurization, jet mixing, and destratification tests will be performed first at 3 fill levels with and without Particle Imaging Velocimetry (PIV)
- 30 Tests will be repeated with particles injected & PIV performed as Tech Validation

### Type of Test | Method & Mode |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurization</td>
<td>Heater Strip</td>
</tr>
<tr>
<td></td>
<td>Vacuum Jacket Heating</td>
</tr>
<tr>
<td></td>
<td>Heater and Vacuum Jacket</td>
</tr>
<tr>
<td>Mixing Only</td>
<td>Uniform Temperature</td>
</tr>
<tr>
<td></td>
<td>After Self-Pressurization</td>
</tr>
<tr>
<td>Subcooled Mixing</td>
<td>Uniform Temperature</td>
</tr>
<tr>
<td></td>
<td>After Self-Pressurization</td>
</tr>
</tbody>
</table>

#### Input Variables (Tolerances)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Tolerances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater Power</td>
<td>(w/ in 5 mW RMS)</td>
</tr>
<tr>
<td>Vacuum Jacket Offset</td>
<td>(+/- 0.2°C)</td>
</tr>
<tr>
<td>Fill Level</td>
<td>(70% +/- 3%, 80% +/- 3%, 90% -3%)</td>
</tr>
<tr>
<td>Jet Temperature</td>
<td>(+/- 0.25°C)</td>
</tr>
<tr>
<td>Jet Velocity/Flow rate</td>
<td>(10% of reading)</td>
</tr>
</tbody>
</table>

#### Outputs as Time Evolution

<table>
<thead>
<tr>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
</tr>
<tr>
<td>Fluid Temperature (6 locations)</td>
</tr>
<tr>
<td>Wall Temperature (17 locations)</td>
</tr>
<tr>
<td>Jacket Temperature (21 locations)</td>
</tr>
<tr>
<td>Jet Penetration Depth</td>
</tr>
<tr>
<td>DPIV Velocity/Flow Structures</td>
</tr>
</tbody>
</table>

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**Perfluoro-n-Pentane**

(PnP, or C5F12) n-isomer (Straight Chained) Chemical Structure

- Refigerant/Cleaning fluid
- High purity (99.7% straight-chained n-isomer)
- Boiling Point = 29°C @ 1 atm
- Vapor Pressure = 12.5 psia @ 25°C

**Benefits**

- Boils Near Room Temperature
- Near zero contact angle with test tank
- Tox 0 – Approved by JSC toxicology and MSFC ECLSS groups as safe for use within International Space Station

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Ground Based Model Validation Experiment in Flight Hardware:
1G Self-Pressurization - Vacuum Jacket Heating

VJ Heating (3.75 W/m²), 70%, Self-Pressurization: \{ \text{Ra}_L \approx (10)^{11}, \text{Ra}_V \approx (10)^8 \}
Ground Based Model Validation Experiment in Flight Hardware: 1G Self-Pressurization – Strip Band Heating

Strip Band Heating (1W), 90%, Self-Pressurization: $\{ \text{Ra}_L \rightarrow (10)^{11}, \text{Ra}_V \rightarrow (10)^8 \}$

Time = 12600s
Validation Against ZBOT-Flight 1G Pressurization – Energy Flow & Distributions During SB Heating & VJ Heating

SB Heating Self-Pressurization

VJ Heating Self-Pressurization

\[ \dot{m}L = Q_{IL} - Q_{IV} \]

Evaporation

\[ Q_{IL} > Q_{IV}, \quad \dot{m} > 0 \]

\[ Q_{IL} < Q_{IV}, \quad \dot{m} > 0 \]

Evaporation

\[ \dot{m}L = Q_{IL} - Q_{IV} \]
3D VOF Model Simulation of Jet Mixing & Ullage Penetration in Microgravity

- 4 cm/s laminar
- 15 cm/s transitional
- 20 cm/s turbulent
- 23 cm/s turbulent
- 25 cm/s turbulent
Vacuum Jacket Self-Pressurization in Microgravity - Followed by Subcooled Jet Mixing

