Effect of Residual Noncondensables on Pressurization & Pressure Control of a Zero-Boil-Off Tank in Microgravity. M. Kassemi¹, S. Hylton¹, O. Kartuzova¹. ¹National Center for Space Exploration (NCSER), NASA Glenn Research Center, Cleveland, OH 44135, USA.

The Zero-Boil-Off Tank (ZBOT) Experiment is a small-scale experiment that uses a transparent ventless Dewar and a transparent simulant phase-change fluid to study sealed tank pressurization and pressure control with applications to on-surface and in-orbit storage of propellant cryogens. The experiment will be carried out under microgravity conditions aboard the International Space Station in the 2014 timeframe. This paper presents preliminary results from ZBOT’s ground-based research that focuses on the effects of residual noncondensible gases in the ullage on both pressurization and pressure reduction trends in the sealed Dewar. Tank pressurization is accomplished through heating of the test cell wall in the wetted and un-wetted regions simultaneously or separately. Pressure control is established through mixing and destratification of the bulk liquid using a temperature controlled forced jet flow with different degrees of liquid jet subcooling.

A Two-Dimensional axisymmetric two-phase CFD model for tank pressurization and pressure control is also presented. Numerical prediction of the model are compared to experimental 1g results to both validate the model and also indicate the effect of the noncondensible gas on evolution of pressure and temperature distributions in the ullage during pressurization and pressure control. Microgravity simulations case studies are also performed using the validated model to underscore and delineate the profound effect of the noncondensables on condensation rates and interfacial temperature distributions with serious implications for tank pressure control in reduced gravity.

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Affordable and reliable in-orbit or on-surface cryogenic storage for propellant and/or life support consumables is essential to all stages of NASA’s Exploration Program.

Heat leaks from the surroundings can lead to liquid vaporization resulting in significant mass loss and/or significant increase in tank pressure.

NASA has identified cryogenic storage & transfer as an area with greatest potential for cost saving

Dynamic storage tank pressure control that involves some mode of mixing of the bulk liquid with or without active or passive cooling is needed to realize cost savings.

To combat the unwanted effects of cryogen vaporization several strategies exist:

- Venting ➔ Mixing/Venting ➔ **Considerable mass Loss**
- Venting ➔ Mixing/Passive Cooling (TVS) ➔ **Reduced Mass Loss**
- Ventless ➔ Active Cooling ➔ **ZBO**
Fundamental Multiphase Science Issues

- Natural Convection
- Forced Mixing
- Evaporation Condensation
- Microgravity Superheats
- Non-Condensable Gases
- Transport Barrier
- Marangoni Convection
- Interfacial Kinetics
- Free Surface Dynamics
- Contact Angle Dynamics
- Sloshing/Droplet Transport
- Phase Control/Positioning

Due to unavailability of microgravity Data:

- Empirically-based engineering correlations for pressurization, mixing, destratification, pressure reduction, and fluid transfer time constants are scarce or based on ill-applied theory.
- Customized, and fully validated CFD models are not available to aid the scale-up.
- Prediction of engineering models lack desired accuracy by a wide margin due to scarcity of microgravity relevant empirical correlations.
A small-scale simulant-fluid experimental platform to be accommodated in the Microgravity Science Glovebox (MSG) unit aboard the ISS.

Obtain microgravity data for tank stratification, pressurization, mixing, destratification, and pressure control time constants during storage.

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.

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.
ZBOT: Small-Scale *Simulant* Fluid ISS Experiment
(Preliminary Ground-Based Tests)

- Small Scale Experiment: 20 cm x 40 cm
- Simulant Fluid: HFE7000
- Transparent Dewar: Acrylic
- Liquid from a reservoir is degassed and pumped into the test cell.
- Pressurization is induced by Kapton strip heaters on the wetted and unwetted tank walls
- Pressure control is achieved through simultaneous mixing and cooling of the bulk liquid using a forced jet flow
- Temperature of the jet is maintained by a heat exchanger in the fluid support unit (FSU)
- Ullage Pressure measured by MKS Transducer
- Wall temperatures monitored with RTDs
- Ullage and liquid temperatures monitored by accurate thermistors (+/- 0.04 K)
Two–Phase Storage Tank CFD Model

Interfacial Energy Balance:

\[ LJ_v = -k_l \mathbf{\nabla} T_l \cdot \hat{n} + k \cdot \mathbf{\nabla} T \cdot \hat{n} \]

\[ T_l = T_{sat}(P_v) \] \(\times\)

Schrage Interfacial Mass Transfer:

\[ I_v = \frac{2 \sigma}{2 - \sigma} \frac{1}{\sqrt{2 \pi R T_l}} [P_{sat}(T_l) - P_v] \]

\[ \frac{P_{sat}(T_l)}{P_r} = e^{\frac{L}{R} \left( \frac{1}{T_r} - \frac{1}{T_l} \right)} \]

\[ P_v = \frac{\omega_v M_g}{\omega_v M_g + (1 - \omega_v) M_v} P \]

Stefan Wind:

\[ I_v = -\left( \frac{\rho D_m}{1 - \omega_v} \right) \mathbf{\nabla} \omega \cdot \hat{n} \] \(\checkmark\)

### Table

<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 SST)</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>
Effects of Residual Air (Non-Condensable) in the Ullage on Transport
1G Self-Pressurization: Model Prediction vs Experiment

No air

Air at 20 Torr

With Residual Air

Time = 6000s

Temperature (T [K]):
- 296.30
- 296.07
- 295.84
- 295.61
- 295.38

Graph showing pressure difference ($P - P_0$) vs time (s) for experimental data and CFD simulations with pure vapor and vapor with air.
1G Self-Pressurization Simulations

Time = 6000s

Temperature (K)

- 296.30
- 296.07
- 295.84
- 295.61
- 295.38

Graphs showing:
- Mass flow rate as a function of distance along tank radius (m)
- Interface temperature (K) as a function of distance along tank radius (m)

Graphs comparing Pure Vapor vs. Vapor w/ Air.
Pressure Control: Model Prediction vs Experiment

- Over-prediction of pressure drop lag.
- Good prediction of pressurization reduction rate.
- Good prediction of the main features of the non-intuitive temperature behavior/trend.
- Noticeable under-prediction of local ullage temperature.

