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.
Validation Cases That Have Been Performed

- 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

Notional Pathway to Mature Understanding Of CFM Fluid Physics and Validated Computational Models

**1-g Data**
K-Site, MHTB

**μg-Fundamentals (Simulant Fluids)**
ZBOT, TPCE

**μg-Subscale Experiments (Cryogens)**
RMM3, Other Notional ISS JEM Cryo Experiments

**Multinode Models: GFSSP, Sinda/Fluint**

**CFD Models: Ansys/Fluent, Flow3D**

**Cryo Demonstrations**
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 Test Tank inside the Vacuum Jacket

Acrylic Test Tank Dome

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

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

Camera Package
Illumination Package
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
--- | ---
Pressurization | Heater Strip
 | Vacuum Jacket Heating
 | Heater and Vacuum Jacket
Mixing Only | Uniform Temperature
 | After Self-Pressurization
Subcooled Mixing | Uniform Temperature
 | After Self-Pressurization

Input Variables (Tolerances)
- Heater Power (w/ in 5 mW RMS)
- Vacuum Jacket Offset (+/- 0.2°C)
- Fill Level (70% +/- 3%, 80% +/- 3%, 90% -3%)
- Jet Temperature (+/- 0.25°C)
- Jet Velocity/Flow rate (10% of reading)

Outputs as Time Evolution
- Pressure
- Fluid Temperature (6 locations)
- Wall Temperature (17 locations)
- Jacket Temperature (21 locations)
- Jet Penetration Depth
- DPIV Velocity/Flow Structures

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

- Refrigerant/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: \( \{ Ra_L \rightarrow (10)^{11}, Ra_V \rightarrow (10)^8 \} \)
Ground Based Model Validation Experiment in Flight Hardware: 1G Self-Pressurization – Strip Band Heating

Strip Band Heating (1W), 90%, Self-Pressurization: \{ Ra_L \rightarrow (10)^{11}, Ra_V \rightarrow (10)^8 \}
Validation Against ZBOT-Flight 1G Pressurization – Energy Flow & Distributions During SB Heating & VJ Heating

**SB Heating Self-Pressurization**

\[ Q_{WV} \]
\[ \dot{m}L \]
\[ Q_{IL} > Q_{IV} \]
\[ \dot{m} > 0 \]

Evaporation

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

**VJ Heating Self-Pressurization**

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

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

V [m/s]
0.25
0.19
0.13
0.06
0.00
Vacuum Jacket Self-Pressurization in Microgravity - Followed by Subcooled Jet Mixing

FL = 70%
$T_{VJ} = T_T + 1$ K

$V_{jet} = 10$ cm/s

$T_{jet} = T_o - 1$ 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

- \( FL = 70\% \)
- \( Q = 0.5 \text{ W} \)
- \( T_{VJ} = T_T \)
- \( V_{jet} = 15 \text{ cm/s} \)
- \( T_{jet} = T_{outlet} \)

\( P - P_a \) (Pa)

Time (hours)

- \( T_{Heater} \) & \( T_{Sat} \)

5.15 K
Microgravity Isothermal Jet Mixing (Without Cooling)

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

**Tank Pressure**

- FL = 70%
- $T_0 = 38$ C
- $T_{VJ} = T_T$
- $V_{jet} = 15$ cm/s

**LAD & Sat Temperatures**
Microgravity Subcooled Jet Mixing at Jet $V = 6 \text{ cm/sec}$

Tank Pressure

LAD & Sat Temperatures

$F_L = 70\%$
$T_0 = 38 \text{ C}$
$T_{\text{J}} = T_T$
$V_{\text{jet}} = 6 \text{ cm/s}$
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 liquifaction
Validation Against ZBOT 1G Pressurization & Pressure Control Simulant Fluid (PnP) – Small Scale

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

\[ mL = Q_{IL} - Q_{IV} \]
\[ mL < 0 \]

Condensation

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

\[ m < 0 \]
## 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>

### Equations

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

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

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

**Species:**
\[
\frac{\partial (\rho \omega)}{\partial t} + \nabla (\vec{\nu} \rho \omega) = \nabla \left( \rho D_m \nabla \omega \right)
\]

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

### Schrage Interfacial Mass Transfer:
\[
J_v = 2\sigma \frac{1}{2 - \sigma} \frac{1}{\sqrt{2\pi RT_1}} \left[ P_{\text{sat}}(T_1) - P_v \right]
\]

### 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:
\[ \frac{1}{\rho_q} \left[ \frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \mathbf{v}_q) \right] = S_{\alpha_q} \]

Continuum Surface Force (Brackbill et al.):
\[ F_{vol} = \sum_{\text{pairs } ij, i < j} \alpha_i \rho_i h_j \nabla \alpha_j + \alpha_j \rho_j h_i \nabla \alpha_i \]
where \( h_i = \nabla \cdot \mathbf{n} \)

Interfacial mass transfer per unit volume:
\[ S_{\alpha_q} = \mathbf{m}_i \cdot \mathbf{A}_i \left[ \frac{kg}{m^3 \cdot \text{sec}} \right] \quad \mathbf{A}_i = |\nabla \alpha|, \]
\( \mathbf{m}_i \) is a mass flux vector in kg/(m²·sec)

Schrage Interfacial Mass Transfer:
\[ \mathbf{m}_i = I_v = \frac{2\sigma}{2 - \sigma} \frac{1}{\sqrt{2\pi RT_I}} \left[ P_{sat}(T_I) - P_v \right] \]
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

- Adjusted Experimental Data
- CFD: Pure Vapor
- CFD: Vapor w/ Air
Microgravity Strip Band Heating (0.1 W) Self-Pressurization In Microgravity