VJ Self-Pressurization

- FL = 70%
- \( T_{VJ} = T + 1 \) K

Subcooled Jet Mixing

- FL = 70%
- \( T_{VJ} = T + 1 \) K
- \( V_{jet} = 10 \) cm/s
- \( T_{jet} = T - 1 \) K
Microgravity Strip Band Heating (0.5 W) Self-Pressurization In Microgravity - Followed by Isothermal Jet Mixing

Case ZBOT-208-Self-Press-0_5W :

Case ZBOT-204-35s-PressControl-afterSelf-Press-0_5W-15cm/s

SB Self-Pressurization & Subcooled Jet Mixing

\[ \text{FL} = 70\% \]
\[ Q = 0.5 \text{ W} \]
\[ T_{\text{VJ}} = T_{\text{T}} \]
\[ V_{\text{jet}} = 15 \text{ cm/s} \]
\[ T_{\text{jet}} = T_{\text{outlet}} \]

\[ T_{\text{Heater}} & T_{\text{Sat}} \]

5.15 K
Microgravity Isothermal Jet Mixing (Without Cooling)

- FL = 70%
- $T_0 = 38 \, ^\circ C$
- $T_{Vj} = T_T$
- $V_{jet} = 6, 15 \, \text{cm/s}$
- $T_{jet} = T_{outlet}$
Microgravity Subcooled Jet Mixing at Jet $V = 15$ cm/sec

**Tank Pressure**

- FL = 70%
- $T_0 = 38$ C
- $V_{\text{jet}} = 15$ cm/s

**LAD & Sat Temperatures**

- $T_0 = 38$ C
- $V_{\text{jet}} = 15$ cm/s
Microgravity Subcooled Jet Mixing at Jet V = 6 cm/sec

**Tank Pressure**

**LAD & Sat Temperatures**

\[ T_{LAD} - T_{Sat} \]

- FL = 70%
- \( T_0 = 38 \) C
- \( T_{VJ} = T_T \)
- \( V_{jet} = 6 \) cm/s
Backup Charts
Develop a computational platform to study and simulate the engineering performance of propellant storage tanks in 1g and microgravity with physical and numerical fidelity:

- **Multiphase CFD Models**: Capture the intricate two-phase transport and interfacial phenomena that control tank pressurization, pressure control, filling and cryogen transfer in 1g, partial g and microgravity with physical accuracy.

- **Multinode Models**: Be able to predict tank engineering performance with numerical efficiency.

- **Coupled CFD-Multinode simulations necessary to predict tank performance during long duration (up to 1 year) missions.**

- **Increase capabilities of both CFD and multi-node analysis tools to perform predictive simulations of different Cryogenic Fluid Management (CFM) operations under settled and unsettled conditions for future missions:**
  - Self-Pressurization
  - Pressure control (axial jet, spray bar TVS, Broad Area Cooling)
  - Pressurization (helium and autogenous, different submergence)
  - Transfer line chilldown (pulse, continuous)
  - Tank chilldown (charge-hold-vent)
  - Tank filling and draining
  - ISRU liquification

**Development & Validation of Analysis Tools (DVAT) For CFM**

Cryogenic Propellant Depots (credit: ULA concept)

In Situ Resource Utilization (ISRU) Lox/CH4 Spacecraft Propulsion

Large Propulsion Stages
Validation Against ZBOT 1G Pressurization & Pressure Control Simulant Fluid (PnP) – Small Scale

1W Strip Heater, Jet Mixing Pressure Control, Vjet = 25cm/sec, Tjet = 294 – Tliquid ~ 296

3D with air t = 10,000 s

3D with air t = 11,500 s

\[ Q_{IL} < Q_{IV} \]

\[ \dot{m} < 0 \]

Condensation

\[ \dot{m}L = Q_{IL} - Q_{IV} \]

\[ Q_{IV} < Q_{IL} \]

\[ \dot{m} < 0 \]

Condensation

\[ \dot{m}L = Q_{IL} - Q_{IV} \]
Two-Phase Sharp Interface Storage Tank CFD Model