Flow Field

Temperature Field
1G Pressure Control Simulations

Flow Field
9720s

Temperature Field
9720s

Concentration Field
9720s

Flow Field
11160s

Temperature Field
11160s

Concentration Field
11160s
1G Pressure Control Simulations
• In Microgravity, the ullage is spherical, the interface is curved and the tank wall is all wetted.
• A prominent laminar natural convective torroidal flow ensues mainly near the heater and interface.
• The Microgravity thermal stratification pattern and its magnitude is significantly different from the 1G case.
• Ullage pressure still rises due to wall heating from the top.
• Flow becomes steady and stable.

Test Tank is enclosed in a vacuum jacket
Tank is heated by a strip-heater placed circumferentially on the outside wall of the tank
ZBOT Simulations - Microgravity Pressurization

No air

Time = 43200s

T [K]
311.00
307.75
304.50
301.25
298.00

311.00
0.999275
0.999262
0.999249
0.999236
0.999223

With Residual Air

Time = 43200s

T [K]
311.00
307.75
304.50
301.25
298.00

311.00
0.999275
0.999262
0.999249
0.999236
0.999223

36000s

distance along axis (m)

Pure Vapor

Vapor w/ Air

36000s

distance along axis (m)

Vapor w/ Air

36000s

T_{\text{interface}} [K]
305.495
305.49
305.485
305.48
305.475
305.47
305.465
305.46
305.455
305.45
305.445
In Microgravity, a forced sub-cooled jet is used to control the tank pressure.

The sub-cooled jet flow impinges on the interface and isolates it from the heaters.

Initially, the test tank thermally de-stratifies rapidly using a 5 cm/s jet flow.

The extent of pressure drop is however very sensitive to the residual air (noncondensable in the ullage).

- Test Tank is enclosed in a vacuum jacket
- Tank is heated by a strip-heater placed circumferentially on the outside wall of the tank
- A forced sub-cooled jet is used for pressure control
ZBOT Simulations: Micro-G Pressure Control

No air

With Residual Air

Time = 8s

T [K]
313.00
308.25
303.50
300.00
298.75
294.00

ρ (Vapor) T [K]
0.999000
0.996000
0.992000
0.989000
0.986000
0.983000

m dot_{interface} (kg/s)
0.14
0.15
0.16
0.17
0.18
0.19
0.2

distance along axis (m)

8s

 Pure Vapor

Vapor w/ Air

8s

Ω_{interface}
0.975
0.98
0.985
0.99
0.995
1
1.005

distance along axis (m)

0.14
0.15
0.16
0.17
0.18
0.19
0.2

Vapor w/ Air

T_{interface} (K)
297
298
299
300
301
302
304
305

distance along axis (m)

0.14
0.15
0.16
0.17
0.18
0.19
0.2
In presence of residual non-condensable in Microgravity, a relatively strong Marangoni convection vortex restricts the spread of cooled-jet flow over the interface.

- Initial rate of pressure drop is significantly reduced.
- Pressure in the tank eventually rises due to accumulation of non-condensable in the ullage impeding the transport of vapor to the interface.
ZBOT Simulations: Micro-G Pressure Control

Residual Air-Marangoni

Graphs showing temperature and mass flow rate over distance along the axis.

- Pure Vapor
- Vapor w/ Air
- Vapor w/ Air - Marangoni Effect

Time = 500s

\(\omega_{\text{vapor}}\) T [K]

- 0.9993 to 0.9550
- 313.00 to 294.00

\(m_{\text{dot,interface}}\) (kg/s)

- 0.0004 to 0.0004
- 0.14 to 0.2

\(T_{\text{interface}}\) (K)

- 304.00 to 294.00
- 0.14 to 0.2
ZBOT Simulations: Micro-G Pressure Control

No air  Residual Air  Residual Air-Marangoni  No Air-Marangoni

Time = 1790s  Time = 1800s  Time = 1800s  Time = 1800s

T [K]
313.00
308.25
303.50
298.75
294.00

ω (Vapor)
0.9993
0.9870
0.9747
0.9623
0.9500

T [K]
313.00
308.25
303.50
298.75
294.00

ω (Vapor)
0.9993
0.9882
0.9871
0.9771
0.9661

P (Pa)
135000
125000
115000
105000
95000
85000
75000
0
300
600
900
1200
1500
1800

time (s)

Pure Vapor
Vapor w/ Air
Pure Vapor - Marangoni Effect
Vapor w/ Air - Marangoni Effect
Closure: Noncondensable Gas Effects

- **Transport in the Ullage:**
  - Noncondensable impediment to vapor transport in ullage
    - Panzarella & Kassemi (IJH&MT 2009)

- **Fluid flow & mixing in the liquid:**
  - Noncondensable instigates gravity-independent Marangoni mixing
    - (Straub-2001)

- **Mass transfer kinetics at the interface:**
  - Noncondensable forms kinetics barrier – further mitigates condensation
    - (Pong & Moses-1986)