<table>
<thead>
<tr>
<th>Equation</th>
<th>Liquid</th>
<th>Ullage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuity</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Navier Stokes</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Energy</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Species</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Turbulence (k-ω)</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

**Continuity:**
\[
\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{v}) = 0
\]

**Momentum:**
\[
\frac{\partial}{\partial t} (\rho \mathbf{v}) + \nabla (\rho \mathbf{v} \cdot \mathbf{v}) = -\nabla p + \nabla \left[ \mu_{\text{eff}} (\nabla \mathbf{v} + \nabla \mathbf{v}^T) \right] + \rho \mathbf{g} + \mathbf{F}_{\text{vol}}
\]

**Energy:**
\[
\frac{\partial}{\partial t} (\rho E) + \nabla (\rho E + p) = \nabla (k_{\text{eff}} \nabla T) + S_h
\]

**Species:**
\[
\frac{\partial}{\partial t} (\rho \omega) + \nabla (\mathbf{v} \rho \omega) = \nabla \cdot (\rho D_m \nabla \omega)
\]

**Interfacial Energy Balance:**
\[
P_v = \frac{\omega_v M_g}{\omega_v M_g + (1 - \omega_v) M_v} P
\]

**Schrage Interfacial Mass Transfer:**
\[
T_1 = T_{\text{sat}}(P_v)
\]
\[
L J_v = -k_{i} \nabla T_1 \cdot \hat{n} + \kappa \cdot \nabla T \cdot \hat{n}
\]

**Stefan Wind:**
\[
J_v = -\left( \frac{\rho D_m}{1 - \omega_v} \right) \nabla \omega \cdot \hat{n}
\]
Energy and Temperature as mass average scalars:

\[
E = \frac{\sum_{q=1}^{2} \alpha_q \rho_q E_q}{\sum_{q=1}^{2} \alpha_q \rho_q}
\]

Properties:

\[
\rho = \sum_{q=1}^{2} \alpha_q \rho_q, \quad \mu_{eff} = \sum_{q=1}^{2} \alpha_q \mu_{eff q}, \quad k_{eff} = \sum_{q=1}^{2} \alpha_q k_{eff q}
\]

Continuity of Volume Fraction of the \(q\)-th phase:

\[
\frac{1}{\rho_q} \left[ \frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{V}_q) \right] = S_{\alpha_q}
\]

Continuum Surface Force (Brackbill et al.):

\[
F_{vol} = \sum_{\text{pairs } i,j, i < j} \sigma_{ij} \alpha_i \rho_i h_i \nabla \alpha_j + \alpha_j \rho_j h_j \nabla \alpha_i
\]

where \( h_i = \nabla \cdot \hat{n} \)

Interfacial mass transfer per unit volume:

\[
S_{\alpha_q} = \dot{m}_i \cdot \mathbf{A}_i \left[ \frac{\text{kg}}{\text{m}^3 \cdot \text{sec}} \right]
\]

\[
\mathbf{A}_i = |\nabla \alpha|,
\]

\( \dot{m}_i \) is a mass flux vector in \( \text{kg}/(\text{m}^2 \cdot \text{sec}) \)

Schrage Interfacial Mass Transfer:

\[
\dot{m}_i = J_v = \frac{2\sigma}{2 - \sigma} \frac{1}{\sqrt{2\pi RT_i}} [P_{\text{sat}}(T_i) - P_v]
\]
K-Site & MHTB 1G LH2 Self-Pressurization: CFD Results vs Experiment – Tank Pressure, Temperature and Flow Field
ZBOT Experiment: Flight Test Tank & Fluid Support Hardware

ZBOT Hardware in Microgravity Science Glovebox Mockup at NASA MFSC

ZBOT Fluid Support Unit (FSU) & Reservoir Schematic
Validation Against ZBOT 1G Pressurization & Pressure Control Simulant Fluid (PnP) – Small Scale - Strip Heater

Jet Mixing Pressure Control - 20 Torr Residual Air – 2 deg Subcooled Jet

3D with air $t = 10,000$ s  
3D with air $t = 11,500$ s

Pressure

Temperature
Microgravity Strip Band Heating (0.1 W) Self-Pressurization In Microgravity